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Achieving the 17 Sustainable Development Goals within 9 planetary boundaries

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ABSTRACT

Non-Technical Summary (96 words)
In 2015 the UN agreed to achieve 17 sustainable development goals (SDGs) by 2030. Our study seeks to clarify whether this is a feasible ambition, and what will be the resulting human pressures against global environmental constraints. Our study is important in two ways. It indicates what additional measures may be necessary to achieve the SDGs. And it illustrates one way of doing such analyses – using formal models and simulation. Our 'global systems model' calculates the number of SDGs achieved at various times under various conditions, and the safety margin relative to 9 planetary boundaries (PBs).

Technical Summary (179 words)
We built a simulation model, Earth3, to clarify whether achieving all the 17 SDGs within 9 PBs is a feasible ambition. We analyzed three scenarios – business as usual; accelerated economic growth; and a concerted strong focus on achieving the SDGs – to investigate the degree of success, and the resulting human pressures against global biophysical constraints. In Earth3, world society does not achieve all 17 SDGs within 9 main PBs by 2030, or even by 2050, neither in the business-as-usual scenario, nor in the two other scenarios analyzed. Furthermore, the global safety margin relative to 9 PBs continues to decline. Tougher measures are needed to achieve wellbeing for all and, ultimately, sustainability.

Our study illustrates how formal models and simulation provide one flexible and transparent way of doing analyses, and help inform the global public debate around the SDGs. Earth3 combines a socio-economic model of human activity with a biophysical model of the global environment. The resulting 'global systems model' generates consistent and transparent pathways into the global future. Much more work is needed to improve Earth3 and its pathways.

SOCIAL MEDIA SUMMARY

(137 characters)

A global simulation model study shows what it will take to achieve the 17 UN sustainable development goals within 9 planetary boundaries.

KEYWORDS

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

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(5585 words)

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Introduction

The world's societies are currently seeking to achieve the 17 Sustainable Development Goals (SDGs) agreed by the UN in 2015 (United Nations, 2015; see Table 1). There are concerns that if the 14 socioeconomic SDGs are achieved, then the human ecological footprint (Wackernagel et al., 2002) will exceed the sustainable carrying capacity of planet Earth (O'Neill et al., 2018). This would defeat the achievement of the three environmental SDGs, SDG 13 - Climate action, SDG 14 - Life below water, and SDG 15 - Life on land. There are also concerns that humanity's pressure on one or more planetary boundaries (PBs; see Table 1) will generate continuing deterioration of the biophysical environment – or even trigger large-scale ecological collapse (Rockström et al., 2009; Steffen et al., 2015), undermining development gains. And there are already concerns that insufficient financial resources and political support will be made available to achieve all SDGs by 2030 as agreed, and to assure the wellbeing of the world's citizens (Sachs et al., 2018). The most influential integrated global models are severely constrained in their ability to analyze these issues (TWI2050, 2018). Their structural rigidity means few combinations of SDG objectives can be addressed, and their historic focus on the climate/energy/economy nexus means they can only provide a partial perspective on the biophysical dynamics that underlie the planetary boundaries. And they are opaque about many of the assumptions embedded within them (Zimm et al. 2018).

This paper seeks to describe some of the options ("pathways") open to humanity given the long-term goal of achieving the SDGs within the PBs. We want to describe how humanity can move towards a safe and just world (Raworth, 2012, 2017). Our effort builds on an earlier attempt at assessing the likelihood of achieving the SDGs by 2030 with an emphasis on energy transitions (DNV-GL, 2015), and it explains the research and rationale behind our recent popular contribution to the debate on the need for a wider societal transformation for SDG achievement, *Transformation is feasible!* (Randers, Rockström et al., 2018).

We seek to answer the following questions:

1. If global society continues business-as-usual, how many of the 17 UN Sustainable Development Goals (SDGs) will be achieved by 2030 and by 2050?
2. What will be the resulting pressures on 9 planetary boundaries (PBs)?
3. How will different pathways to SDG achievement affect people's wellbeing in the long run?

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 (we explain our reasons for this starting point in the Methods section below). The ways that societies react to emerging problems vary among the world's regions, hence we trace this pathway by region. We then explore other scenarios, following other pathways than business-as-usual.

Our method

To explore our questions, we built and used a quantitative global simulation model called *Earth3* (Figure 1, Figures S1 and S2). This highly aggregated global system model simulates linked socio-economic and biophysical development over time towards 2050. It consists of three interacting sub-models:

1. The *socio-economic sub-model* (Earth3-core) generates forecasts of the level of human activity to 2050, for seven world regions: the United States, other rich countries, emerging economies, China, Indian subcontinent, Africa south of Sahara, and the rest of the world (details provided in Table S1). 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) calculates the 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* 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 9 PBs); and an average wellbeing index (again by region).

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 the seven regions for the time period 1980 to 2015. The 1980 starting point is a partly 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.).

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, 2018) and Educational Statistics (World Bank, 2018). Data on other global constraints are taken from Randers et al. (2016), Rockström et al. (2009) and Steffen et al. (2015).

Earth3 builds on our long experience in modeling the global socio-economic and biophysical systems (Meadows et al., 1972, 1974, 1992, 2004; Randers, 2012). Earth3 continues in the tradition of simulation models that seek to represent the cause-and-effect relationships that drive development over time – in contrast with the (often linear) equilibrium models based on estimated parameter values without independent physical meaning (Randers et al., 2016). Earth3 stops short of being a complete system dynamics model, as we have not closed major causal loops. The model illustrates our preference for simple models that are intentionally transparent and easy to understand – for both the model user and the eventual user of the model output. Other examples of simple models related to planetary boundaries include Anderies et al. (2013) who explored non-linear behavior in 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 properties of sustainability-and-collapse oscillations in energy systems. We hope that Earth3 can act as a condensation nucleus for a new generation of integrated Human World-Biophysical Earth models designed to simulate, analyze and understand the ever-increasing entanglement of humanity and the 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).

Description of Earth3

The Earth3 model system is described more fully in the supplementary materials to this paper, especially in "The Earth3 model system" (Goluke et al, 2018) and "The empirical basis for the Earth3 model system" (Collste et al., 2018)

The structure of the socio-economic sub-model

The socio-economic sub-model – Earth3-core – is a spreadsheet model written in Excel. It creates consistent scenarios of the level of human activity in seven regions for the period 2018 to 2050. Global activity levels are computed as the sum of the regional activity levels, weighted by population.

The causal structure of Earth3-core is shown in Figure S1, and the detailed equations and parameter values are available in Goluke et. al. (2018). Earth3-core is relatively simple because we utilize the fact that strong correlations exist between many of the socio-economic variables in Earth3 and the variable "GDP per person" (GDPpp). This makes it possible to replace detailed causal descriptions with simple and transparent correlations. See two examples in Figure 2, the full list in Tables S3 and S4, and the discussion in Collste et.al. (2018). Earth3-core is furthermore based on a simple and transparent way of forecasting future values of GDPpp, as discussed in Randers (2016) and illustrated in Figure 2.

The simulation sequence is as follows:

1. Earth3-core first 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 rates and death rates that, in turn, depend on the value of GDPpp.
3. Total GDP is calculated as the product of population 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 set exogenously in this version of 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 in some cases 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. the GDPpp).

In order to make sensible comparisons between countries and over time, we use fixed (inflation adjusted) dollars, adjusted for purchasing power parity among nations. Thus, we measure GDPpp in 2011 PPP $ per person-year.

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. In some instances, we discovered additional variation over time – for example indications of rapid technological advance – and these were included as separate terms in the equations (see Table S3).

Figure 3-top shows some of the outputs from Earth3-core. We see the world as a system away from equilibrium and have chosen causal assumptions and parameter values in line with this view. We are grounded in the system dynamics tradition of modeling and model validation (Barlas, 1996): the validation of a system dynamics model is contingent upon the model's purpose and typically includes not only behavioral pattern tests, as typically used in statistical models, but also structure tests and structure-oriented behavior 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 further model refinement.

The structure of the biophysical sub-model

The biophysical sub-model ESCIMO-plus is a slightly modified version of the ESCIMO model (Randers et al, 2016), adding relationships that deal with more of the planetary boundaries and their interactions. ESCIMO is a simple biophysical system model, built to calculate the biophysical effects of human activity as both evolve over time. It can be used to simulate the effect of various human policy measures, and to simulate the effects of various natural catastrophes.

ESCIMO-plus is a system dynamics model written in Vensim®. In contrast to the regionalized Earth3-core, ESCIMO-plus is a global model, which 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, and the detailed equations and parameter values are available in Goluke et.al. (2018).

ESCIMO-plus keeps track of carbon flows and stocks in the global ecosystem and describes how they change over time in response to varying greenhouse gas emissions. ESCIMO-plus also tracks global heat flows and stocks, and the change in the areal extent and productivity of varying land types, also in response to human activities. Thus, ESCIMO-plus ensures conservation of carbon, heat, and land area in model simulations, and thereby increases the consistency in the scenarios. The model does not yet conserve water as such: it appears in different forms in ESCIMO-plus- as ocean water, fresh water, ice and snow, vapor, and in clouds.

The outputs from ESCIMO-plus include global average temperature rise, average sea level rise, ocean acidity, the extent of different land types, and other of relevance to planetary boundaries. Figure 3-bottom shows some examples. The output from ESCIMO for given drivers has been compared with the output of other more complex earth system models (Randers et al, 2016). Although ESCIMO is very simple to use, running in seconds on a laptop computer, the results were similar when subject to the same drivers.

The structure of the performance sub-model

The outputs of Earth3-core and ESCIMO-plus are used as inputs in the performance sub-model, in order to generate three performance indicators relating to our global sustainability objectives. We calculate 1) the number of SDGs achieved, 2) the global safety margin calculated as the number of PBs kept within the low-risk zone, and 3) the average wellbeing of the typical citizen in the region of interest based on five components. These performance indicators (Figure 1-right) facilitate the comparison of alternative pathways as they evolve over time. All three performance indicators are calculated every fifth year, and for every region except in those cases where we only have global data.

The number of 17 SDGs achieved

This performance indicator[1] 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 modelable indicator which is closely related to the main topic of the SDG (see Table 1). Next, we define two threshold values for each indicator, defining the green, amber and red zones in the pathway plots. Finally, the indicators are converted to scores as follows: In the green (safe) zone we give score 1, in the red (danger) zone we give score 0, and in the amber (halfway) zone we give score 0.5.

The indicator values are driven by outputs from Earth3-core and ESCIMO-plus. The calculation is made simpler by the existence of strong correlations between those outputs and the indicators we have chosen. See table S4 for details.

The number of 17 SDGs achieved is the sum of achievement scores for all 17 SDGs. This is calculated per region, see Figure 4a. By summing the regional results weighted by population, we obtain an aggregate measure of the global average number of SDGs achieved, see Figure 4b. In doing this, we place the same weight on each SDG. In Agenda 2030, the SDGs are "integrated and indivisible", so we do not treat any one SDG as more critical than any other. 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.

Global safety margin with respect to 9 PBs

This performance indicator[2] measures the intensity (in the model system) of the human pressure on Earth's life-supporting systems relative to our estimate of the boundaries to the safe operating space for humanity.

The global safety margin is given on a scale from 9 (no pressure on any of 9 planetary boundaries, and hence the maximum safety margin) to 0 (when human impacts have pushed beyond the safe operating space for all 9 of the planetary boundaries, leaving a minimum safety margin). As for SDG achievement, for each PB we define two threshold values for the pressure, marking a green low-risk zone (safety margin score 1), an amber medium-risk zone (safety margin score 0.5), and a high-risk red zone (safety margin score 0). See Table 1 for details.

The global safety margin with respect to the PBs is the sum of the safety margin scores for all 9 PBs. This is done at the global level only, see Figure 4c.

[1] For pedagogic reasons we use the label "SDG Success ratio" in the popular report on our work.
[2] For pedagogic reasons we use the label "Safe operating space" in the popular report on our work.

Average wellbeing index

This indicator[3] tracks the wellbeing of the average inhabitant in a region (in the model system). The average wellbeing index is defined as the arithmetic mean of the scores on five indicators of personal wellbeing (see Table S2). The five indicators – and their "satisfactory level" – are as follows:

1) the private consumption of goods and services (> 2011 PPP US$ / person-year);
2) the 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) the 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 degrees C warming in 20 years).

We chose these 5 components mainly as an illustration, other choices are fully possible and defendable. The important point is that subjective wellbeing is influenced by a broad selection of factors, including material consumption, social security, equity, environmental quality, and hope for the future. We also chose the satisfactory levels mainly as an illustration, again other choices are equally plausible. The important point is that diminishing returns do set in when indicators pass a certain level.

Each indicator is measured relative to its satisfactory level. As a consequence, 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 S3 provides an example, by region, 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. The resulting global average provides a single time series for each scenario, and makes it simpler to compare different scenarios, see Figure 4d.

Experiments with Earth3

We use the Earth3 model system to produce scenarios from 2018 to 2050 for the level of human activity and the resulting biophysical effects, and to calculate the associated consequences for achievement of SDGs, pressure on PBs, and average wellbeing (in the model system). The details of each scenario are determined by the parametrization chosen for each simulation run; the system structure remains the same throughout.

In this paper we discuss three scenarios, "business-as-usual", "accelerated economic growth", and "stronger focus on SDGs". For each of these scenarios, the output from Earth3 constitutes a consistent, quantitative backbone. We have used these backbones as the basis for communicable scenario narratives in our popular report on the Earth3 study (Randers, Rockström, et al., 2018).

Scenario 1: Business-as-usual.

Scenario 1 is the baseline run of the Earth3 model. Here we use the parameters which best track the 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 the business-

[3] For pedagogic reasons we might use the label "Subjective wellbeing of a typical inhabitant" in the popular reports on our work, as it seeks to measure the wellbeing of the ordinary man or woman, not that of the elite.

as-usual scenario that the decision makers of the world will continue to perceive and respond to emerging problems in the conventional manner, without taking any extraordinary action. This scenario shows the gradual institutional development seen in the past few decades that we believe is likely to take place in the decades ahead.

The Earth3-core sub-model tells the following story in the business-as-usual scenario (see Figure 3-top): 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 special 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.

Energy use increases, but the use of electricity grows faster than the use of fossil fuels, which reaches a peak around 2040. Electricity increasingly comes from renewable sources, and the use of fossil fuels for electricity generation peaks and declines in the 2030s. In the 2030s, greenhouse gas emissions (covering both CO_2 and the other Kyoto and Montreal gases) also peak, because of increasing energy efficiency, the shift to wind and solar power, and the phasing out of other gases. The use of nitrogen and freshwater, as well as the release of lead, continue to rise, but at slowing rates.

The ESCIMO-plus sub-model tells the following story about the resulting biophysical effects to 2050 (see Figure 3-bottom): Global warming continues and reaches +2 °C already by 2050, sea level rises by another ~30 cm, the oceans become more acidic, the on-land glaciers shrink, as does the permafrost area. The area of old growth forest – both tropical and Northern – declines by another 20%. The fertilization effect of CO_2 on soil productivity is increasingly counteracted by the 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.

In summary, in the 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 5 shows the result, for each SDG and for each region from 1980 to 2050. Many social SDGs were already achieved in rich regions long ago. In other regions, more SDGs will be achieved in the decades ahead. But many SDGs in many regions will remain in the red zone, far from being achieved. For the three environmental SDGs (Goals 13, 14 and 15), the situation deteriorates over time, as human pressures on climate, water, and land continue to rise.

It is easier to see the overall picture when we aggregate the detailed results. Figure 4a shows the number of SDGs achieved by region from 1980 to 2018. A maybe surprising result is that the SDG achievement score in the rich regions declines over the coming decades, as the pressures on the environment continue to rise. Figure 4b shows the global average – the sum of regional results weighted by population. It shows the sustainable development progress made since 1992. 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.

And what will be the resulting pressure on the PBs in the business-as-usual scenario? Figure 6 shows the situation for the individual PBs. For nearly all of them, the indicators move in the wrong direction – towards the higher risk red zone, farther away from the safe operating space for human societies. The only exceptions to these problematic trends are Ozone depletion, as the man-made releases of Montreal-gases continue to decline towards safer levels, and Air pollution, where the population affected by anthropogenic haze declines from 2020 onwards.

Again, the aggregated global measure gives a less noisy picture of the environmental situation in the business-as-usual scenario. Figure 4c shows that the global safety margin continues to decline, from 8 in 1980, down to 4.5 in 2018 and the same in 2030, to a final 3.5 in 2050. In other words, total human pressure on the planetary boundaries continues to rise, steadily eroding the safety margin. By mid-century humanity (in the model system) has transgressed 8 of the 9 PBs and is deeply into the high-risk (red) zone for 4 of them. The safety margin is slim.

Finally, how will average wellbeing evolve in the business-as-usual scenario? Figure 4d shows the global picture. The global average wellbeing remained more or less constant from 1980 to 2020, because economic growth is not sufficient to compensate for the combined effect of increasing inequity, increasing pollution levels, and increasing worries about dangerous climate change. It rises towards 2050 in the business-as-usual scenario, 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 is slower 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 S3 shows these results by region.)

Needless to say, this assessment depends on the weights chosen for the 5 components of the average wellbeing index. We have weighted them equally as a demonstration of the Earth3 system. It would be simple to defend other weightings, if Earth3 is used for further research and policy advice.

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 the 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.

Since the business-as-usual scenario certainly does not achieve the globally agreed goals, we analyze two other pathways towards the future, based on two more simulation runs with Earth3. In scenario 2 we study the effect of accelerating the rate of economic growth in all regions, and in scenario 3 we study the effect of a more focused effort to achieve the SDGs.

Scenario 2: Accelerated economic growth

In scenario 2 we explore the question: What will happen if global society manages to increase the rate of economic growth in all regions? Many think that higher economic growth would accelerate the move towards achieving SDGs.

We implement scenario 2 in Earth3 by assuming an exogenous increase in the rate of growth in GDP per person of 1 % per year – in all regions, starting in 2018. This leads to an increase in the average rate of growth in global GDP from 2.8 to 3.5 % per year during the 32 years to 2050[4]. It amounts to success in continuing the average rate of economic growth of the world economy from 1970 to 2010. Scenario 2 assumes that the regions continue to stick to conventional policy tools.

The accelerated-economic-growth scenario differs from the business-as-usual scenario in some important ways: It leads to higher GDP, more energy use, more CO_2 emissions, and more use of resources. Per capita income and government spending are higher, as is the ecological footprint and biophysical damage. But the biophysical effects (the outputs from ESCIMO-plus) are nearly indistinguishable in the short run from those in Figure 3-bottom, because of the enormous inertia in the global ecosystem. It takes decades of major reduction in the human impact in order to achieve an observable difference in global warming, sea level rise and the like.

But there are visible effects in the achievement of SDGs. Figure 4b shows that globally, the number of SDGs achieved in 2030 rises to 11 (compared to 10.5 in business-as-usual), and to 11.5 in 2050. Average wellbeing improves (see Figure 4d), because the consumption benefits from higher GDP per person outweighs the rising dis-amenities from more pollution and higher inequity. But the global pressures on planetary boundaries also increase and the global safety margin declines faster towards the minimum values of 3.5 in both 2035 and 2050 (see Figure 4c).

In summary, accelerating the growth of the world economy improves the situation, but does not fully solve the problem. It leads to the satisfaction of a few extra social SDGs, but at the cost of increasing pressure on the global environment (and less progress on achieving the biophysical SDGs). This makes it interesting to explore more direct ways of increasing the number of SDGs achieved.

Scenario 3: Stronger focus on SDGs

In scenario 3, we explore the consequences if we assume that the world increases its effort to achieve the SDGs. In this scenario, the world shifts more of its human resources and finance from current activities to projects that help achieve SDGs and/or reduce the pressure on PBs. Other analyses have shown that shifting a few percent of total GDP from conventional to green activity has the potential to solve most sustainability challenges (Global Commission on the Economy and Climate, 2018; Business & Sustainable Development Commission, 2017; DNV-GL, 2018). Recently IPCC (2018) estimated the additional energy investment cost of keeping warming below 1.5 deg C to be 0.9 % of GDP. This amounts to shifting a percent of all jobs from conventional to green activity. The stronger-focus-on-SDGs scenario explores the effects of a step in this direction.

Scenario 3 is implemented in Earth3 by reducing by 50% the time it takes to reach the targets for those SDGs that can be attained without fundamental change of the current world order (capitalist, consumerist, short-termist) – that is, without a fundamental redistribution of income or wealth. (In technical terms, this amounts to halving the value of the parameter ***c*** in all the exponential terms ("exp ((*time* – 1980) / *c*)") in Tables S3 and S4). In addition, we

[4] The growth in GDP is lower than the growth in GDP per person because of feedback effects in the Earth3 model system. First of all, higher levels of GDP per person lead to lower birth rates and slower population growth. Also, as regions get richer, the rate of change in annual growth per person tends to decline, following the empirically observed global trend in Figure 2.

assume a slow increase in the rate of introduction of renewable electricity, and a slow reduction in the freshwater use per person, the footprint per person, and the greenhouse gas emissions (all by 0.5% per year).

Scenario 3 is a clear improvement relative to scenarios 1 and 2 (see Figure 4). The stronger focus on SDGs leads to the achievement of more of the goals – a full 12 in 2030, up from 10.5 in business-as-usual – and to a halt in the downward trend of environmental goals seen since the 1980s. The global safety margin rises to 5 in 2050, up from 3.5 in business-as-usual. It even leads to a rise in average wellbeing, albeit not as much as in scenario 2. Still, scenario 3 remains a long way from achieving all SDGs by 2030, and even by 2050. The global safety margin remains narrow but offers a glimmer of hope as it starts to improve towards the end of the simulation period in 2050.

Discussion and conclusions

In the Earth3 model system, world society does not achieve the SDGs within the PBs by 2030, or even by 2050, neither in the business-as-usual scenario, nor if the world chooses to go for accelerated economic growth or for a stronger focus on achieving the SDGs. It appears that tougher interventions are necessary, addressing head-on the problems arising from increasing consumption, enduring greenhouse gas emissions, increasing population, rising inequity and continuing poverty in a finite world. Non-conventional - even transformational - action seems necessary to create a sustainable world and satisfactory levels of wellbeing for all (Randers, Rockstrõm et al, 2018).

On the methodological side, the Earth3 study shows that it is possible to build a "global system model" and use it to analyze future achievement of SDGs within PBs. But like in all modelling studies, our conclusions depend on the assumptions made. Earth3 should be seen as a starting point for further elaboration and enhancement.

The relative simplicity of the model structure makes our principal assumptions transparent, but in some cases other assumptions may be equally plausible and lead to different conclusions. Important examples are our choice of indicators for the individual SDGs and PBs, the choice of thresholds, and the choice of functional form, satisfactory level and weighting in the wellbeing index.

Consistent with system dynamics practice (Barlas, 1996) we have done enough informal sensitivity testing (varying both parameter values and structural assumptions) to conclude that our conclusions from the socio-economic sub-model are relatively robust: reasonable variation lead to change in numerical values, but not in curve shapes. An exception is the choice of demand functions for electricity and fuel in mature economies. Similarly, the biophysical sub-model is also generally robust, except here 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 modeling 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 simple, solutions in future work.

In our current formulation, there is no feedback from the biophysical sub-model to the socio-economic model. An example of this weakness is our exogenous treatment of inequity and near-exogenous treatment of forest cut – both tropical and northern. In our view, this matters much more in the long run (i.e. after 2050) than in the next few decades – because history indicates that humanity responds slowly to changes in the environment.

On the methodological side, the Earth3 study shows that it is possible to build a global system model and use it to analyze future achievement of SDGs within PBs. But despite its usefulness as an exploratory tool, Earth3 is far from perfect. New generations of integrated Human World-Biophysical Earth models are needed to test and sharpen our conclusions, and to study the feasibility and consequences of transformational change.

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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 performed analyses. PES devised the scenario perspective, JD and SC positioned the study in the sustainability science literature. JR 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.
Details in Report S1 in supplementary materials to this paper.
GDP and Government spending are in 2011 PPP US$.

Global Sustainability Objectives		Modeled 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/m³	> 35 µg PM2.5/m³
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 Mkm²	< 17 Mkm²
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 Mkm²	≤ 17 Mkm²
5	Nutrient overloading	Release of bioactive nitrogen	< 100 N Mt/y	≥ 200 Mt/y
6	Freshwater overuse	Freshwater withdrawal	< 3000 km³/y	≥ 4000 km³/y
7	Biodiversity loss	Unused biocapacity	> 25 %	≤ 18 %
8	Air pollution	Urban aerosol concentration	< 10 µg PM2.5/m³	≥ 35 µg PM2.5/m³
9	Toxics contamination	Release of lead	< 5 Mt/y	≥ 10 Mt/y

This is a non-peer reviewed preprint submitted to EarthArXiv: https://doi.org/10.31223/osf.io/xwevb

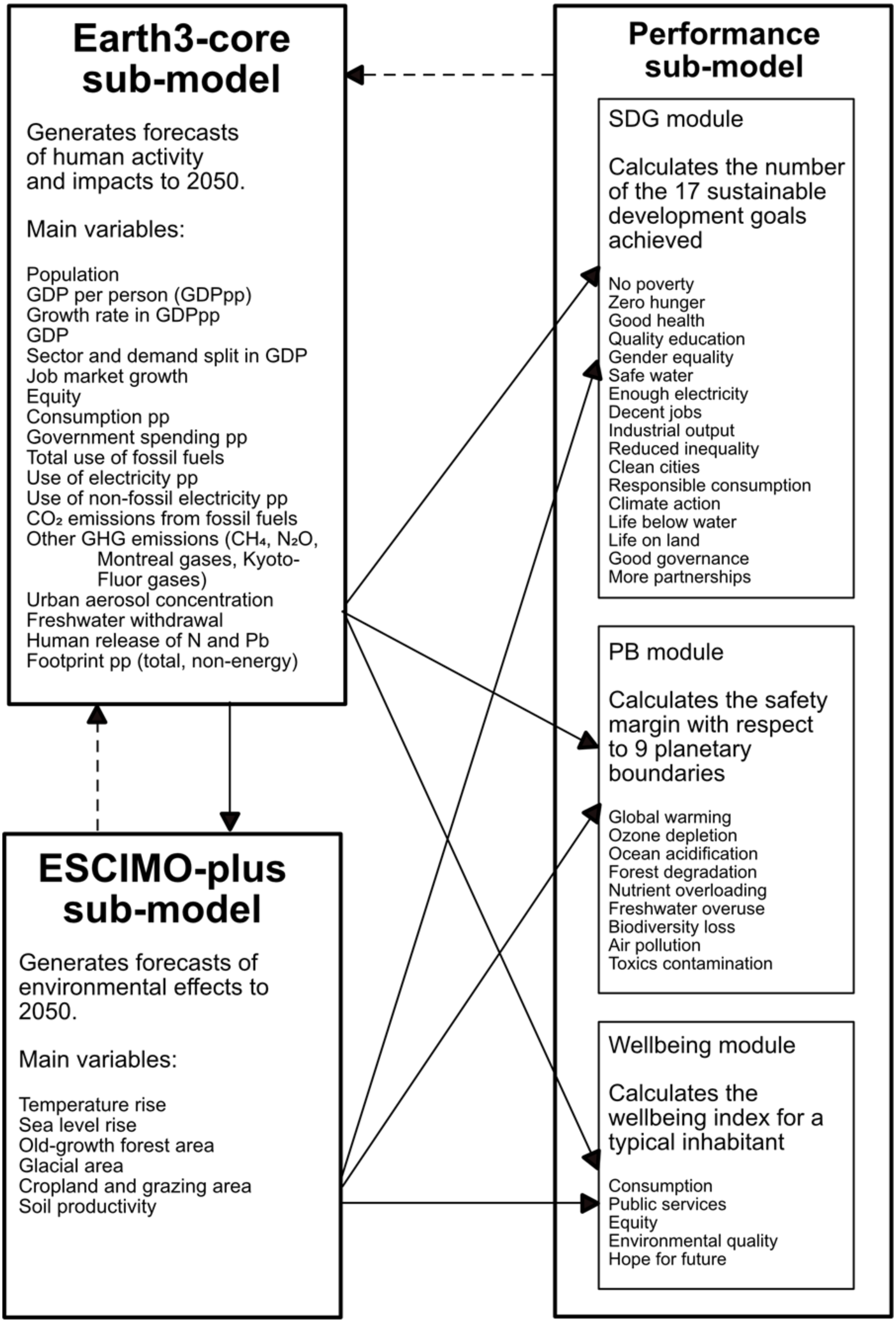

Figure 1. Overview of the Earth3 model system.
Details in Goluke et al (2018)
Dashed lines indicate feedbacks needed to convert Earth3 into a full system dynamics model.

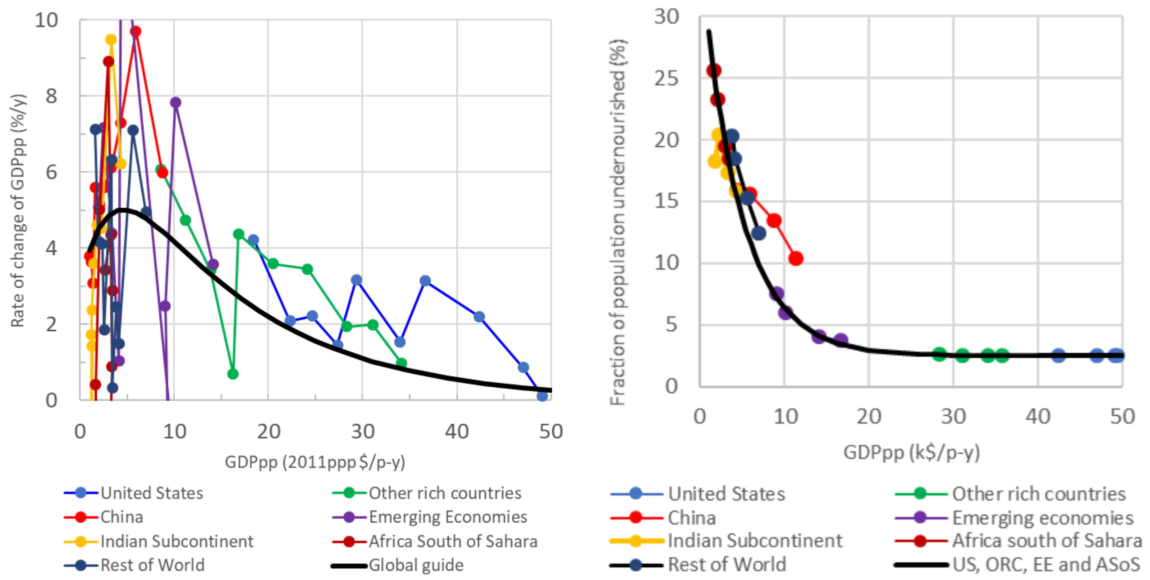

Figure 2. Examples of correlations used in Earth3-core (left) and the SDG-module (right), based on historical data 1980-2015 for seven world regions.
Goluke et al (2018) and Collste et al (2018)

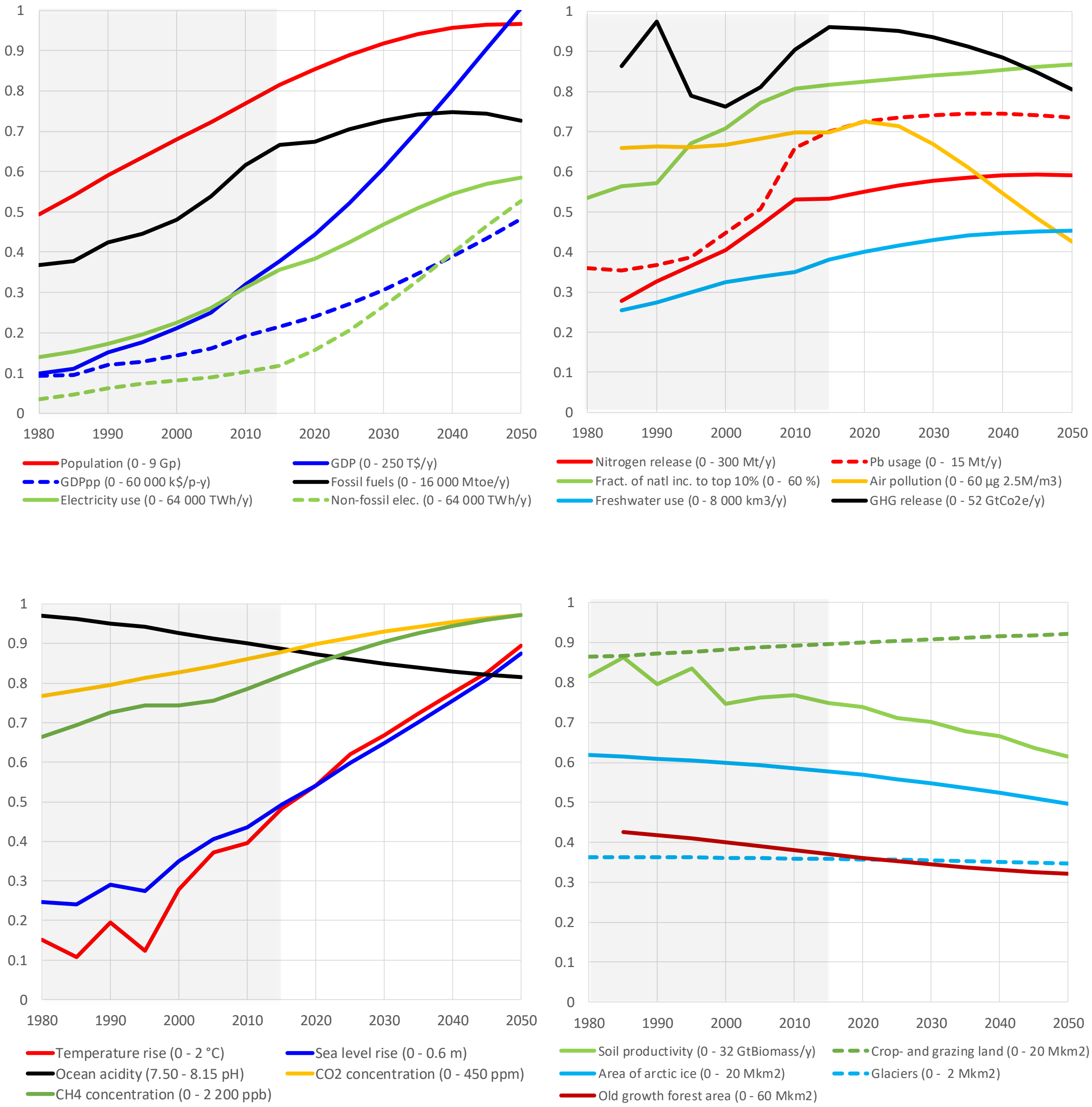

Figure 3. Outputs from the socio-economic sub-model Earth3-core *(top)* and the biophysical model ESCIMO-plus *(bottom)* - used to drive the Performance sub-model.
Goluke et al (2018)

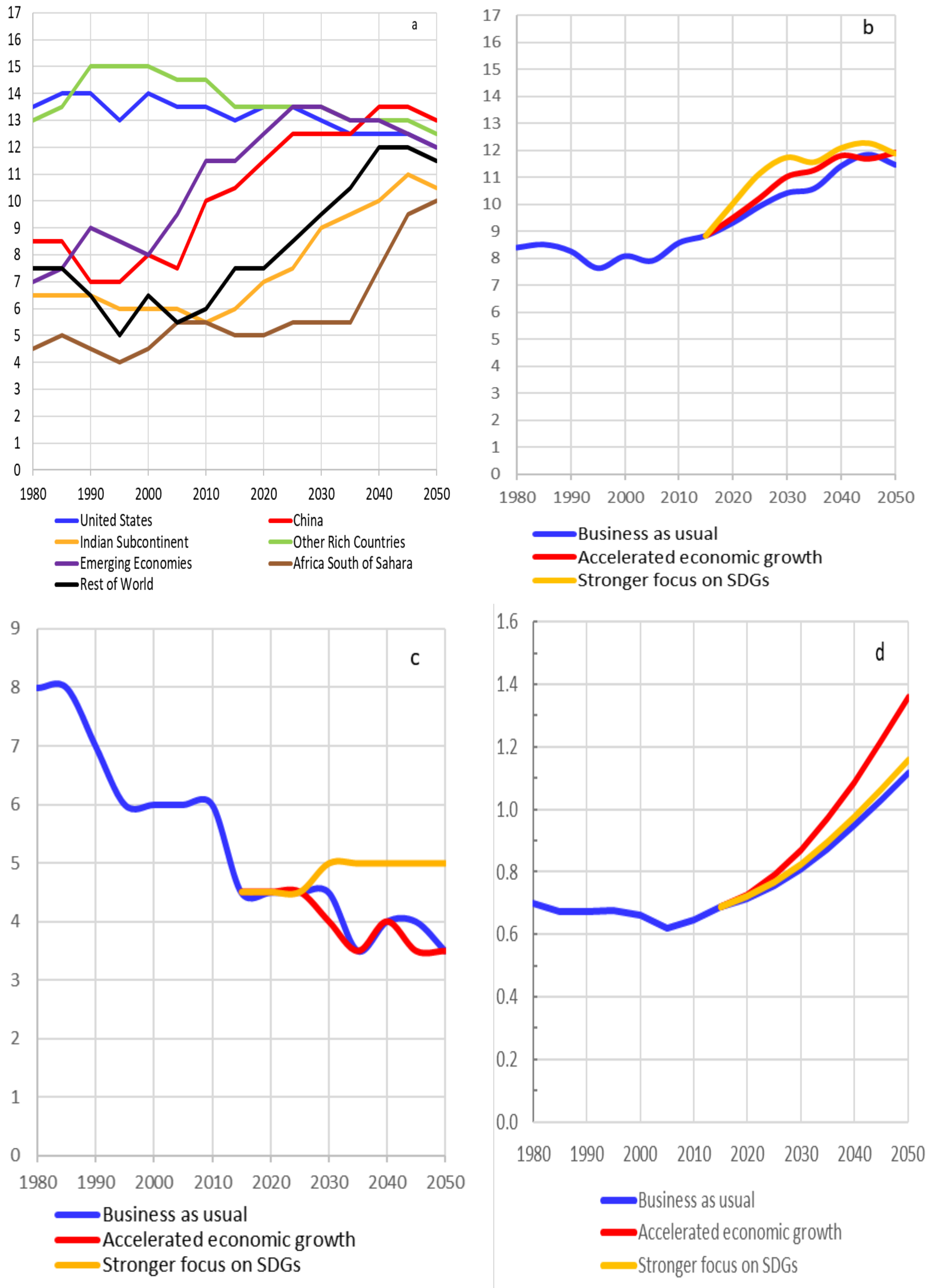

Figure 4. Aggregated outputs from Performance sub-model 1980-2050.
4a: The number of SDGs achieved. Business-as-usual scenario, by region.
4b: The number of SDGs achieved, world average. *4c:* The global safety margin.
4d: The average wellbeing index, world average.

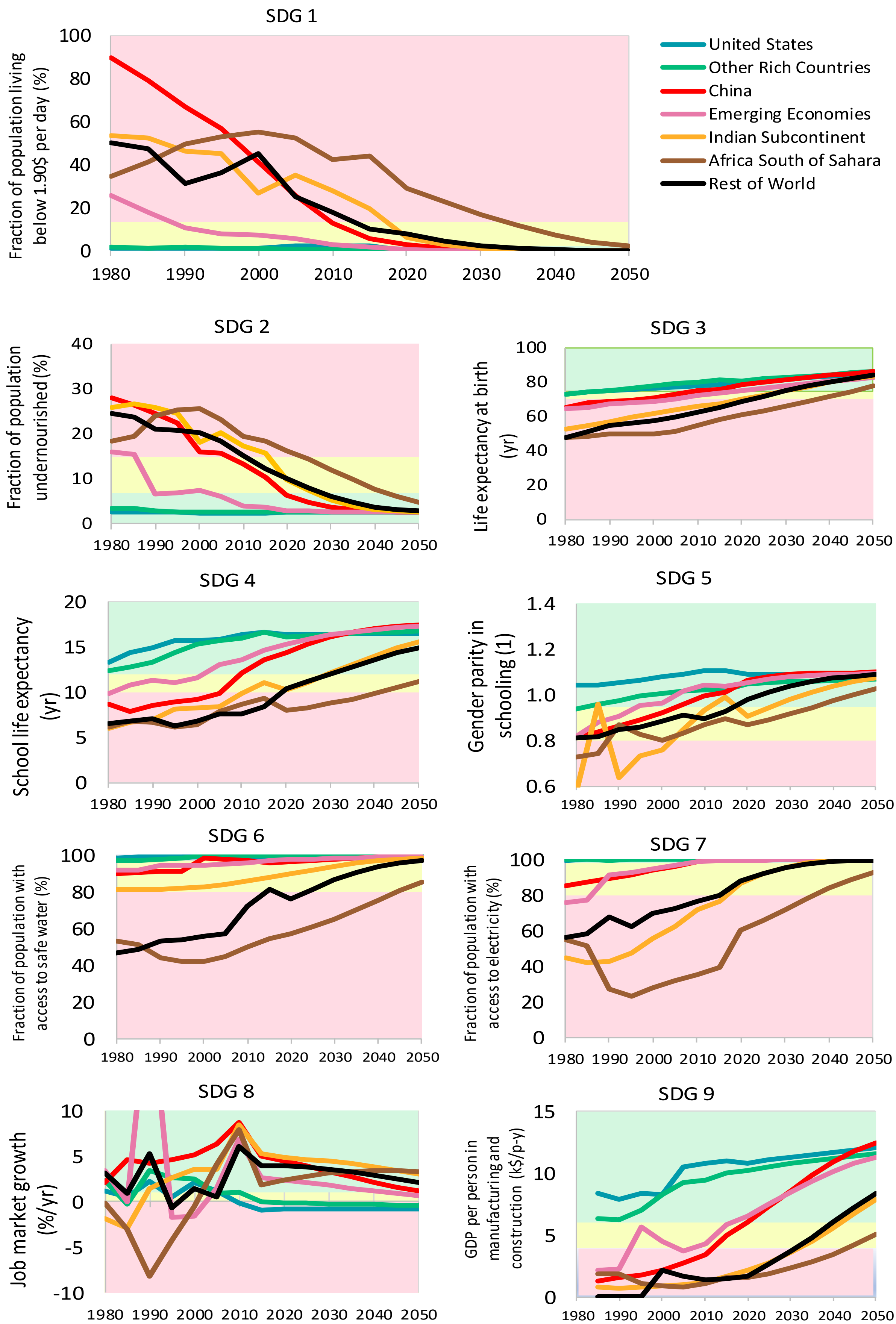

Figure 5 (page 1 of 2). See caption on next page.

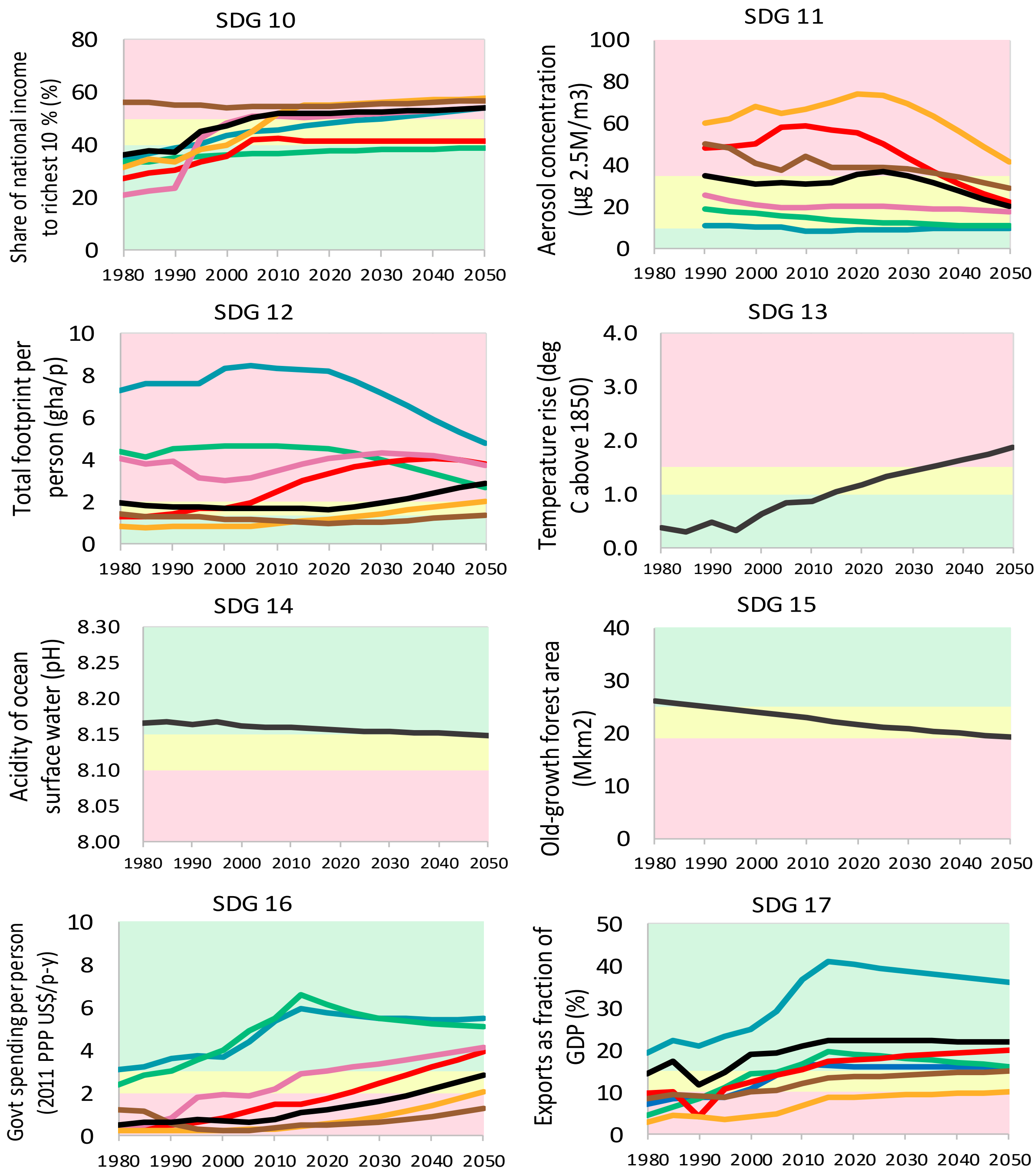

Figure 5. (page 2 of 2) Achievement of individual SDGs. Business-as-usual scenario, by region, 1980-2050.
Green zone shows full achievement of an SDG, amber zone shows partial achievement, red zone shows failure to achieve the goal.

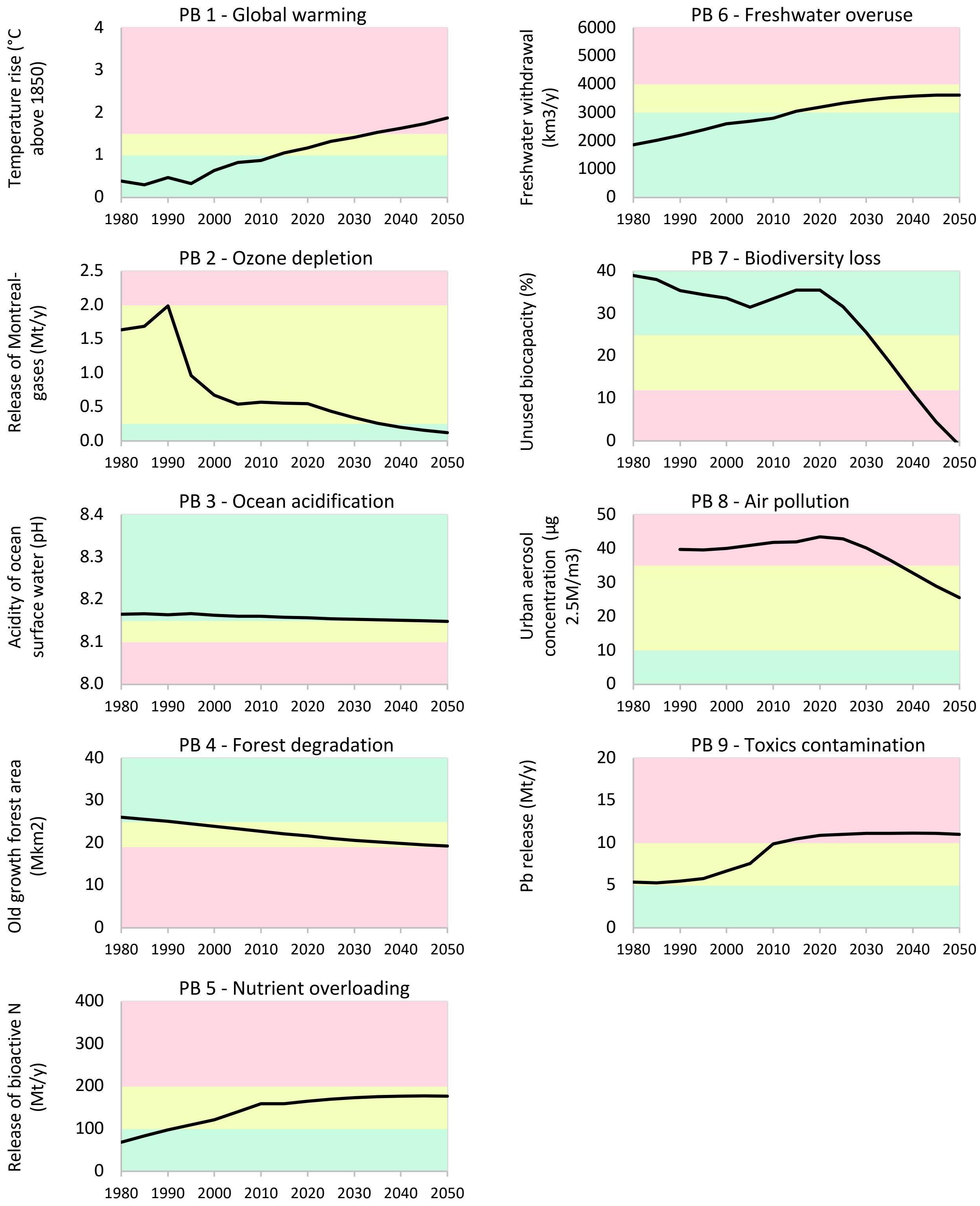

Figure 6. The global pressure on individual PBs. Business-as-usual scenario, 1980-2050. Green zone shows PB within safe level, amber zone shows PB transgression, red zone shows PB at high risk levels.