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Achieving the 17 Sustainable Development Goals within 9 planetary boundaries

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ABSTRACT

Non-Technical Summary (96/100 words)

The world agreed to achieve 17 Sustainable Development Goals by 2030. Nine planetary boundaries set an upper limit to Earth system impacts of human activity in the long run. Conventional efforts to achieve the 14 socio-economic goals will raise pressure on planetary boundaries, moving the world away from the three environmental SDGs. We have created a simple model, *Earth3*, to measure how much environmental damage follows from achievement of the 14 socio-economic goals, and we propose an index to track effects on people's wellbeing. Extraordinary efforts will be needed to achieve all SDGs *within* planetary boundaries.

Technical Summary (194/200 words)

Near-term gains on socio-economic goals under the 2030 Agenda could reduce the Earth system 'safety margin' represented by the nine planetary boundaries. We built an intentionally simple global systems simulation model, *Earth3*, that combines a socio-economic model of human activity with a biophysical model of the global environment. *Earth3* fills a key gap in the family of integrated models, by being capable of simulating the complex dynamic implementation challenge of the full 2030 Agenda. *Earth3* generates consistent, transparent pathways from 1980 to 2050 for seven world regions. With these pathways, we assess the extent to which the 14 socio-economic SDGs are achieved and quantify the associated pressure on planetary boundaries to calculate endogenously the extent to which the three environmental SDGs are achieved. Sensitivity analysis indicates uncertainty of the order of ±20% in the number of SDGs achieved and in the biophysical safety margin. The Business-as-Usual scenario indicates that the social and environmental SDGs cannot be achieved together, nor within the planetary boundaries. Combined with an index tracking effects on people's wellbeing and with simple formulations that keep assumptions transparent, *Earth3* can help identify and communicate policies that could improve the global sustainability situation.

SOCIAL MEDIA SUMMARY

(max 140 characters)

Earth3 global simulation model enables option exploration to achieve all 17 SDGs within planetary boundaries: extraordinary action needed.

KEYWORDS

Global modelling, global system model, integrated modelling, socio-economic dynamics, biophysical dynamics, futures, scenarios, SDGs, sustainable development goals, planetary boundaries.

Achieving the 17 Sustainable Development Goals within 9 planetary boundaries

Introduction

Seventeen global Sustainable Development Goals were agreed by the UN in 2015, with the ambition to achieve them by 2030. Our focus is the apparent conflict between the three 'environmental' goals (SDGs 13, 14 and 15) and the 14 'socio-economic' goals. Griggs et al. (2013) pointed out the need to give priority to the environmental goals: *'so that today's advances in development are not lost as our planet ceases to function for the benefit of a global population.'* Efforts to achieve the 14 socio-economic goals in the coming decade could increase the human ecological footprint, and thereby intensify the pressure on planetary boundaries (Rockström et al. 2009) moving the world further *away* from the three environmental SDGs.

We study this conflict by creating a relatively simple desk-top model, *Earth3,* to analyse scenarios for world development towards 2050. This practical tool is a first attempt at treating all SDGs *and* the planetary constraints within one quantitative framework. The existing literature on SDG analysis relies mainly on large, detailed integrated assessment models (IAMs), which occupy the space between comprehensive earth system models covering the biophysical domain and economic equilibrium models covering the socio-economic domain (van Vuuren et al. 2015; TWI2050 2018; Hughes 2019). These IAMs are highly complex, thus opaque, requiring specialist expert teams merely to run them (Zimm et al. 2018). More fundamentally, these IAMs are not configured for analysis of all the SDGs nor can they readily be modified to do so (Allen et al. 2016, van Vuuren et al. 2016), limiting their ability to responsively inform policymakers and civil society about SDG implementation. Many actors are calling for changes well beyond 'business as usual' (Hagedorn et al. 2019, Cohen 2018), so it is timely to supplement the large IAMs with transparent dynamic tools that are cheap to run by everyone and easy to understand – for both the model user and the eventual user of model insights.

This study builds on an earlier effort at assessing the likelihood of achieving the SDGs by 2030 with an emphasis on energy transitions (DNV-GL, 2018), and it explains the research and rationale behind our popular contribution to the debate on the need for wider societal transformation for SDG achievement, *Transformation is feasible!* (Randers, Rockström et al., 2018). Other examples of simple models related to planetary boundaries include Anderies et al. (2013) on land/ocean/atmosphere carbon dynamics; Heck et al. (2016) whose study linked carbon cycle dynamics with societal land management to explore climate engineering options; and Nitzbon et al. (2017) who investigated sustainability-and-collapse oscillations in energy systems. *Earth3* also contributes to emerging efforts towards integrated World-Earth models of low complexity designed to simulate, analyse and understand the entanglement of humanity and the biophysical environment in the Anthropocene (Verburg et al., 2016; van Vuuren et al., 2016; Donges et al., 2017; Donges et al., 2018; Robinson et al., 2018).

Earth3 is designed to measure how much environmental damage follows from a given degree of achievement of the 14 socio-economic goals. Additionally, we introduce a metric – the Earth3 Wellbeing Index – that covers the entire domain of reaching SDGs within planetary boundaries, and summarizes the overall attractiveness of scenarios. Widely used indices focused on just part of the scope of the SDGs may give misleading guidance when used to inform efforts to reach *all* SDGs *within* planetary boundaries.

We seek to answer the following questions:

1. If global society continues business-as-usual, how many of the 17 SDGs will be achieved by 2030 and by 2050?
2. What will be the resulting pressures on nine planetary boundaries?

We define business-as-usual as a pathway where decisions are made – at individual, corporate, national, and global levels – following the same patterns that have dominated decision-making since 1980. The ways that societies react to emerging problems vary among the world's regions, hence we trace pathways by region. In our business-as-usual scenario, we assume that technologies will continue to advance at historical rates, ultimately depending on rates of learning and diffusion which embody technology in global infrastructure.

Our method: global systems modelling

We have built and used a quantitative simulation model which we call *Earth3* (Figure 1, S1 and S2). It combines a description of the global socio-economic system and Earth's biophysical system into one integrated framework. *Earth3* stops short of being a complete system dynamics model as we have not closed major causal loops, but this confers it with a high degree of flexibility and transparency. This relatively simple 'global systems model' can run on a desktop computer to clarify the evolving conflict between socio-economic change and planetary constraints. *Earth3* produces internally consistent scenarios for the combined socio-economic and biophysical system from 2018 to 2050. To place these futures in a bigger perspective, they are presented as continuations of historical data for seven world regions for the time period 1980 to 2015. The regions are: the United States of America, other rich countries, emerging economies, China, Indian subcontinent, Africa south of Sahara, and the rest of the world (details in Table S1).

Data sources

Our 1980 starting point is a pragmatic choice because a broad set of global socio-economic and biophysical data sets are available for our analysis. Also, the 1980s have been argued to mark the onset of today's global 'world system', with a geographically widespread political shift towards laissez-faire capitalist systems (Newell, 2012), increasingly globally interconnected trade and finance (Mol and Spaargaren, 2012), and the start of instantaneous social connectivity through the widespread use of computers (Held et al. 1999). The 1980s also mark the time when the human ecological footprint first exceeded the global carrying capacity (Wackernagel et al., 2002 as quoted in Meadows et al., 2004).

Data sources for *Earth3* include UN population data (United Nations Population Division, 2017), The Penn World Tables (Feenstra et al., 2015), BP's Energy Statistics (BP, 2017), Oak Ridge's CO_2 data (Boden et al. 2017), Ecological Footprint data (Global Footprint Network, 2018), the World Bank Development Indicators (World Bank, 2018a) and Educational Statistics (World Bank, 2018b). Data on other global constraints are taken from Randers et al. (2016a), Rockström et al. (2009) and Steffen et al. (2015).

Description of Earth3

The detailed equations, parameter values and empirical basis of the *Earth3* model system are described more fully in Goluke et al. (2018) and Collste et al. (2018). *Earth3* consists of three interacting sub-models (Figure 1):

1. The *socio-economic sub-model* (Earth3-core) generates forecasts of the level of human activity to 2050, for seven world regions. Outputs include: population, GDP, income

distribution, energy use, greenhouse gas release, and some other resource use and emissions.

2. The *biophysical sub-model* (ESCIMO-plus, Randers et al. 2016a) calculates biophysical effects arising from human activity over the same time period. Outputs include: global warming, sea level rise, ocean acidity, forest area, extent of permafrost and glaciers, plus the productivity of biologically active land.
3. The *performance sub-model* (two modules, for SDGs and planetary boundaries) uses the outputs from the socio-economic and biophysical sub-models to calculate the development over time of three performance indicators: the number of the 17 SDGs achieved (by region); the safety margin (with respect to nine planetary boundaries); and an average Wellbeing Index (again by region).

The socio-economic sub-model

Earth3-core is a spreadsheet model written in Excel® 2016. The causal structure of Earth3-core is shown in Figure S1. Earth3-core utilizes high level relationships between SDG-relevant socio-economic variables and economic output expressed as Gross Domestic Product per person (*GDPpp)*. In order to make comparisons between countries and over time, we use fixed (inflation adjusted) dollars, adjusted for purchasing power parity among nations, with 2011 as the base year. To give an example, we detail the relationship between births (*CB* in 'percent of the population per year' and *GDPpp*. Figure 2a plots *GDPpp* on the horizontal axis as the independent variable and *CB* on the vertical axis as the dependent variable. Data are from 1960 to 2015, every fifth year, by region. Visual inspection confirms the central element of the demographic transition, namely falling birth rates for all regions and times where late-comers experience faster falling rates – when incomes rise. Figure 2b shows the same data but *not* by region. Using GNUplot to fit an exponential curve over the data in the form of

$$f(\mathrm{x}) = a + b \cdot \mathrm{e}^{\left(-\frac{\mathrm{GDPpp}}{\mathrm{c}}\right)}$$

gives $a = 1.32$ $b = 2.97$ and $c = 5.22$ with a root mean square of the residuals (RMSE) of 0.580.

We adjusted these parameters before using them in the model to better reflect demographic change. The dependent variable, births per population, contains the historical age pyramid of population in its historical data – it cannot do otherwise. Future age pyramids will likely be less pyramidal and more cylinder-like, with some nations even developing a top-heavy pyramid where older people outnumber younger people. We have adjusted *a*, which gives the minimum value for *CB* at high levels of *GDPpp*. We chose to set it at 0.8 to reflect age structures that become more dominated by old people in the future. We also rounded *b* to 3.0 and *c* to 5.0 giving a RMSE of 0.797 – statistically worse but causally better. (To be even more correct, we could replace our high-level formulation with a detailed age structure for each region and let that structure evolve causally dynamically – but then we would have left our intended path of low complexity modelling.) Finally, we forecast future values with this equation:

$$CB_{\mathrm{t}} = CB_{\mathrm{t-5}} - \left(CB_{\mathrm{t-5}} - \mathrm{f(x)}\right) \cdot \frac{\mathrm{dt}}{\mathrm{AT}} \qquad [1]$$

where *dt* is the solution interval, 5 years in our case, and *AT* is the adjustment time, which we set to 20 years. The causal meaning of this is that the crude birth rate approaches the value given by *f(x)* over a 20-year horizon. Equation [1] is a numerical approximation to the differential equation

$$\frac{dCB}{dt} = \frac{\left(CB - f(x)\right)}{AT}$$

where

$$f(x) = f(GDPpp) = 0.8 + 3.0 \cdot e^{\left(-\frac{GDPpp}{5.0}\right)}$$

and

$$\frac{dGDPpp}{dt} = f(GDPpp)$$

In this way we are able to replace very detailed mathematics with simple and transparent causal descriptions for many relationships in Earth3-core and the performance modules (Collste et al., 2018; Goluke et al. 2018). Figure 2c and 2d show other examples; the full list is shown in Tables S3 and S4.

We have been unable to endogenize some causal relations in a mathematical fashion. Inequality is one example, since it requires the dynamic development of income distributions as independent variables which we do not track in the Earth3-core spreadsheet. We therefore included a forecast for inequality exogenously. To leave the likely changes in inequality over the decades ahead in the business-as-usual scenario out would, in our judgment, be even less precise than to include it exogenously.

The forecast for the rate of change of $GDPpp_t$ as a function of $GDPpp_{t\text{-}5}$ is based on the approach of Randers (2016b) illustrated in Figure 2c.

In brief, values are calculated every five years through the following sequence:

1. Earth3-core simulates for each region the total output (GDP) per person through numerical integration, based on the historically observed correlation between the variables *GDPpp* and *'rate of change in GDPpp'*.
2. The size of the population is calculated based on values for birth and death rates that, in turn, depend on the value of *GDPpp*.
3. Total GDP is calculated as the product of population size and *GDPpp*.
4. Energy use (split between *'use of electricity'* and *'direct use of fossil fuels'* primarily for transport, heating and as raw material) is calculated as functions of *GDPpp* and population size.
5. CO_2 emissions from energy use are calculated from the total use of fossil fuels and the fuel mix. The fuel mix is currently set exogenously in *Earth3*, as is the fraction of electricity from various sources, including renewable sources.
6. The use of resources and the release of other pollutants are calculated as functions of output and population and slowed by exogenous technological advance.
7. Income distribution, measured as the *'share of national income to richest 10% of the population'*, is exogenously determined based on historical trends.
8. Finally, the composition of GDP and of total demand is determined by the productivity level (i.e. *GDPpp*).

Whenever regional data exist, we estimated different parameter values for the different regions, thereby capturing the diversity of regional characteristics. Otherwise we estimated global averages. Where we discovered additional variation over time – for example indications of rapid technological advance – we included them as separate terms in the equations (see Table S3). Global activity levels are computed as the sum of the regional

activity levels, weighted by population. Figure 3a and b shows some outputs from Earth3-core.

The biophysical sub-model

The biophysical sub-model ESCIMO-plus is a modified version of ESCIMO, a fully dynamic endogenous biophysical system model of low complexity (Randers et al, 2016a), written in Vensim®. The modifications allow it to be driven by Earth3-core greenhouse gas emission scenarios. In contrast to the regionalized Earth3-core, ESCIMO-plus generates global average values for its variables when driven by outputs from Earth3-core. The causal structure of ESCIMO-plus is shown in Figure S2.

ESCIMO-plus dynamically and endogenously keeps track of carbon flows and stocks in the global ecosystem, of global heat flows and stocks, and of the areal extent and productivity of varying land types. ESCIMO-plus ensures conservation of carbon, heat, land area and biomes in model simulations, assuring consistency among scenarios. The current model does not conserve water, which appears in different forms in ESCIMO-plus – as ocean water, freshwater, ice and snow, vapor, and low and high clouds. Sensitivity analysis shows Randers et al. 2016a) that the biophysical sub-model is generally robust, except minor changes in the treatment of clouds and water vapor lead to major change in the model output, particularly in the long run (i.e. after 2050). These physical processes are persistently challenging issues in much more comprehensive modelling of Earth's dynamics (Boucher et al., 2013; Flato et al., 2013). We have stuck to our simple formulations, in the hope of finding less sensitive, but still tractable, solutions in future work.

Outputs from ESCIMO-plus include global average temperature rise, average sea level rise, ocean acidity, the extent of different land types, and others of relevance to planetary boundaries. Figure 3c and d shows some examples. The output from ESCIMO for given drivers has been compared with the output of other much more complex earth system models, including the models of the Climate Model Intercomparison Project (CMIP, 2016). Although ESCIMO is very simple to use, it generates similar results to the bigger models when subject to the same drivers (Randers et al, 2016a).

The performance sub-model

The performance sub-model consists of two parts: one module measures the performance of achieving the SDGs and the other measures how well humanity stays within the planetary boundaries while trying to achieve the SDGs.

The outputs of Earth3-core and ESCIMO-plus are used as inputs in the performance sub-model, to generate three performance indicators relating to global sustainability objectives: the number of SDGs achieved; the global 'safety margin' calculated as the number of planetary boundaries kept within their low-risk zone; and the average wellbeing of the typical citizen in the region of interest, based on five components. Together, these performance indicators (Figure 4) facilitate comparison of alternative pathways as they evolve over time. All three indicators are calculated every fifth year, for every region except in cases where we only have global data.

The SDG success rate: the number of 17 SDGs achieved

This performance indicator measures the extent to which the SDGs are achieved in the model system, on an overall scale from 0 (no achievement at all) to 17 (full achievement of all goals). For each SDG, we specify one modellable indicator and define two threshold values for each indicator (Table 1), defining green, amber and red zones in the pathway plots. Green

means that the SDG in question has been reached, red means it has not been reached. For example, for SDG1, the *green* zone denotes less than 2% of the population living below $1.90/day and is assigned a score of 1. The *red* zone is more than 13% of the population living below $1.90/day, assigned a score of 0. The zone between green and red we call *amber* and assign a score of 0.5.

The *number of 17 SDGs achieved* is the sum of achievement scores for all 17 SDGs, calculated per region (Figure 4a). By summing the regional results weighted by population, we obtain an aggregate measure of the global average number of SDGs achieved (Figure 4b). In doing this, we weight each SDG equally in line with Agenda 2030, where the SDGs are 'integrated and indivisible'. It is of course fully possible to choose different weights for different SDGs, by making minor changes in the spreadsheets in the SDG module of the performance sub-model.

The safe operating space for humanity: the global safety margin with respect to 9 PBs

This performance indicator measures the intensity (in the model system) of human pressure on Earth's life-supporting systems relative to our estimate of the planetary boundaries (termed PBs in the model system). The global safety margin is given on a scale from 9 for no pressure on any of nine planetary boundaries to 0 when human impacts have pushed beyond the safe operating space for all planetary boundaries. As for SDG achievement, we define two threshold values for the pressure on each planetary boundary (Table 1), marking a *green* low-risk zone (safety margin score 1), an *amber* medium-risk zone (score 0.5), and a high-risk *red* zone (score 0). For example, for PB1 – global warming – the green zone is an increase of less than 1°C over pre-industrial global average temperature, with a score of 1. The red zone is a temperature increase of 2°C or more, scoring 0. The *global safety margin with respect to 9 PBs* is the sum of the safety margin scores for all planetary boundaries, assessed globally. The result can be seen already by splitting the SDGs into 14 socio-economic and 3 environmental ones (Figure 4c; PBs see Figure S3a)

Average Wellbeing Index

Reaching 17 SDGs within 9 PBs over time is a lot of indicators to track. Merely enumerating them one by one is possible, but drowns any message, even for one country (European Commission, 2019). Others have flagged the need for a transparent aggregated index but have not progressed beyond theoretical considerations of what such an index should accomplish (O'Neill et al. 2014; Clift et al. 2017; Riahi et al. 2017; Wackernagel et al. 2017; Chandrakumar & McLaren, 2018; O'Neill et al. 2018; Moyer & Bohl, 2019).

We suggest a new indicator that is suited to the task of summarizing the status of humanity's effort to achieve 17 SDGs within 9 PBs, and that can be useful as a high-level communication device. The *average Wellbeing Index* is intended to measure the wellbeing of a typical inhabitant in a region. It is defined as the arithmetic mean of the scores on five indicators of personal wellbeing (Table S2). The five indicators and their 'satisfactory level' are as follows:

1. private consumption of goods and services (> 2011 PPP US$ / person-year);
2. supply of public services available to each person (> 2011 PPP US$ / person-year);
3. equity in income distribution, defined as the share of national income going to the richest 10 percent (< 40%);
4. quality of the biophysical environment, defined as fine particulate matter concentration in urban aerosol (< 10 μg PM2.5/m3); and

5. hope for a better future, defined as the recent rise in global temperature (< 0.05 ºC warming in 20 years)

These five components are meant to illustrate the approach. Other choices are fully possible and defensible, but they need to span the domain of reaching *all* SDGs *within* PBs and engage with the dynamics of sustainable development. Well established indicators, like the Human Development Index, Ecological Footprint and even GDP per person, do not suffice because they do not cover the entire domain.

Each indicator is measured relative to its satisfactory level. Therefore, the average Wellbeing Index will equal 1 when all indicators are at the satisfactory level, and 0 when there is no satisfaction at all of any of the components. Figure 4d shows, by region, the result in the business-as-usual scenario.

We calculate the global average wellbeing as the sum of the Wellbeing Indices for all regions weighted by their population. This provides a single time series for the business-as-usual scenario (Figure 4d), and for any other scenario (Figure S3b), making it simpler to compare different scenarios

Results: Business-as-usual in *Earth3*

In this paper we discuss one scenario produced with the *Earth3* model system. We run 'business-as-usual' from 2018 to 2050 to describe the consequences on the level of human activity and the resulting biophysical effects. We have made other scenarios of accelerated economic growth, a stronger focus on SDGs and sustainability transformation (Randers, Rockström, et al., 2018). For each of these scenarios, the output from *Earth3* constitutes a consistent, quantitative backbone of the broad developments towards 2050.

Business-as-usual is the baseline run of *Earth3*. It is made to match recent history and provides a picture of what is likely to happen if there are no extraordinary changes in human behaviour. We use parameters that track general trends in historical data from 1980 to 2015 to project regional and world development to 2050. The chosen parameters reflect our overall assumption in this scenario that the decision makers of the world will continue to perceive and respond to emerging problems in the conventional manner, with the gradual institutional development seen in the past few decades that we believe is likely to extend to the decades ahead.

Earth3-core tells the following story in the business-as-usual scenario:

> *Towards 2050, population growth slows down. In most regions population numbers stagnate, and in some they decline, with exception of the poorest regions, where population growth continues. Economic production (GDP) continues to grow everywhere, at high rates in China and many emerging economies, but at low rates in the rich regions, with stagnation in some cases. Per capita incomes continue up, but inequity – measured as the share of national income accruing to the richest 10% of the population – continues to rise in most regions, especially in the free market economies. (Figure 3a)*
>
> *Energy use increases, but electricity use grows faster than fossil fuel use, which peaks around 2040. Electricity increasingly comes from renewable sources, and fossil fuel use for electricity generation peaks and declines in the 2030s. In the 2030s, greenhouse gas emissions also peak, because of increasing energy efficiency, the shift to wind and solar power, and the phasing out of other Kyoto and Montreal gases. The use of*

> *nitrogen and freshwater, as well as the release of lead, continue to rise, but at slowing rates. (Figure 3b)*

ESCIMO-plus tells the following story about the resulting biophysical effects to 2050:

> *Global warming continues and reaches +2°C already by 2050. Sea level rises by ~30 cm, the oceans become more acidic, on-land glaciers and permafrost area shrink. Old-growth forest area – both tropical and Northern – declines by another 20%. The fertilization effect of CO_2 on soil productivity is increasingly counteracted by negative effects of higher temperatures and more variable precipitation. On the positive side, the concentrations of greenhouse gases decline and the amount of unused biocapacity stays above a lower threshold. (Figure 3c and d)*

In summary, in business-as-usual scenario from 2018 to 2050, human societies become richer, in the sense that people live in countries with higher GDP per person, but they live in more unequal societies and in an environment that is increasingly damaged by human activity.

To what extent will the SDGs be achieved in this business-as-usual scenario? Figure 4a shows the number of SDGs achieved by region from 1980 to 2018. (Figure S4 shows the result for each SDG, by region.) Figure 4b shows the *global* average sustainable development progress since 1992. Figure 4c distinguishes between socio-economic and environmental SDGs and suggests that humanity has chosen to try to meet the former at the expense of the latter. For the environmental goals 13, 14 and 15, the situation deteriorates (Figure 4c-lower lines), as human pressures on climate, water, and land continue to rise. In rich regions, the impact of the declining environmental SDGs on overall SDGs achievement leads to a general decline over coming decades. Going forward, global society (in the model system) achieves 10.5 of the 17 SDGs by 2030 and 11.5 by 2050 – up from 9 in 2015.

Figure S5 shows the resulting pressure on the planetary boundaries under business-as-usual. For most, the indicators move towards the higher-risk red zone. The exceptions to this problematic trend are ozone depletion, as releases of Montreal gases continue to decline, and air pollution, where the population affected by anthropogenic haze declines from 2020 onwards.

Again, the aggregated global measure gives a less noisy picture. Figure S3a-blue line shows a steadily shrinking global safety margin, from 8 in 1980, to 4.5 in 2018 and 2030, and 3.5 in 2050. In other words, by mid-century humanity (in the model system) has transgressed eight of the nine planetary boundaries and is deeply into the high-risk red zone for four of them.

Finally, to illustrate how humanity deals with reaching socio-economic and environmental SDGs *and* staying within planetary boundaries we look at how average wellbeing evolves under business-as-usual. Figure S3b shows that global average wellbeing remained largely constant from 1980 to 2020, because economic growth was insufficient to compensate for the combined effect of increasing inequity, increasing pollution levels, and increasing concern about dangerous climate change. Wellbeing rises towards 2050 in the business-as-usual scenario (blue line), because more people become better off: increased consumption counterbalances the negative effects of inequity, pollution and climate change. In the rich world, average wellbeing grew to 2020, but progress slows going forwards, because the dis-amenities of inequity, pollution and despair grow faster than consumption and public service supply. In other regions, wellbeing rises from 2020, albeit from lower levels. In China, average wellbeing reaches Western levels at the end of the simulation period. (Figure 4d)

This assessment depends on the weights chosen for the five components of the average Wellbeing Index. We weighted them equally as a demonstration of the *Earth3* system. It

would be simple to defend other weightings, and users of *Earth3* are encouraged to do so in their exploration of policy ideas.

In sum, the business-as-usual scenario does lead to a rise in the number of SDGs achieved by 2030, and to a rise in average wellbeing globally. But there is little improvement on the SDGs to 2050, and at the same time the human pressure on the environment grows, eroding the global safety margin relative to the planetary boundaries.

Sensitivity analysis

For those used to equilibrium models and seeing the world in equilibrium terms, it is important to note that we see the world as a system *away* from equilibrium, with causal assumptions and parameter values selected in line with this view. We work in the system dynamics tradition of modelling and model validation (Barlas, 1996). The validation of a system dynamics model is contingent upon the model's purpose and typically includes not only behavioural pattern tests, as typically used in statistical models, but also structure tests and structure-oriented behaviour tests. An overall check of model plausibility was conducted by comparing the output of Earth3-core with two major global modelling efforts: DNV-GL's Energy Transition Outlook 2018 (DNV-GL, 2018) and IIASA's global population model (Lutz et al, 2018). We found no discrepancies that warranted model adjustment.

All models are subject to uncertainties. *Earth3* is work in progress, so we remain uncertain about the level of precision in our conclusions due to the sensitivity in the numerous inputs used to generate them. If it were a fully endogenized model, Monte Carlo sensitivity analysis would be possible and appropriate. In order to get a better feel for *Earth3* as it currently stands, we performed a simple sensitivity analysis focused on *GDPpp,* because it is such a central variable in the model. We changed our assumption about economic growth in the following manner:

Our formula for the rate of change of *GDPpp* is

$$\mathrm{RoC}(\mathrm{GDPpp}_t) = \left(\mathrm{RoC}(\mathrm{GDPpp}_{t-5}) - \left(\mathrm{RoC}(\mathrm{GDPpp}_{t-5}) - a \cdot e^{(-b \cdot \mathrm{GDPpp}_{t-5})} - c \cdot e^{(-d \cdot \mathrm{GDPpp}_{t-5})}\right) \cdot \frac{dt}{AT}\right)$$

where $a = 9.0$, $b = 0.07$, $c = 6.0$, $d = 0.3$, $dt = 5$ and $AT = 20$ (using logic like the crude birth rate formulation detailed above). To run the sensitivity test, we add an additive term of either +1 percentage point (accelerated economic growth) or –1 percentage point (slower economic growth).

The resulting impact on world SDGs and PBs is shown in Figures 4b, 4c and S3a. In 2050, 11.9 SDGs are reached for both accelerated and slower growth, as opposed to 11.5 under business-as-usual. However, the trajectory towards 2050 is better (i.e. more SDGs reached) for accelerated growth and much better for slower growth. Thus, adding or subtracting 1 percentage point to our formula above results in a 3.5% increase in global SDGs met by 2050. For PBs, both business-as-usual and accelerated growth end up with 3.5 boundaries met in 2050 and with 5 boundaries met for slower growth. Here, slowing growth by 1 percentage point results in a 35% increase in staying within PBs. This high sensitivity points to the need to endogenize the model.

Still, our main finding holds, that humanity will not be able to achieve the social and environmental SDGs, within planetary boundaries – without extraordinary action.

Discussion and conclusions

In the *Earth3* model system, humanity does not achieve the SDGs within planetary boundaries by 2030, nor even by 2050 in the business-as-usual scenario. It also points out that whatever achievement humanity reaches on the socio-economic SDGs it pays a heavy price on the environmental SDGs, raising the spectre that Griggs' warning of 2013 (Griggs et al. 2013) might indeed come true. A sensitivity analysis shows little effect on this main conclusion from changes in the rate of change in GDP per person. But as in all modelling studies, our conclusions depend on the assumptions made.

Earth3 in its current form should be seen as a starting point – a proof of concept – for further elaboration. The low complexity of the model structure makes our principal assumptions transparent, but in some cases other assumptions may be equally plausible and would lead to different conclusions. Important examples are our choice of indicators for the individual SDGs and PBs, the choice of thresholds, and the choices of functional form, satisfactory levels and weighting in the Wellbeing Index. Thus, *Earth3* is not a sustainability forecaster, but a 'what-if' calculator – which, in the end, all models are, even the high complexity IAMs and comprehensive earth system models that currently inform much global policy. When reality differs from the assumptions made, the more transparent and flexible the model, the more useful it can be in re-diagnosing the issues.

In its current formulation, *Earth3* has no feedback from the biophysical sub-model to the socio-economic model. Examples where this matters are our exogenous treatment of inequity and near-exogenous treatment of forest cut. In our view, this limitation matters much more in the long run (i.e. after 2050), because history indicates that humanity responds slowly to changes in the global environment.

Methodologically, the *Earth3* study shows that it is possible to build a global system model and use it to analyse future achievement of *all* SDGs *within* PBs. But despite its usefulness as an exploratory tool, *Earth3* is far from perfect. New generations of integrated World-Earth models are needed to test and sharpen our conclusions, and to study the feasibility and consequences of transformational change. Much work remains to achieve a fully causally endogenous global model system that can provide better assessments of the consequences of alternative global policy sets on the achievement of the 17 SDGs and the evolution of the safety margin relative to planetary constraints. We plan to continue the work of developing and using a transparent low complexity dynamic model, cheap to run by everyone, and hope to inspire others to do likewise.

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Author Contributions

JRo conceived the study of SDGs within PBs. JRa designed the approach and built the central models in close cooperation with UG. DC gathered data on SDGs and PBs and contributed to the SDG module. PES devised the scenario perspective, JD and SC positioned the study in the sustainability science literature. JRa wrote the paper, greatly assisted by SC.

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Publishing Ethics

Both the paper and the *Earth3* model system are the original work of the authors.

Conflict of Interest

None.

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Table 1. The 17 Sustainable Development Goals and 9 Planetary Boundaries in *Earth3*. GDP and Government spending are in 2011 PPP US$.

Global Sustainability Objectives		Modelled Indicator	Threshold value for green zone	Threshold value for red zone
Sustainable Development Goals (UN Agenda 2030, agreed in 2015)			**Target**	**Halfway-target**
1	No poverty	Fraction of population living below 1.90$ per day	< 2 %	> 13 %
2	Zero hunger	Fraction of population undernourished	< 7 %	> 15 %
3	Good health	Life expectancy at birth	> 75 years	< 70 years
4	Quality education	School life expectancy	> 12 years	< 10 years
5	Gender equality	Gender parity in schooling (ratio F:M = 1)	> 1	< 0,8
6	Safe water	Fraction of population with access to safe water	> 98 %	< 80 %
7	Enough energy	Fraction of population with access to electricity	> 98 %	< 80 %
8	Decent jobs	Job market growth	> 1 % / year	< 0 % / year
9	Industrial output*	GDP per person in manufacturing & construction	> 6000 US$/p-y	< 4000 US$/p-y
10	Reduced inequality	Share of national income to richest 10 % of population	< 40 %	> 50 %
11	Clean cities	Particulate matter (aerosol) concentration in urban air	< 10 µg PM2.5/m^3	> 35 µg PM2.5/m^3
12	Responsible consumption	Total ecological footprint (global hectares) per person	< 1.5 gha/p	> 2 gha/p
13	Climate action	Temperature rise (degrees C above 1850 level)	< 1 deg C	> 1,5 deg C
14	Life below water	Acidity of ocean surface water	> 8,15 pH	< 8,1 pH
15	Life on land	Old-growth forest area	>25 Mkm^2	< 17 Mkm^2
16	Good governance*	Government spending per person	> 3000 US$ / p-y	< 2000 US$ / p-y
17	More partnership	Exports as fraction of GDP	> 15 %	< 10 %
Planetary Boundaries			**Limit of safe zone**	**Limit to high-risk zone**
1	Global warming	Temperature rise (degrees C above 1850 level)	< 1 deg C	≥ 2 deg C
2	Ozone depletion	Montreal-gas emissions	< 0,25 Mt/y	≥ 2 Mt/y
3	Ocean acidification	Acidity of ocean surface water	> pH 8.15	≤ pH 8.1
4	Forest degradation	Old-growth forest area	> 25 Mkm^2	≤ 17 Mkm^2
5	Nutrient overloading	Release of bioactive nitrogen	< 100 N Mt/y	≥ 200 Mt/y
6	Freshwater overuse	Freshwater withdrawal	< 3000 km^3/y	≥ 4000 km^3/y
7	Biodiversity loss	Unused biocapacity	> 25 %	≤ 18 %
8	Air pollution	Urban aerosol concentration	< 10 µg PM2.5/m^3	≥ 35 µg PM2.5/m^3
9	Toxics contamination	Release of lead	< 5 Mt/y	≥ 10 Mt/y

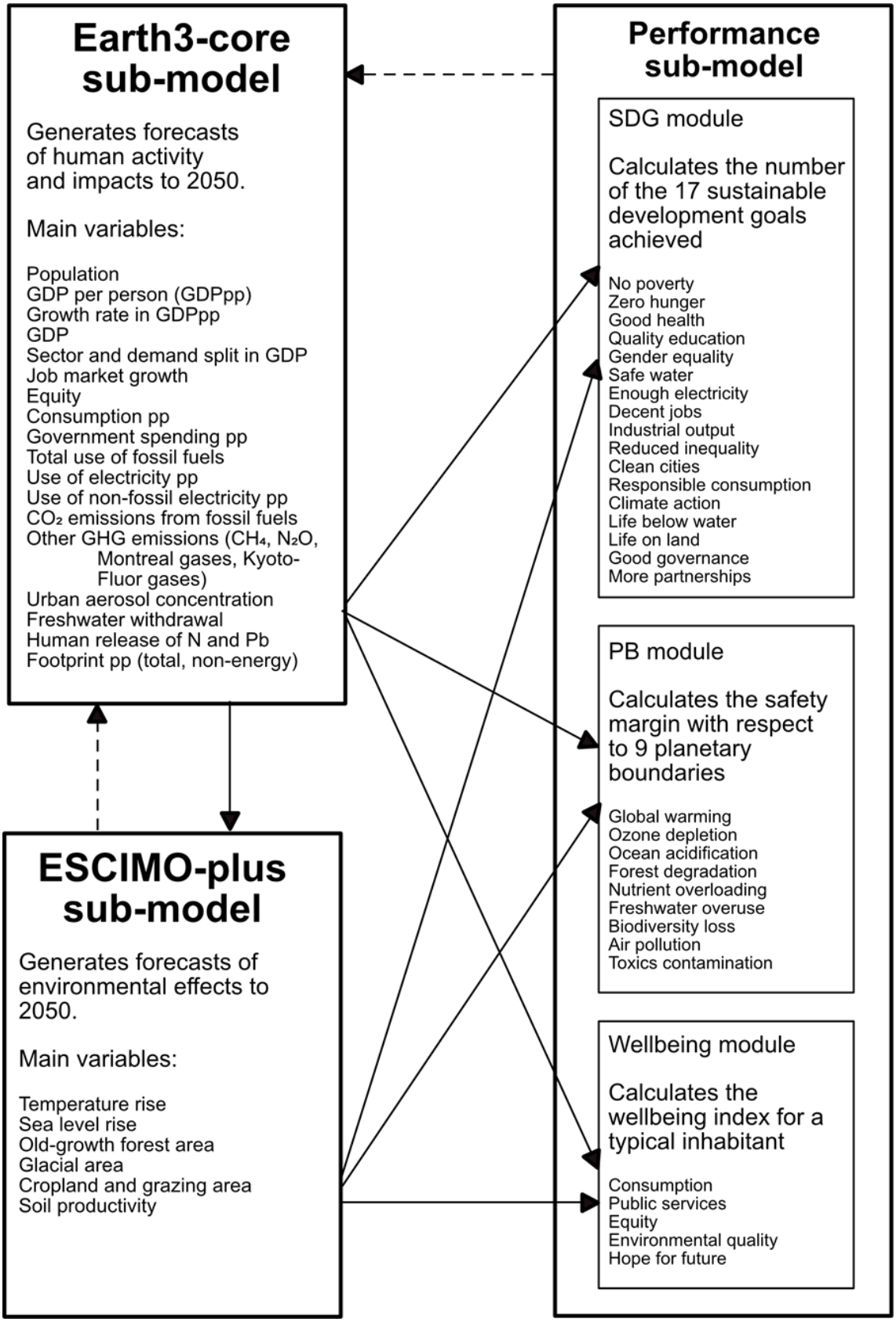

Figure 1. Overview of the *Earth3* model system.
Details in Goluke et al. (2018) Dashed lines indicate where added feedbacks would convert *Earth3* into a full system dynamics model.

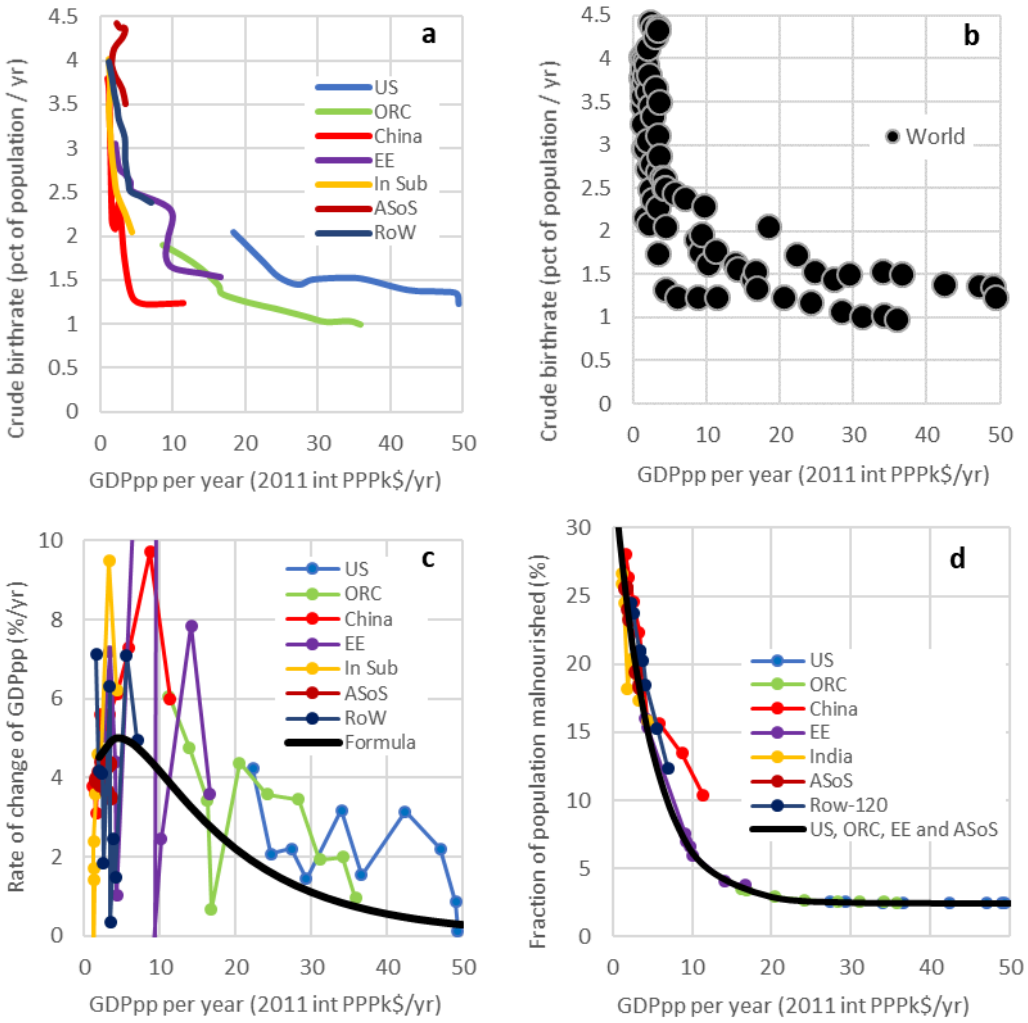

Figure 2. Examples of correlations used in Earth3-core (a-c) and the SDG performance module (d), based on historical data 1980-2015 for seven world regions.

GDPpp is the independent variable in all cases. Panel a: births, as percent of the population per year by *region*; b: births, *globally*; c: rate of change of GDPpp; d: fraction of population undernourished, as an indicator for SDG2. Details of correlations for all parameters are given in Goluke et al. (2018) and Collste et al. (2018)

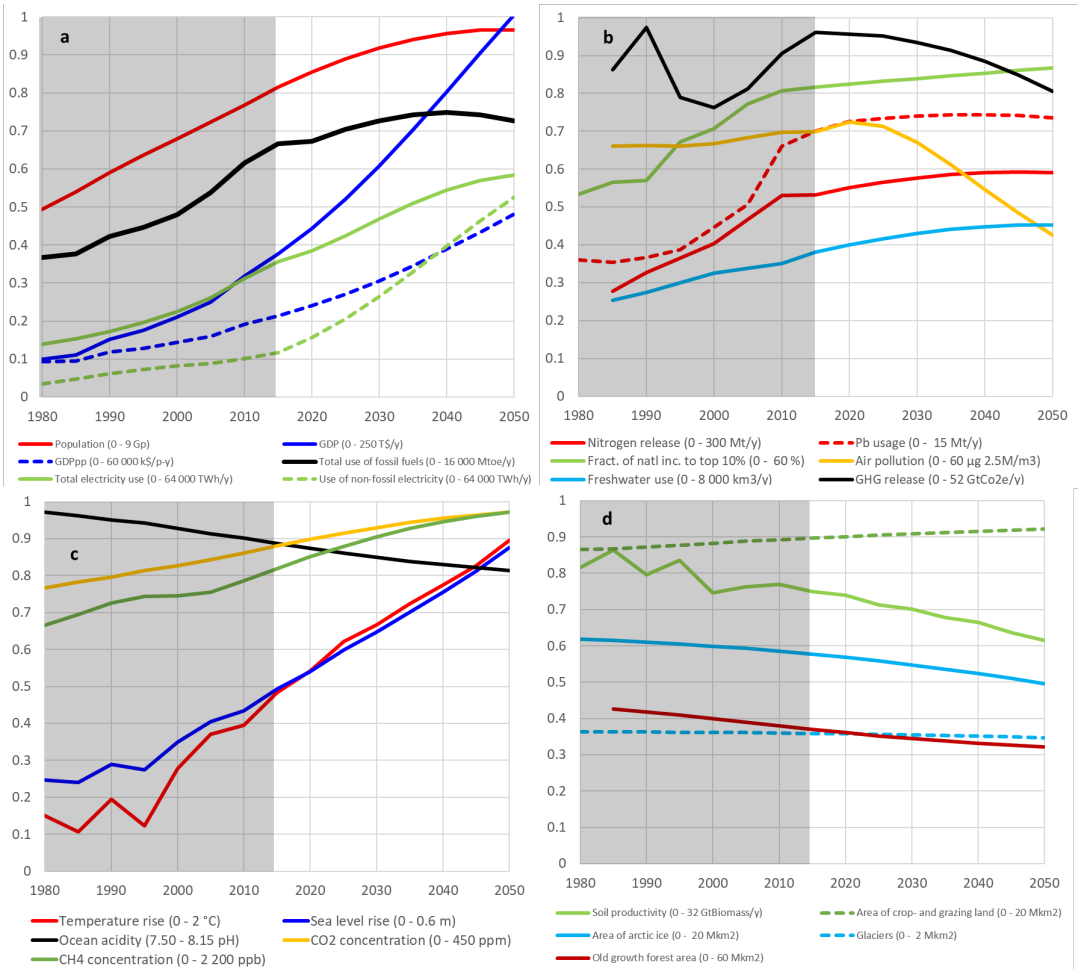

Figure 3. Outputs from the socio-economic sub-model Earth3-core *(a and b)* and the biophysical model ESCIMO-plus *(c and d)* used to drive the Performance sub-model. Grey zones denote history.
Details in Goluke et al. (2018) All outputs scaled from 0-1; output scale range given in key below each panel.

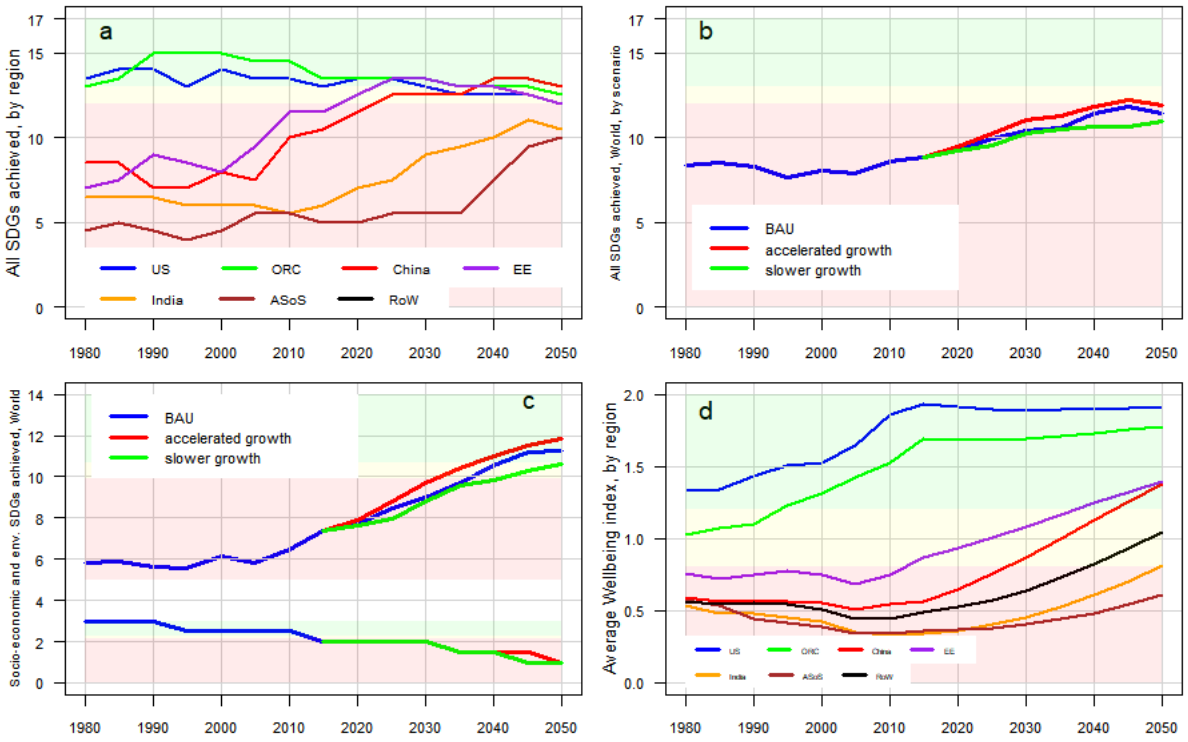

Figure 4. Outputs from the Performance sub-model 1980-2050.

a: The number of SDGs achieved in a business-as-usual scenario, by region.

b: The overall global SDG success score, showing the sensitivity analysis to ±1 percentage point in GDPpp growth

c: The number of socio-economic (top lines) and of environmental (bottom lines) SDGs achieved, globally.
Green zone shows 13-17 SDGs have been reached, red zone shows 0-12 SDGs have been reached, amber zone shows 12-13 SDGs have been reached. For panel **c** these numbers have been scaled to 14 (top lines) and 3 (bottom lines)

d: The average wellbeing index, by region (see text for colour meaning)