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Reconciling a positive ecological balance with human development: A quantitative assessment

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ABSTRACT

Clear indicators and evaluation criteria are essential to keep humanity's environmental impact within planetary boundaries. We introduce a new criterion based on two constraints, accounting for both ecological and human sustainability. The ecological constraint is defined through a novel indicator, the eco-balance, grounded on the well known concept of ecological footprint and the new concept of population biodensity. The human sustainability constraint is based on the estimated level of biocapacity consumption needed to achieve an acceptable level of human development. The application of our criterion to world countries shows where technological improvements and changes in consumption patterns are sufficient to reach sustainability, and where actions on population and/or restoring ecological capital are also needed. This highlights synergic patterns going beyond simplistic schemes, such as overconsumption vs. overpopulation or developed vs. developing countries.

1. Introduction

To be sustainable, humanity needs to reduce its environmental impact below planetary boundaries (O'Neill et al., 2018; Steffen et al., 2015). Humanity's total impact is given by the product of population by per capita impact, which in turn depends on the level of consumption (also referred as affluence) and the adopted technology, as highlighted by the well known $I = PAT$ equation (Ehrlich and Holdren, 1971; York et al., 2003). Although per capita impact can be decreased through reduced consumption and smarter technology, it cannot be reduced to zero because a certain amount of natural resources and ecological services is required to satisfy people's basic needs (Goodland, 1995; Knight and Rosa, 2011; Smil, 2021).

When multiplied by a large population, even a small impact can become significant, leading to an overshoot of planetary boundaries. An important question hence is whether changes in consumption patterns and technological improvements (resp. A and T in the $I = PAT$ equation) enable a sufficient reduction of environmental impact (I) without reducing human well-being and development at unacceptable levels, or whether the population factor (P) needs to be used as well — clearly avoiding coercion and learning from existing examples of successful voluntary family planning programs, e.g., based on women empowerment, expansion of educational opportunities for girls, and easier access to contraception (Robinson and Ross, 2007; Wolf et al., 2021; O'Sullivan, 2018). This important question cannot be answered by theoretical reasoning alone and alternative options need to be systematically evaluated on the light of reliable criteria and indicators (Bell and Morse, 2019; Bravo, 2014).

One of the most widely used sustainability indicator is the *ecological footprint* (*EF*) (Kitzes et al., 2009; Zhang et al., 2017). The *EF* was originally developed in the 1990s by Mathis Wackernagel and colleagues as an estimate of people's consumption of ecological capital (Wackernagel and Rees, 1996; Wackernagel et al., 1999). Although not exempt from criticisms (e.g., Giampietro and Saltelli, 2014; Kitzes et al., 2009, see Section 2.1), the *EF* presents several advantages in comparison with other environmental indicators (Čuček et al., 2012; Hoekstra and Wiedmann, 2014; Wiedmann and Barrett, 2010). First, it is based on consumption, hence internalising any eventual displacement of environmental impact outside national borders (Andersson and Lindroth, 2001; Grazi et al., 2007; Peters et al., 2011; Hoekstra and Wiedmann, 2014). Second, it is accounted using "global hectares" (gha) — units of surface with world average bio-productivity (Global Footprint Network, 2020) — and is thus directly comparable with the *biocapacity* indicator (*BC*), which is expressed in the same units and refers to the amount of

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ecological services provided by the natural and man-managed lands of a given area. This relates the *EF* to the concept of planetary boundaries (Downing et al., 2020; Wackernagel et al., 2018) and allows to directly estimate the quota of biocapacity consumed by human activities in a given period of time (Hoekstra and Wiedmann, 2014).

Taking the *EF* framework as starting point, we introduce a new sustainability criterion, applicable to any country or geographical area, given by the combination of two constraints and accounting for both environmental and human sustainability. The first constraint is a condition of ecological sustainability, operationalised through a novel indicator, the *eco-balance* (*EB*), which in turn is based on the new concept of *population biodensity* (*PB*). Although derived from the *EF* framework, the eco-balance is better able to reflect the actual ecological burden of a country while keeping inter-country comparability (see Section 2.2).

The second constraint represents a condition of human sustainability. It includes the satisfaction of physical needs but also the development of a sufficient level of human and social capital (Knight and Rosa, 2011). This cannot be achieved without a certain ecological impact (Goodland, 1995; Smil, 2021). The constraints hence states that the per capita *EF* must be greater than a given threshold, which represents the per capita impact to achieve a high level of human development. Clearly, the estimate of such a threshold depends not only on the adopted technology (which is accounted by the *EF*) but also on the definition of "development". In order to reduce arbitrariness, here we define it based on the United Nations' *Human Development Index* (*HDI*), a commonly accepted composite indicator of human development, which aggregates data on life expectancy, education, and income (UNDP, 2020) (see Section 2.3).

It is worth noting here that the satisfaction of the two constraints does not automatically translate into environmental and human sustainability. This because they are based on simple synthetic indicators, which are intrinsically limited and do not necessarily capture all relevant aspects of the real world. For instance, the *HDI* neglects dimensions of human well-being such as life satisfaction, social support, and the quality of democracy (O'Neill et al., 2018; Knight and Rosa, 2011). On the ecological sustainability side, the *EB* inherits the limits of the ecological footprint analysis and can only be considered a *necessary* condition for sustainability although not a sufficient one (see Section 2.1). Even considering these caveats, a recent review recognises significant merits to the *EF* method for both scientific research and policy making, especially when used in conjunction with other indicators and sustainability criteria (Zhang et al., 2017), as we do in this work.

The application of our new comprehensive sustainability criterion allowed us to identify the possible paths to reconcile ecological sustainability with human development, at the scale of both single countries and the whole world. More specifically, we estimated for each country whether ecological sustainability and human development can be reconciled thorough a reduction of the average per capita impact (e.g., through smarter technology, consumption reduction, better resource distribution), or if a biocapacity increase and/or a change in population are needed as well.

2. Material and methods

2.1. Ecological footprint analysis

The ecological footprint analysis provides a simple condition for ecological sustainability: the total *EF* of a country (or any other geographical area) needs to be smaller or equal to its *BC*. Based on this condition, the *ecological deficit/reserve*[1] of a country is usually computed as the difference between its biocapacity and its total *EF*.

Despite being widely used for both scientific enquiry and policy making, the *EF* analysis is not exempt from criticism. Earlier critics, mainly focusing on conceptual and measurement issues, have been addressed by changes in the way the *EF* and *BC* indicators are estimated (see Kitzes et al., 2009). More recent criticism highlights that the *EF* neglects crucial aspects of environmental sustainability, such as water consumption, soil health, and biodiversity losses (Blomqvist et al., 2013; Giampietro and Saltelli, 2014). From this point of view, it identifies a *necessary* condition for sustainability although not a sufficient one, a point acknowledged by Wackernagel et al. (2018) himself. Even considering these caveats, a recent review recognises significant merits to the EF method for both scientific research and policy making, especially when used in conjunction with other indicators and sustainability criteria (Zhang et al., 2017).

A further limit when analysing the *EF* of world countries is that its total value also depends on the country population, which makes difficult to compare countries having vastly different sizes. To circumvent this issue, per capita *EF*, *BC* and eco-deficits are often computed. However, per capita measures do not properly reflect the pressure exerted on the local natural systems. Countries with extremely large eco-deficits may actually have small per capita deficits just because they are densely populated. For instance, India has a per capita eco-deficit of only 0.8 gha/cap., while its total deficit is about 10.23×10^8 gha, namely over 175% of the country's biocapacity (Global Footprint Network, 2021). To overcome this limit of the *EF* analysis, we introduce the new concept of *population biodensity* and the new indicator *eco-balance* (*EB*).

2.2. Population biodensity and eco-balance

The *population biodensity* (*PB*) is defined as the ratio between the population (*P*) and biocapacity (*BC*) of a given area:

$$PB = P/BC \tag{1}$$

where the biocapacity is measured in global hectares (gha) and follows the definition given by the Global Footprint Network (Global Footprint Network, 2020).

PB can be computed for any geographical area and is intuitively linked to the idea of population density. However, while population density is defined as the ratio between the population and surface of a given area, *PB* uses biocapacity as denominator. In contrast with biocapacity, the surface has little ecological meaning in itself. As a consequence, population density can only indicate how crowded is a territory, while it does not inform about the burden exerted on it by the people living there. Population biodensity is specifically designed to capture this aspect.

We then define the *eco-balance* (*EB*) of a geographical area as:

$$EB = 1 - PB \times EF_{pc} \tag{2}$$

where EF_{pc} refers to the average per capita ecological footprint of people living in the area. Given Eq. (1) and since $EF_{pc} = EF/P$, this is equivalent to $EB = 1 - EF/BC$. The eco-balance *EB* provides a simple criterion for ecological sustainability, i.e., to be ecologically sustainable, a geographical area needs to satisfy the condition $EB \geqslant 0$. This can be easily derived from the common sustainability constraint used by the Global Footprint Network, namely $BC \geqslant EF$:

$$BC \geqslant EF \Leftrightarrow \frac{EF}{BC} \leqslant 1 \Leftrightarrow 1 - \frac{EF}{BC} \geqslant 0 \Leftrightarrow EB \geqslant 0 \tag{3}$$

A positive *EB* means that people in the area have an impact below the local biocapacity, leaving some natural resources to the functioning of ecological systems. When $EB < 0$, people in the region instead use more biocapacity than the available amount. The *EB* value can vary in the range $(-\infty, 1]$. It holds $EB = 1$ if and only if $EF_{pc} \times PB = 0$. As the individual ecological footprint can never be exactly zero, this only occurs

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[1] Note that the Global Footprint Network (2020) defines what is commonly labelled *ecological deficit* such as positive values represent (rather counter-intuitively) an excess of *BC* over *EF*. We hence prefer to use the more complete expression *ecological deficit/reserve* to avoid misunderstanding.

when $PB = 0$, i.e., in absence of humans. Eco-balance is related to the concept of Earth-fullness used in Toth and Szigeti (2016) to represent the ecological burden of countries. Moreover, being computed for a single unit of biocapacity, it allows inter-country comparability, hence overcoming some of the limits of the ecological footprint identified in Section 2.1.

In Section 2.4, the condition $EB \geqslant 0$ is used to define a new sustainability criterion applied at the country level. The underlying assumption is that all countries need to be sustainable, which may be questioned. While at the global level a positive EB is a necessary condition for environmental sustainability, each country does not necessarily need to be self-sufficient in biocapacity. International trade could allow densely-populated/low biocapacity countries to "import sustainability" from others, eventually reaching on a larger scale the balance that is not achievable locally. However, this can only work if, at the global level, a surplus of biocapacity to be redistributed does exist. This unfortunately is not the case, given the current strong global biocapacity deficit (Global Footprint Network, 2021). As a consequence, sustainability trade not only cannot solve the global deficit but also risks exacerbating it by allowing the illusion of local sustainability at the expenses of the global one, as highlighted by several studies (Andersson and Lindroth, 2001; Bagliani et al., 2008; D'Odorico et al., 2010). We hence choose to apply the sustainability criterion to both the world as a whole and to all world's countries.

2.3. A threshold for human sustainability

In order to define the human sustainability threshold, the per-capita impact needed to achieve a sufficient level of development needs to be expressed in units comparable with the ones used in the ecological footprint analysis. The problem here is that EF is neither an indicator of well-being nor of human development. Depending on the adopted technology, different entities (countries, regions, single individuals) may achieve similar well-being levels with different ecological footprints, and vice versa. Nevertheless, EF_{pc} is computed starting from consumption data, which represent a crucial component of well being, at least for low- and middle-income levels (Pretty, 2013), and strongly correlates with several income and development indicators, most notably with the per capita Gross Domestic Product (GDP) ($r = 0.74$) and the Human Development Index (HDI) ($r = 0.74$).

We decided to select the latter indicator, which is commonly used in the development literature and regularly estimated by the United Nations by aggregating data on life expectancy, education, and income (UNDP, 2020). We estimated the per capita EF required to achieve a high level of human development, as defined by the United Nations, i.e., $HDI \geqslant 0.7$. According to the UN, this level only represents a minimum acceptable level of development, while a "very high" level is defined as $HDI \geqslant 0.8$. Taking the latter value as threshold would be clearly preferable in terms of human well-being but, given the correlation between HDI and EF_{pc}, would make even harder to reconcile human and ecological sustainability.

Although the correlation between EF_{pc} and HDI is quite strong, the relation between these two variable does not look perfectly linear, as moving from medium to high EF_{pc} level only leads to a small increase in human development (Fig. 1). This is confirmed by the fact that Pearson's linear correlation coefficient ($r = 0.74$) is lower than Spearman's coefficient ($\varrho = 0.87$), which only assumes a monotonic relation.

To account for both the non-linearity of the relation and the fact that HDI has, by definition, a maximum of 1, we estimated a Michaelis–Menten model, which has the desirable property to monotonically grow up to a saturation point and is often used in ecology (e.g., Hsu et al., 2001; Tamburino and Venturino, 2012). Specifically, we fitted the model $HDI = EF/(k + EF)$ corresponding to a Michaelis–Menten function with 1 as asymptote, corresponding to the highest possible HDI. The coefficient estimate resulted in $k = 0.92$ ($SE = 0.03$, $t = 29.53$, $p < 0.001$). Fig. 1 shows the resulting model, which fits well the data with a (pseudo)$R^2 = 0.72$. We then set the threshold τ of human sustainability at the point where the function intersects the $HDI = 0.7$ line of high human development, i.e., $\tau = 2.14$ gha/cap (95% CI $[1.97, 2.31]$ based on 100 bootstrap replicates).

As a robustness check, we also estimated τ using a different indicator, namely the *Inclusive Development Index* (IDI), computed by the World Economic Forum for 103 countries (World Economic Forum, 2018), which also strongly correlates with EF_{pc} ($r = 0.76, \varrho = 0.81$). Selecting the minimum IDI value among the countries identified as "advanced economies" by the World Economic Forum and replicating the analysis above (using an asymptote of 7, corresponding to the maximum theoretical value for the IDI) led to $\tau = 1.97$ (bootstrapped 95% CI $[1.82, 2.16]$), i.e., within the CI of the HDI-based estimation.

The definition of τ completes the set of indicators used in the paper, summarised in Table 1. The next section employs them to define a comprehensive sustainability criterion.

2.4. The EH criterion

Combining the eco-balance EB with the threshold τ, we define a comprehensive sustainability criterion, called EH criterion, based on two constraints that need to be simultaneously satisfied in order to

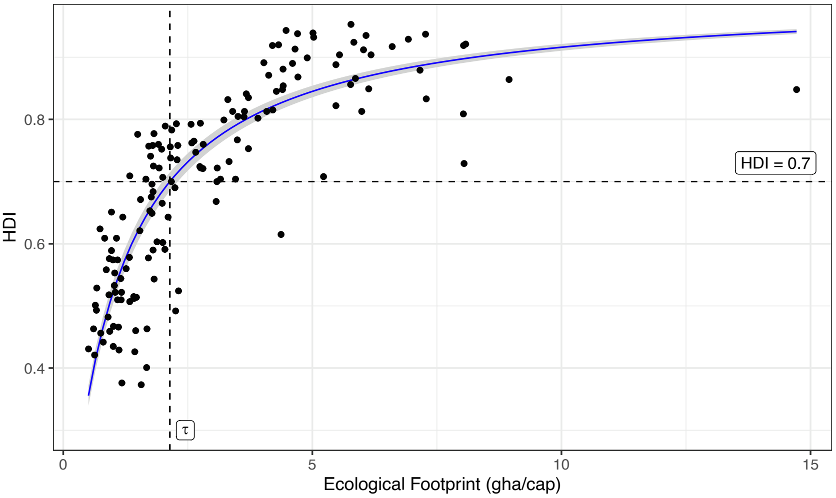


Fig. 1. EF_{pc} vs. HDI of world countries with Michaelis–Menten model estimation. Shaded area represents 95% CI of the parameter estimates. The horizontal dashed line shows the high human development lower limit, the vertical one the estimated τ value.

Table 1
Summary of used indicators and parameters with definitions and units. The table includes both existing (EF, BC, P, HDI) and novel indicators (PB, EB, τ).

Variable	Definition	Measurement units
BC	Biocapacity	gha
EF_{pc}	Per capita ecological footprint	gha/cap.
P	Population	individuals (capita)
HDI	Human Development Index	pure number
PB	Population biodensity $PB = P/BC$	cap./gha
EB	Eco-balance $EB = 1 - EF_{pc} \times PE$	pure number
τ	EF_{pc} required to achieve HDI$\geqslant$0.7 : $\tau = 2.14$	gha/cap.

reconcile a positive ecological balance (E) with human development (H):

$$\begin{cases} (E) & EB = 1 - PB \times EF_{pc} \geqslant 0 \\ (H) & EF_{pc} \geqslant \tau \end{cases} \tag{4}$$

The criterion can be graphically visualized in a Cartesian plane with axes $x = EF_{pc}$ and $y = PB$ (Fig. 2). The area below the hyperbola of equation $y = 1/x$ satisfies the (E) constraint, as can be easily derived from the EB definition:

$$EB \geqslant 0 \Leftrightarrow 0 \leqslant 1 - EF_{pc} \times PB \Leftrightarrow EF_{pc} \times PB \leqslant 1 \Leftrightarrow PB \leqslant \frac{1}{EF_{pc}} \tag{5}$$

The (H) constraints is instead satisfied in the area on the right-hand side of the vertical line of equation $x = \tau$. The two curves split the plane into four regions: E−H−, where neither constraint is satisfied; E+H−, where only the (E) constraint is satisfied, E−H+, where only the (H) constraint is satisfied; E+H+, where both constraints are satisfied.

In this representation, paths towards sustainability are vectors linking countries to the E+H+ region. The horizontal component of the vectors represents a change in EF_{pc}, the vertical component a change in PB. In Section 3.3, we apply the criterion (4) to all the world countries, identifying the paths towards sustainability and hence quantifying the required changes in both EF_{pc} and PB. Although more than one path is possible, we privilege a change in EF_{pc}, trying to avoid any PB decrease when possible, i.e., we always select those vectors minimizing the vertical component. This choice reflects the main research question of our work, namely whether changes in individual impact may alone bring humanity below planetary boundaries or whether the population lever needs to be used as well (although, in principle, a reduction in PB could be achieved through an increase in biocapacity as well, see the discussion in Section 4).

2.5. Data availability

EB and PB estimates are enclosed to this paper as Supplementary materials (file mmc1.csv). Data used to compute them are publicly available. Specifically: Ecological footprint and Biocapacity data are downloadable from the Global Footprint Network website (http://data.footprintnetwork.org); Population data are downloadable from the World Bank Database https://data.worldbank.org/indicator/SP.POP.TOTL; Human Development Index data are downloadable from the UN's Human Development Data Center http://hdr.undp.org/en/data; Inclusive Development Index data are included in the Web Economic Forum report downloadable from https://www.weforum.org/reports/the-inclusive-development-index-2018.

3. Results

3.1. Eco-balance

We computed EB estimations for all countries with surface ⩾10,000 km^2 using data from the 2021 National Footprint Accounts (Global Footprint Network, 2021) (Fig. 3). The country with the highest EB value is Suriname, with $EB = 0.97$, the lowest is Israel, with $EB = -24.45$.

Although EB and eco-deficit are both based on the relation between ecological footprint and biocapacity, the two indicators may lead to different outcomes. The ranking of world countries highlights several differences, especially when looking at the bottom part of the list (Table 2). Notably, some developed countries, such as the USA or the Netherlands, leave the bottom-10 positions in the EB rankings, replaced by relatively densely-populated countries with low-biocapacity environments, such as Jordan or Iraq. In Israel, a high per capita impact adds to high population density and low biocapacity, explaining its bottom position. On the other hand, having low PB (and hence high per capita biocapacity) is not sufficient to be in the top 10, as shown by the relatively poor performance of countries with high per capita consumption levels such as Canada or Finland.

The whole world has an EB of −0.73, implying that it is ecologically unsustainable. It is worth noting that 0.73 corresponds to the number of

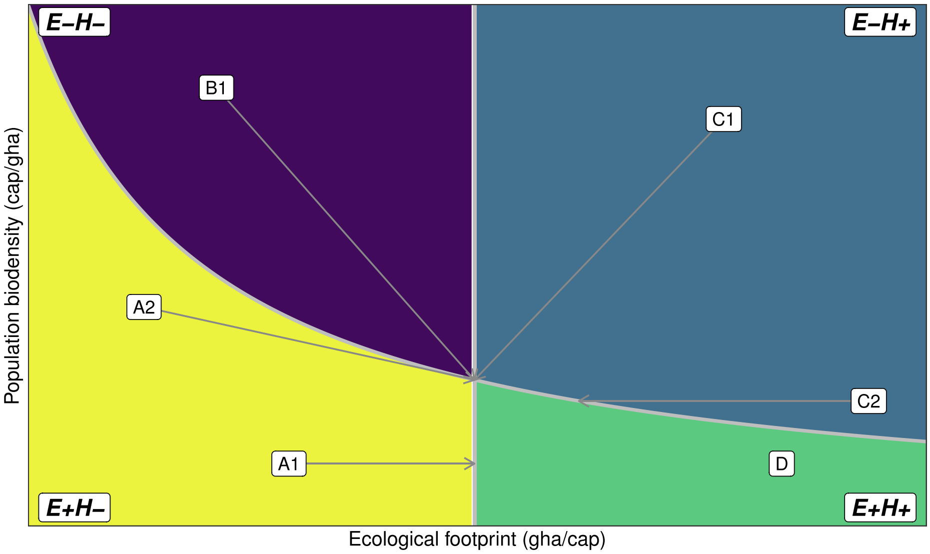


Fig. 2. Graphical representation of the criterion in Eq. (4). Countries, represented by points in the plane, need to reach the E+H+ region to satisfy both constraints of the criterion. Horizontal moves represent a change in EF_{pc}, vertical moves a change in PB. Depending on where they are located, it may be possible to reach the sustainable region by only moving horizontally (for example $A1$ and $C2$). In other cases (for example $A2$, $B1$, and $C1$) a vertical downward move is also needed.

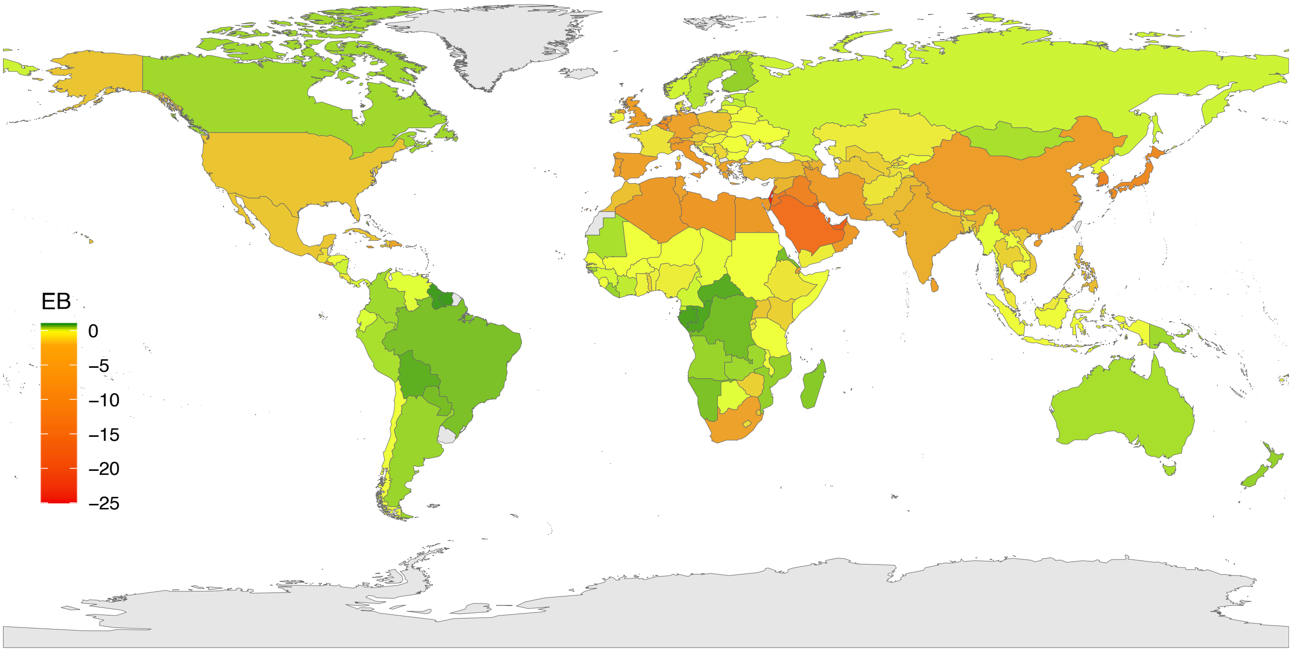


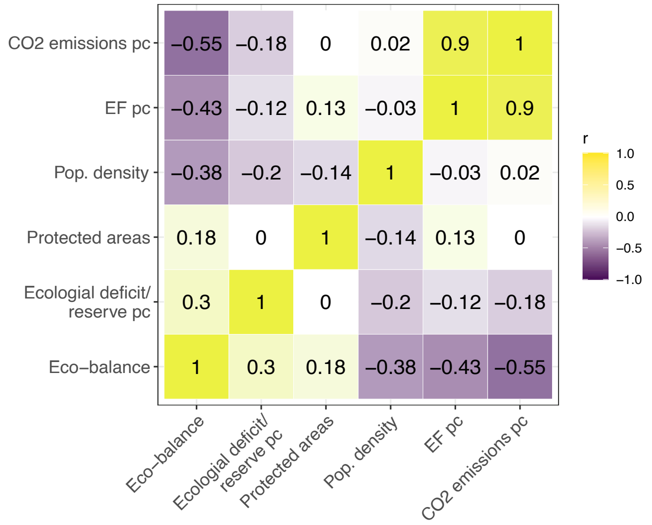
Fig. 3. Eco-balance of world countries. Countries with surface <10,000 km^2 were excluded from the analysis. A negative eco-balance means that the country is ecologically unsustainable (countries in yellow, orange or red in the map). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Top/bottom 10 countries in the per capita ecological deficit and eco-balance rankings 2017.

Country	Ecological reserve/ deficit (gha/capita)	Country	Eco-balance
Suriname	80.88	Suriname	0.97
Guyana	63.98	Guyana	0.95
Gabon	19.28	Gabon	0.90
Bolivia	12.40	Congo	0.88
Congo	7.87	Central African Republic	0.84
Canada	6.90	Bolivia	0.80
Paraguay	6.74	Congo, Democratic Republic of	0.70
Finland	6.61	Paraguay	0.69
Central African Republic	6.35	Eritrea	0.68
Brazil	5.80	Brazil	0.67
Netherlands	−4.21	Belgium	−7.09
United States of America	−4.59	Korea, Republic of	−8.52
Israel	−5.33	Iraq	−8.74
Saudi Arabia	−5.35	Jordan	−10.95
Korea, Republic of	−5.53	Lebanon	−12.00
Belgium	−5.79	Saudi Arabia	−12.88
Oman	−5.83	Qatar	−14.22
Kuwait	−7.55	Kuwait	−15.68
United Arab Emirates	−8.41	United Arab Emirates	−15.74
Qatar	−13.75	Israel	−24.45

“extra planets” needed by humanity to be sustainable with current consumption, as commonly reported by the Global Footprint Network (Global Footprint Network, 2019).

Fig. 4 shows the correlations between *EB* and other commonly used indicators: CO_2 emissions, EF_{pc}, per capita ecological deficit/reserve, population density, and proportion of protected areas. It is interesting to note that *EB* only exhibits a weak negative correlation with the eco-deficit at the country level, showing that *EB* adds significant information about the pressure that countries exert on their natural capital.



	Eco–balance	Ecologial deficit/ reserve pc	Protected areas	Pop. density	EF pc	CO2 emissions pc
CO2 emissions pc	−0.55	−0.18	0	0.02	0.9	1
EF pc	−0.43	−0.12	0.13	−0.03	1	0.9
Pop. density	−0.38	−0.2	−0.14	1	−0.03	0.02
Protected areas	0.18	0	1	−0.14	0.13	0
Ecologial deficit/ reserve pc	0.3	1	0	−0.2	−0.12	−0.18
Eco–balance	1	0.3	0.18	−0.38	−0.43	−0.55

Fig. 4. Correlation between EB and other indicators (Pearson’s *r*). Data for population density (measured in people/ km^2), CO_2 emissions per capita (t) and the proportion protected terrestrial and marine areas (% of the country surface) refer to 2017 and were downloaded from the World Bank Open Data database (https://data.worldbank.org/).

3.2. *Application of the EH-criterion*

The application of the *EH* criterion leads to the identification of four groups of countries: E+H+, E+H−, E−H+, E−H− (see Section 2.4). Fig. 5 shows a map of the world with countries coloured accordingly to their respective group.

The E+H+ group includes 24 countries. Their EF_{pc} potentially allows them to reach a high *HDI*, even if this does not necessarily happen in all

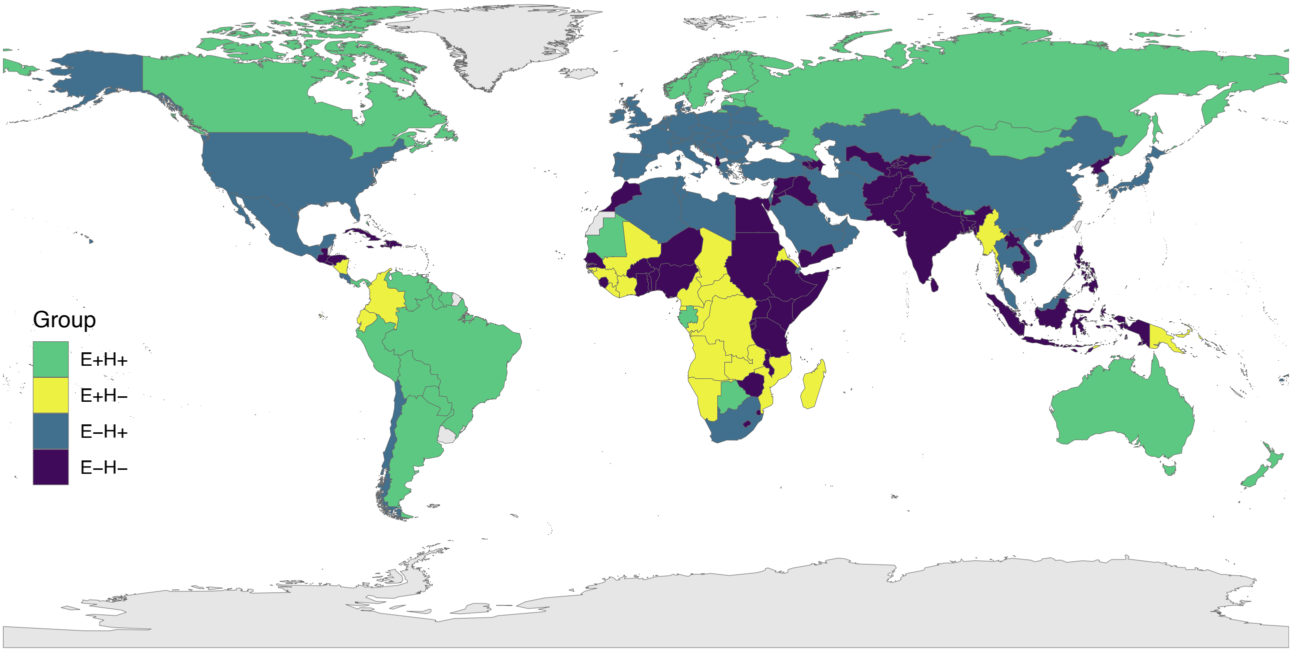


Fig. 5. World map with countries coloured according to the *EH*-criterion. E+H+, countries that satisfy both constraints, ecological (*E*) and human (*H*); E−H−, countries that do not satisfy any constraints; E+H−, countries that only satisfy the *E* constraint; E−H+, countries that only satisfy the (*H*) constraint.

practical cases. Three countries in this group do not actually have $HDI \geqslant 0.7$ — Bhutan, Guyana, and Mauritania — which means that they are not actually using their biocapacity as efficiently as they could given the best empirical examples. The group also includes countries, such Australia and Brazil, that exert strong pressures on freshwater resources (Lam et al., 2016) or have high deforestation rates (Seymour and Harris, 2019). This reflects the limits of the *E* criterion, which is able to capture the carbon-related aspects of sustainability but misses other ecological dimensions, as discussed in Section 2.1.

The E+H− group includes 23 countries, mainly located in Africa, that only satisfy the environmental sustainability constraint. As in the previous case, this group also includes countries with high deforestation rates, such as the Democratic Republic of the Congo (Tyukavina et al., 2018).

The E−H+ group includes 55 countries that only satisfy the human sustainability constraint. Similarly to the E+H+ case, two of them — Djibouti and Viet Nam — do not actually have a high *HDI*.

The E−H− group finally includes 51 countries that do not satisfy either of the two constraints in Eq. (4).

The world as a whole has a negative eco-balance ($EB = -0.73$) and a per capita footprint above the threshold τ ($EF_{pc} = 2.78$ gha). It hence belongs to the E−H+ group. Noticeably, the current global $HDI = 0.74$ (UNDP, 2020) is consistent with our attribution of the world to the E−H+ group.

3.3. Potential eco-balance and paths towards sustainability

To identify the paths towards sustainability, we first computed the *EB* that countries would achieve by equating their EF_{pc} to the threshold τ, calling this value *potential eco-balance*.

All countries in E+H+ group could decrease their ecological impact without loosing the possibility of keeping a high *HDI* by moving their EF_{pc} closer to τ, for instance, through reduced consumption. Countries that could gain most from this reduction are those with $EF_{pc} \gg \tau$, e.g., Sweden, Estonia and Canada. The potential *EB* gain achievable through this reduction is highlighted by the grey bars in Fig. 6A.

Countries in the E+H− should increase their EF_{pc} to at least τ. This would lead to a decrease in *EB* (grey bars in Fig. 6B), which would become negative in cases such Cameroon, Eritrea, Mali, and Timor-Leste. This highlights the difficult trade-off between human and environmental sustainability.

All countries in the E−H+ group could reduce their EF_{pc} to τ, increasing their *EB* by $PB \times (EF_{pc} - \tau)$ (grey bars in Fig. 6C). However, only in a few cases — e.g. Chile, Denmark, Lithuania, and USA — that would be sufficient to achieve a positive eco-balance. In most other cases, the resulting improvement is not sufficient to bring *EB* above zero.

Finally, all the countries in the E−H− group already have a negative *EB*. If they increased their EF_{pc} to τ, they would further decrease their *EB* by $PB \times (\tau - EF_{pc})$ (grey bars in Fig. 6D).

We then placed all countries in Cartesian plane of coordinates (EF_{pc}, *PB*), as explained in Section 2.4. As shown in Fig. 7, many countries cannot reach the sustainable region on the bottom right side of the plane by only moving horizontally, but also need a downward move. These countries clearly correspond to the ones with a negative potential *EB*.

The world as a whole has both a negative *EB* and a negative potential *EB* (-0.33), which means that by reducing the world's EF_{pc} to the threshold τ, the global eco-balance would improve but not enough to satisfy the (*E*) constraint in Eq. (4). This is clear from the inset in Fig. 7, showing that the world cannot reach the area below the hyperbola by only moving leftwards without crossing the τ line. A downward move is also needed. We can quantify the minimum vertical component of the path towards sustainability as $PB - 1/\tau$, which represents a *PB* reduction of about 24% from the 2017 value.

4. Discussion

This paper introduces the concept of *population biodensity* and uses it to derive a new indicator — the *eco-balance* — able to reflect the ecological burden of a country while keeping inter-country comparability (Section 2.2). This indicator is then combined with the threshold τ (Section 2.3) to define a comprehensive sustainability criterion based on two constraints able to reconcile the human and environmental dimensions of sustainability when simultaneously satisfied (Section 2.4). The application of the criterion to all countries and to the world as a whole highlights several differences from usual narratives only based on social or environmental dimensions and, most notably, allows us to

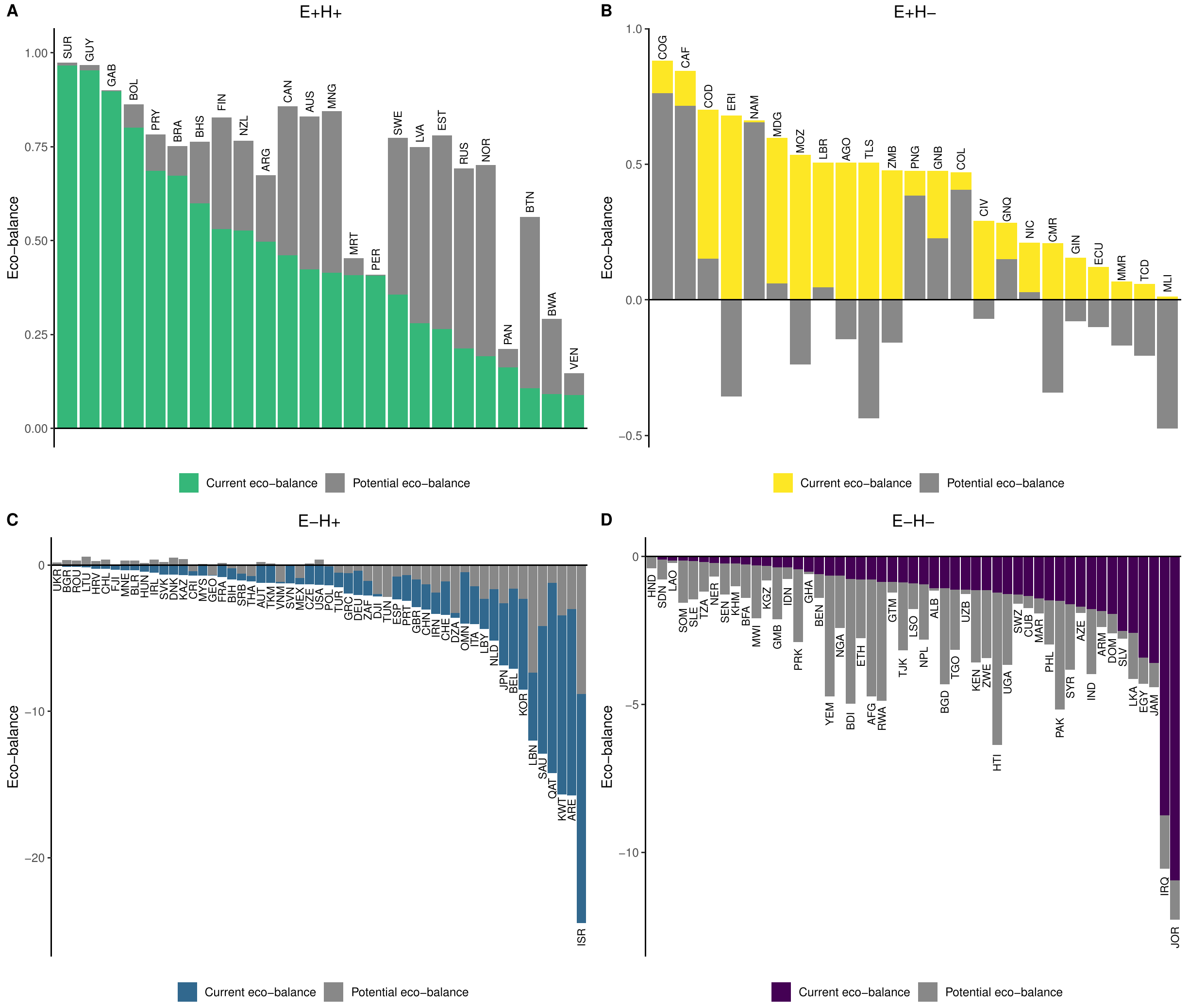


Fig. 6. Country groups following the EH criterion. Countries are identified by ISO alpha-3 codes. Colours indicate group membership consistently with the specification in Fig. 5 (green = E+H+, yellow = E+H−, blue = E−H+, purple = E−H−). Grey bars show the potential change in the country eco-balance by setting the corresponding EF_{pc} to the threshold τ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

identify the paths towards sustainability, quantifying the required changes to fulfil both constraints.

An important result that emerges from the analysis is that following these paths would lead to a more equitable world. This is clearly visible in Fig. 7, where many countries converge at, or at least approach the intersection between the two curves representing the sustainability constraints, leading to a strong reduction in the variance of both EF_{pc} and *PB*. This is in line with the often-advanced idea that reducing inequalities could help decreasing the human footprint on Earth (e.g., O'Neill et al., 2018; Knight and Rosa, 2011). Interestingly, according to our work, equality could also be an effect of the quest for a more sustainable world, not just a driver to reach it, as suggested by previous literature.

A further result emerging from the combined analysis of multiple indicators is that a reduction of the individual impact is important to improve the current situation but insufficient in itself to achieve a positive eco-balance without violating the human constraint. A reduction of *PB* is also needed. Given Eq. (1), a reduction in population biodensity can be achieved by increasing biocapacity and/or by reducing population. The first strategy is often proposed, for instance in relation to the possibility of re-foresting and rewilding significant portions of the planet to fight climate change and biodiversity loss (Wilson, 2016; Bastin et al., 2019; IPCC, 2019). The second one was widely debated in the 1970s and 1980s but subsequently became almost a taboo (Tamburino et al., 2020; Campbell et al., 2007). Nevertheless, recent years have seen a return of the population debate and (possibly) increasing consensus among scientists that population issue should be back in the agenda (Crist et al., 2017; Bongaarts and O'Neill, 2018; Dodson et al., 2020; Wolf et al., 2021; Bongaarts, 2016). Note that a higher population requires more land for anthropic uses (buildings, infrastructures, food production), limiting the available space for reforestation and nature conservation and ultimately reducing the land biocapacity. The two strategies hence are not mutually exclusive and show significant synergies. To sum up, our work indicates that population lever should be at least taken into consideration.

Even if the concern about population growth has increased in many countries (Novus, 2020), we are aware that this result is difficult to accept because population still represents a sensitive topic and demographic policies are often equated to coercion. Nevertheless, several examples show that demographic policies can also take the form of voluntary family planning programs (Robinson and Ross, 2007), and developing countries are the ones that could benefit most from such programs (Smil, 2021). In fact, high fertility rates in developing countries are often not the result of a free choice but, on the opposite, of a lack of choice for women, insufficient access to education, unmet contraception demand, social pressures, and forced marriages at a young age (Sedgh et al., 2016). Voluntary-based family programs aiming to counter these factors can not only result in lower fertility but also in an

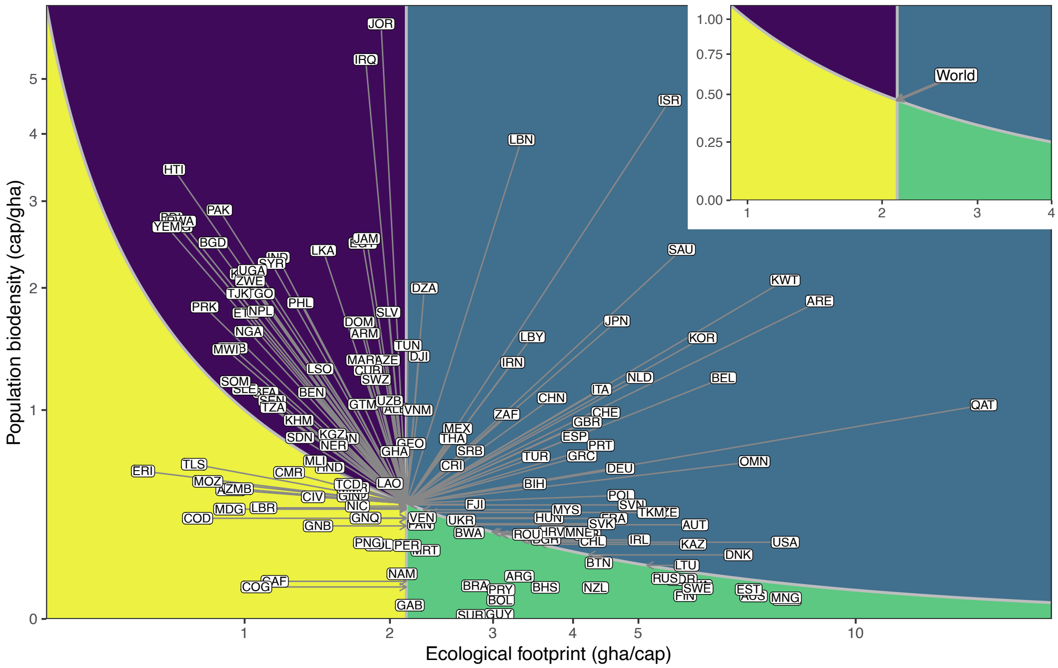


Fig. 7. Paths towards sustainability. The main panel shows country paths needed to achieve sustainability from their 2016 situation; the inset shows the path for the world as a whole. Countries are identified by ISO alpha-3 codes. Note: logarithmic axis scales.

improvement of the social conditions, especially for women and children (Wolf et al., 2021; O'Sullivan, 2018), with significant synergies among different sustainability goals (Abel et al., 2016).

A further critique often advanced to limiting overpopulation as a way to address, or at least lessen, environmental problems is that it disproportionately places blame on developing countries (Campbell et al., 2007). Nevertheless, our analysis shows that population needs to be reduced not only in developing countries (all countries in E−H− group and some countries in E+H− group) but also in several high-income-low-fertility countries in the E−H+ group. Even if these countries have a population that no longer rapidly grows — and sometimes slightly declines — in many cases their population density is already too high compared with their biocapacity. They hence need a reduction in their population to achieve a positive *EB* without crossing the τ line. This raises a dilemma because a declining population implies aging, which is usually perceived as negative for both economy and society. Nevertheless, the example of Japan seems to indicate that the problems connected with aging can be managed at affordable costs. According to prevalent indicators, Japan still is one of the richest and most innovative countries of the world despite its population has been decreasing for years (Dutta et al., 2020). Moreover, recent researches indicate that aging can also bring some advantages, such as less congestion, lower housing costs, decreased per capita consumption of food (especially meat), energy and materials (Götmark et al., 2018; Smil, 2021), while the consequences of overshooting planetary boundaries risk to be catastrophic (IPCC, 2019; Dodson et al., 2020; Steffen et al., 2015).

5. Conclusions

The main research question of this paper was whether changes in individual impact may alone bring back humanity within the planetary boundaries or whether the population lever needs to be used as well. Our analysis highlights the difficulty of reconciling environmental sustainability and human development without an integrated approach, which takes into account all drivers of environmental impact, combining technological improvements with consumption changes and, in some cases, population reduction.

Several of the numeric results depend on the specific estimation of the human sustainability threshold, namely the minimum per capita impact required to achieve an acceptable level of human development. Lower values of the threshold would limit the necessity of a population reduction. Future technological advances could reduce the per capita impact needed to achieve a high human development, leading to lower values of the threshold. Nevertheless, this may be still not enough to reconcile positive eco-balance and human development, since also population is projected to become larger in the future and recent trends show significant increases in material and energy use despite the widespread adoption of better technologies (Smil, 2021). The main message of our work actually is that there are no independent sustainable levels of technology or per-capita consumption, but only sustainable *combinations* of technology, consumption, population, and available biocapacity. Building comprehensive scenarios on how these factors will evolve and affect each other in the future may be an interesting development of this research.

CRediT authorship contribution statement

Lucia Tamburino: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **Giangiacomo Bravo:** Data curation, Formal analysis, Software, Visualization, Writing - original draft.

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.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2021.107973.

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