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Achieving the 17 sustainable development goals within 9 planetary boundaries

Jorgen Randers[1]*, Johan Rockstrøm[2], Per-Espen Stoknes[1],
Ulrich Goluke[1], David Collste[3,4], Sarah Cornell[3]

1. BI Norwegian Business School, Oslo
2. PIK Potsdam Institute for Climate Impact Research, Berlin
3. Stockholm Resilience Center, Stockholm University, Stockholm
4. Centre D'Etudes et de Recherches sur le Développement International, Université Clermont-Auvergne, France

* Corresponding author: jorgen.randers@bi.no

ABSTRACT

(262 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. Both will help inform the global public debate around the SDGs. The study is the basis for our popular contribution to that debate, called *Transformation is feasible!* (Randers J, Rockstrøm J et al, 2018).

We built a simulation model (Earth3) to help answer two research questions: How many of the 17 UN sustainable development goals (SDGs) will be achieved by 2030? And: What will be the resulting pressure on 9 planetary boundaries (PBs)? Our tentative answer is that he world will not reach all SDGs by 2030, nor by 2050, and that the global safety margin (the buffer between the human impact and planetary boundaries) will continue to decline. Additional economic growth and extra focus on SDG achievement does not change this conclusion: Transformational change seems necessary. On the methodological level our main result is "proof of concept": We show that it is possible to combine a socio-economic model of human activity with an ecological model of the resulting environmental effects and use this integrated "global system model" to forecast future achievement of SDGs and the resulting pressure on PBs. But model improvement is needed to reduce the uncertainty in our answers.

SOCIAL MEDIA SUMMARY

(119 characters)

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

KEYWORDS

Global modeling, global system model, scenarios for the global future, combining socio-economic and environmental models, achieving sustainable development goals, exceeding planetary boundaries.

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Contents

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Introduction

Global society is currently seeking to achieve the 17 sustainable development goals (SDGs) agreed by the UN in 2015 (see list in Table 1) (United Nations, 2015). There are concerns that if the 14 socioeconomic SDGs are achieved, then the human ecological footprint (resource use, emissions and habitat destruction)(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 main environmental SDGs, which are SDG 13 - Climate action, SDG 14 - Life below water, and SDG 15 - Life on land (United Nations, 2015). There are also concerns that humanity's pressure on one or more planetary boundaries (PBs) (see list in Table 2) will generate continuing deterioration of the biogeochemical environment – or even trigger ecological collapse (Rockström et al., 2009; Steffen et al., 2015). And there are concerns that insufficient financial resources and political support will be made available to achieve all SDGs by 2030 – as agreed in the UN. Finally, it remains an open question what various possible global futures will mean for the wellbeing of the average global citizen.

Our overall ambition is to clarify the options ("pathways") open to humanity given the long-term goal of achieving the sustainable development goals within the planetary boundaries.

Our research question

As a first step, in this paper, we seek to answer to 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 pressure on 9 planetary boundaries (PBs)?

We define business-as-usual as a future where decisions are made – both at the individual, corporate, national, and global levels – following the patterns that have dominated decision-making since 1980. This means, going forward to 2050, a continuation of the way that societies react to emerging problems. These ways vary among the world's regions, hence we provide our answer by region (we split the world in 7 regions, see list in Table 1).

We also explore other scenarios than business-as-usual, and to facilitate the comparison of alternative futures, we summarize in one number (which we call the Average wellbeing index) the situation in any region for any year. The Average wellbeing index is an aggregate of 5 indicators (see list in Table 5) and seeks to measure the wellbeing of the average person as it evolves over time.

Our method

We answer the research question on the basis of a quantitative simulation model called "Earth3". We built this model to mimic the development over time in our 7 regions towards 2050. The global development is calculated as the sum of the 7 regional futures.
Earth3 is a highly aggregated global system model and consists of three sub-models (see Figure 1) that interact. The three sub-models are:

1. The *socio-economic sub-model* ("Earth3-core") generates forecasts of the level of human activity to 2050, by region. Outputs include: population, GDP, distribution, energy use, greenhouse gas release, some other resource use and emissions.
2. The *environmental sub-model* ("ESCIMO-plus") calculates the environmental effects arising from the 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* calculates the development over time of three performance indicators: the "Number of 17 SDGs achieved", the "Global safety margin with respect to 9 PBs", and the "Average wellbeing index".

Earth3 produces internally consistent scenarios for the combined socio-economic and environmental system from 2018 and 2050. To place these futures in a bigger perspective, they are presented as continuations of historical data for the time period 1980 to 2015. The outputs from the socio-economic and environmental sub-models are finally used to estimate indicators for achievement of 17 SDG, of pressures on 9 PBs, and of 5 factors that influence the average wellbeing of the typical citizen in the region of interest.

Earth3 builds on our long experience in building models of the global socio-economic system and the global environmental system (Meadows et al. 1972, 1974, 1992, 2004), (Randers 2012). Earth3 continues our preference for 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). Finally, Earth3 illustrates our preference for simple models that are intentionally transparent and easy to understand, in order to facilitate criticism and further improvement. Earth3 is freely available as supplemental material to this paper (for the time being on www.2052.info/Earth3).

It is worth mentioning at the outset that constructing Earth3-core was made simpler, and the resulting model more transparent, through our discovery of strong correlations among many of the socio-economic variables in Earth3, especially with the variable GDP per person measured in 2011 PPP $ per person-year. This has made it possible to replace elaborate causal descriptions with simple correlations that provide the desired result. See full list of correlations used in Tables 5 and 6. More detail is available in (Collste et al., 2018) "The empirical basis for the Earth3 model system" as supplemental material to this paper available at https://doi.org/10.31223/osf.io/ephsf.

Description of Earth3

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 7 regions for the period 2018 to

2050. Global activity levels are computed as the sum of the regional futures, weighted by population.

The causal structure of Earth3-core is shown in Figure 2, and the detailed equations and parameter values are available on the web. In essence, Earth3-core first calculates (for each region) total output (GDP) per person - through numerical integration, based on the observed correlation between "rate of change in GDPpp" (ROC of GDPpp) and "GDP per person" (GDPpp). See Figure 4 and a full discussion in (Randers, 2016). Second, the size of the population is calculated based on values for birth rates and death rates that, in turn, depends on the value of GDPpp. Third, total GDP is calculated as the product of population and GDPpp. Fourth, energy use (split in "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. Fifth, CO2 emissions from energy use is calculated from the total use of fossil fuels, and the fuel mix (which is set exogenously in this version of Earth3 – as is the fraction of electricity from various sources, including renewable sources). Sixth, 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. Seventh, income distribution, measured as the "share of national income to richest 10% of the population", is exogenously determined (in this version of Earth3) based on historical trends. Finally, the composition of GDP and of total demand is determined by the productivity level (i.e. the GDPpp). Figure 9 shows some of the outputs from Earth3-core.

As mentioned, these calculations are simplified because we utilize the strong correlations among many of the variables in Earth3-core and GDPpp. Two examples are given in Figure 4, and a full list is given in Tables 5 and 6. We have found that it is crucial to use fixed (inflation adjusted) dollars to obtain good correlations, and, furthermore, that it is essential to adjust for purchasing power parity among nations. In other words, to measure GDPpp in 2011 PPP $ per person-year.

The functional forms and parameter values that we use are described in (Collste et al. 2018). In some cases, we are forced to use global averages, and therefore disregard regional differences, because of lack of regional data. But when possible we use different parameters for the different regions, thereby capturing regional characteristics. In some instances, we found an additional variation with time, for example when there is rapid technological advance, or when we expect a strong political will to phase out harmful practices[1].

Most analyst who sees the world as a system away from equilibrium, will find the causal assumptions in Earth3. The same goes for the parameter values, which are based on available information – both numerical and qualitative. 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 the IIASA's global population model (Lutz et al, 2018). The differences were understandable and acceptable, given our purpose.

[1] Data sources for Earth3 include United Nations Populations data (United Nations Population Division, 2017 and 2018), The Penn World Tables (Feenstra et al., 2015), BP (2017), Boden et al. (2017), Global Footprint Network, Randers et al. (2016), Rockstrom et al. (2009), Steffen et al. (2015) and The World Bank (World Bank Development Indicators, 2018; Educational Statistics, 2018). For data on the ESCIMO, see Randers et al. (2016)

The structure of the environmental sub-model

The environmental sub-model – 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 geo-bio-physical variables when driven by outputs from Earth3-core.

The causal structure of ESCIMO-plus is shown in Figure 3, and the detailed equations and parameter values are available online as supplemental material to this paper (for the time being on www.2052.info/Earth3). In essence, ESCIMO-plus is a slightly modified version of the ESCIMO model (Randers et al, 2016). It is a relatively simple global system model which is made to calculate the environmental effects of human activity as both evolve over time. ESCIMO is made to study the 1900 to 2100 period, but can be run farther into the future, if the necessary socio-economic drivers are provided exogenously.

The outputs from ESCIMO-plus include global average temperature rise, average sea level rise, ocean acidity, the extent of different land types, and many others. Figure 10 shows some examples.

ESCIMO can be used to simulate the effect of various human policy measures, and to simulate the effects of various natural catastrophes. The output from ESCIMO for given drivers have been compared with the output of other more complex earth system models. They give similar results when subject to the same drivers, but ESCIMO is much simpler to use (Randers et al, 2016).

ESCIMO keeps track of the carbon flows (and stocks) in the global ecosystem and describes how they change over time in response to varying human greenhouse gas emissions. ESCIMO also tracks the global heat flows (and stocks), and the change in the areal extent (and productivity) of varying land types, once more in response to human activities. Thus, ESCIMO ensures conservation of carbon, heat, and land area in model simulations, and thereby increases the consistency in the scenarios[2].

The structure of the performance sub-model

The performance sub-model calculates the time development of three performance indicators: the "Number of 17 SDGs achieved", the "Global safety margin with respect to 9 PBs", and the "Average wellbeing Index". All three are calculated every fifth year, and for every region, except in those cases where we only have global data.

– Number of 17 SDGs achieved

This indicator seeks to measure the extent to which the 17 SDGs are achieved, on a scale from 0 (no achievement at all) to 17 (full achievement of all goals). For each SDG we have chosen one indicator to measures the degree to which the SDG has been achieved. We have defined two threshold values. The first threshold indicates the border between the red zone (no achievement – score 0) and the orange zone (part achievement – score 0,5). The second threshold indicates the border between the orange zone and the green zone (full achievement – score 1). See Table 2 for details.

[2] It is a weakness that water is not conserved in ESCIMO, as it appears in many forms in the model: as ocean water, ice and snow, vapor, and in clouds.

For each SDG, an "achievement score" is determined by comparing each indicator level based on outputs from Earth3-core and ESCIMO-plus with the indicator threshold levels. The calculation is made simpler by the existence of strong correlations between those outputs and the indicators we have chosen. See Table 6 for details.

The number of 17 SDGs achieved is calculated as the sum of the achievement scores for all 17 SDGs. This is done per region, see Figure 5. By summing the regional results weighted by population, we obtain the global average number of SDGs achieved, see Figure 6. The result depends, of course, on the scenario of interest.

The global average number of SDGs achieved is our aggregate measure of the extent to which humanity has achieved the 17 SDGs. We chose to place the same weight on each SDG. That means that we do not treat one SDG as more critical than any other. It is of course fully possible to choose different weights for different SDGs[3].

– Global safety margin with respect to 9 PBs

This performance indicator seeks to measure the strength 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 them, leaving zero safety margin). For each PB we have defined a green zone which we see as low-risk (safety margin score 1), an orange zone which we see as medium-risk (safety score 0,5), and a red zone which we see as high-risk (safety margin score 0). See Table 3 for details.

The global safety margin with respect to 9 PBs is calculated as the sum of the risk margin scores for all 9 PBs. This is done at the global level only, see Figure 7.

The global safety margin is a measure of the distance between current human pressure on the planet and the maximum pressure that can be handled by the planet in a safe and sustainable manner. The result depends, of course, on the scenario of interest, see Figure 7.

– Average wellbeing index

This indicator seeks to measure the wellbeing of the average inhabitant in a region. The average wellbeing index is defined as the sum of 5 indicators of personal wellbeing: consumption, public services, equity, environmental quality, and hope – divided by 5. Each indicator is measured relative to what we have chosen as a "satisfactory level" for the indicator. See Table 4 for details. 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. See Figure 8 for an example, by region.

It is possible to 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 8.

[3] This can be done through minor changes in the spreadsheets in the SDG sub-module

Experiments with Earth3

We use the Earth3 model system to produce consistent quantitative scenarios from 2018 to 2050 for the level of human activity and the resulting environmental effects, and to calculate the associated consequences for achievement of SDGs, pressure on PBs, and average wellbeing. The details of each scenario are determined by the parametrization chosen for each simulation run, the model system remains the same throughout. All calculations are made at the regional level and aggregated into global numbers when desired. The exception is the pressure on PBs, which is only analyzed at the global level.

In this paper we discuss three scenarios, which we call “business-as-usual”, “accelerated-economic- growth”, and “stronger-focus-on SDGs”. For each of these scenarios, the output from the Earth3 constitutes a consistent, quantitative backbone. We have used these backbones as basis for verbal, more communicable, scenario narratives. See (Randers, Rockstrøm, Stoknes, Goluke, Collste and Cornell, 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. Furthermore, parameters are chosen to reflect our overall assumption in the business-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. As a consequence, the business-as-usual scenario includes the normal, very gradual, institutional development that is likely to occur in the decades ahead.

The main developments in the business-as-usual scenario is described in words below. This verbal narrative is supplemented with graphs showing the development over time from 2018 to 2050, spliced onto historical data for the period 1980 to 2015. More detail, also at the regional level, is available in the supplementary material (www.2052.info/Earth3).

The Earth3-core sub-model tells the following story in the business-as-usual scenario (see Figure 9): Towards 2050 population growth will slow down. In most regions population numbers stagnate, and in some they decline, with exception of in the poorest regions, where population growth continues. The economy (GDP) continues to grow everywhere, at high rates in regions like China and many emerging economies, but at low rates in the rich regions, with stagnation in some special cases. Per capita incomes will continue up, but inequity – measured as the share of national income accruing to the richest 10 % of the population will continue its upwards trend in most regions, especially the free market economies.

Energy use will increase, but the use of electricity will grow 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. Greenhouse gas emissions (covering both CO_2 and the Kyoto and Montreal gases) also peak, in the 2020s, because of increasing energy efficiency, the shift to wind and sun, 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 environmental effects to 2050 (see Figure 10): Global warming will continue and reach + 2 °C already by 2050, the sea level will rise by another foot or so, the oceans will become more acidic, the on-land glaciers will be smaller, as will be the permafrost area. The area of old growth forest – both tropical and Northern – will be reduced by another 20 percent. The fertilization effect of CO2 on soil productivity will be increasingly counteracted by the negative effects of higher temperatures and more variable precipitation. On the positive side, the concentrations of Montreal protocol gases will decrease, there will be lesser Kyoto gases, and aerosols go down, while the amount of unused biocapacity stays above a lower threshold.

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

To what extent will the SDGs be achieved in this business-as-usual scenario? Figure 11 shows the result, for each SDG and for each region from 1980 to 2050. Many social SDGs were already achieved in the rich regions long ago. In other simulated regions, more SDGs will be achieved in the decades ahead. But many SDGs in many regions will remain in the red zone – far away from being achieved. Concerning the 3 environmental SDGs (i.e. 13, 14, 15), the situation will deteriorate over time – as human pressures on climate, water, and land continue to rise.

It is simpler to capture the general picture in our global measures. Figure 5 shows the number of SDGs achieved by region from 1980 to 2018. A surprising result is that the achievement score in the rich regions tends to decline over the coming decades, as the pressures on the environment continues to rise. Figure 6 shows the global average – the sum of regional results weighted by population. At this level, there has been progress since 1992, and going forward global society will satisfy 10.5 of the 17 SDG 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 12 shows the situation for the individual PBs. For nearly all of them, the indicators move in the wrong direction – towards higher risk farther away from the safe operating space for human societies (towards the red zone). The only exceptions are PB 2 - Ozone depletion, as the man-made releases of Montreal gases continue to decline towards safer levels, and PB 8 - Air pollution, where the population affected by man-made haze declines from 2020 onwards.

Our global measure gives a less noisy, and clearer, picture. Figure 7 summarizes the situation in the business-as-usual scenario. The Global safety margin continues to decline, from 8 in 1980, via 4.5 in 2018 and the same in 2030, to a final 3.5 in 2050. Thus, total human pressure on the planetary boundaries is continuing to rise, steadily eroding the safety margin. By mid-century humanity will be in the high-risk (red) zone for 4 of the 9 PBs. The safety margin will be slim.

Finally, how will average wellbeing evolve in the business-as-usual scenario? Figure 8 shows the result, by region. 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 reach Western levels at the end of the simulation period. Wellbeing grows slowly from 1980 to 2020 because economic growth is not sufficient to compensate for the combined effect of increasing inequity, increasing air pollution levels, and increasing worries about dangerous climate change.

Figure 13 shows the global picture. The global average wellbeing remained more or less constant from 1980 to 2020. It rises towards 2050 in the business-as-usual scenario, because more people are better off, and increased consumption counterbalances the negative effects of inequity, pollution and climate change. Needless to say, these conclusions depend on the weights chosen for the 5 components of the average wellbeing index. We have weighted them evenly. It would be simple to defend other weights. Ideally the weights should be drawn from voter polls.

In sum, the business-as-usual scenario does lead to a rise in the number of SDGs achieved towards 2050 (see Figure 6), and to a rise in the average wellbeing, globally (see Figure 8). But at the same time the human pressure on planetary boundaries grows, eroding the global safety margin relative to the planetary boundaries (see Figure 7).

Since the business-as-usual scenario certainly does not achieve the goals set by the UN in 2015, 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 – and the resulting bigger economic muscle – would accelerate the move towards more satisfaction of SDGs. Scenario 2 assumes that the regions continue to restrain themselves to conventional policy tools in the effort.

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.

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 CO2 emissions, and more use of resources. Per capita income and government spending are higher, as is the footprint and environmental damage. But the environmental effects (the outputs from ESCIMO-plus) are nearly indistinguishable from those in Figure 10, because of the enormous inertia in the global ecosystem. It takes decades of major reduction in the human impact in order to get an observable difference in global warming, sea level rise and the like.

But there is visible effect on the achievement of SDGs. Figure 6 shows that globally, a few more SDGs are achieved by 2030 (11 compared to 10,5 in scenario 1), and by 2050 (11,5 compared to 11). Average wellbeing improves (see Figure 8), 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 (see

[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 guideline. See Figure 4.

Figure 7), and the global safety margin declines faster towards the minimum values of 3.5 in both 2035 and 2050.

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 reduced satisfaction of the environmental 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 the sense that the world decides to shift more manpower and finance from current activities to projects that help achieve SDGs and/or reduce the pressure on PBs. We know from other analyses that shifting 1 % of total GDP from conventional to green activity will solve most sustainability challenges (Global Commission on the Economy and Climate, 2018; Business & Sustainable Development Commission, 2017; DNV GL, 2018 and 2017). This amounts to shifting 1 % of all jobs from conventional to green activity. The stronger-focus-on-SDGs scenario can be seen as exploring the effect of such a shift.

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 term) – that is, without fundamental redistribution of income or wealth. This amounts to halving the value of the parameter "c" in all the exponential terms ("exp ((time – 1980) / c)") in Table 6. In addition, we assume a slow increase in the rate of introduction of renewable electricity, and a slow reduction in the fresh water use per person, the footprint per person, and the greenhouse gas emissions (all with 0,5 % per year).

Scenario 3 is a clear improvement relative to scenario 2. Stronger-focus-on-SDGs leads to the satisfaction of more SDGs – a full 12 in 2030, up from 10.5 in scenario 1 (see Figure 6), and to a significant increase in the safety margin – to 5 in 2050, up from 3.5 in scenario 1 (see Figure 7). It even leads to a rise in average wellbeing, albeit not as much as in scenario 2 (see Figure 8). Still scenario 3 is a long way from achieving all SDGs by 2030, and even by 2050. The global safety margin remains narrow but gives a glimmer of hope as it starts to improve towards the end of the simulation period in 2050.

Our answer to the research question

In summary, Earth3 indicates the world society will 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 SDGs. It appears that much stronger or more focused interventions are necessary, addressing head-on the problems arising from increasing population, increasing consumption, enduring greenhouse gas emissions, rising inequity and continuing poverty in a finite world.

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.

Discussion

The main weakness of the Earth3 study, is that the conclusions drawn depend on the assumptions made – like in all modeling studies. Most of our assumptions are non-controversial, but in some cases other assumptions would have been equally plausible, and led to different conclusions. Examples are our choice of indicators for the individual SDGs, our choice of demand functions (for energy), and our choice of functional form and weights in the wellbeing index.

We have done some sensitivity testing (varying parameter values and structural assumptions) and found that our conclusions from the socio-economic sub-model are relatively robust: the numerical values in our scenarios change, but the curve shapes do not. The same goes largely for the environmental sub-model, except that here minor changes in sensitive parts of the model lead to major change in the model output, particularly in the long run (i.e. after 2050). This applies to our treatment of clouds, water vapor, and the melting of the permafrost.

Notice also the bias that resides in our choice of a dynamic (simulation) perspective, not an equilibrium one. And our choice of a formulation which is mainly causally based, using parameters with independent physical meaning and values obtained from independent sources, not solely based on parameters derived from statistical correlations.

But the biggest weakness in our current formulation is the lack of feedback from the environmental sub-model to the socio-economic model. This matters much more in the long run (i.e. after 2050) than in the next several decades – because humanity arguably responds slowly to changes in the environment. Another weakness is our exogenous treatment of inequity. These weaknesses make it meaningless to run Earth3 far into the future, or to use it to study transformational change. Both weaknesses will be addressed in our next project.

Conclusion

The Earth3 study indicates that world society will 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 SDGs. Non-conventional - even *transformational* - action seems necessary to create a sustainable world, and satisfactory levels of wellbeing for all

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 Earth3 is far from perfect. New generations of 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 and raised the funds. JRa designed the approach. UG and JRa built the central models and documentor. JR wrote the technical report.

DC and SC gathered data on SDGs and PBs and performed analysis. PES invented the scenario perspective and wrote the popular report.

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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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Tables and Figures

Region	Label	Population	GDP	GDP per person	Share of population
		Mp	G$/y	$/p-y	%
1. United States	USA	330	16 700	51 100	5
2. Other rich countries	ORC	750	28 100	37 500	10
3. Emerging economies	EE	890	15 400	17 300	12
4. China	CHINA	1 430	18 500	13 000	20
5. Indian subcontinent	IND	1 660	8 100	4 900	23
6. Africa South of Sahara	ASoS	750	2 800	3 800	10
7. Rest of the World - 120	RoW	1 540	11 500	7 500	20
World	World	7 330	101 100	13 800	100

Table 1. The 7 regions used in Earth3. Rounded data for 2015. ($ = 2011 PPP US$)
Details in The Empirical Bases for the Earth3 model https://doi.org/10.31223/osf.io/ephsf.[6]

[6] To make the group averages more meaningful, we have disregarded an “8. region” consisting of a small number of superrich nations outside the OECD, with ca 50 million people (less than 1 % of the world’s population), These small superrich nations are Qatar, Saudi Arabia, Singapore and UAE.

Sustainable development goal		Indicator	Target	Halfway-target
The 17 goals for humanity agreed by the UN in 2015		*Indicator for the achievement of each sustainable development goal*	*Threshold value for green zone*	*Threshold value for red zone*
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 (years)	> 75 years	< 70 years
4	Quality education	School life expectancy (years)	> 12 years	< 10 years
5	Gender equality	Gender parity in schooling (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 (%/y)	> 1 % / year	< 0 % / year
9	Industrial output	GDP per person in manufacturing & construction (2011 PPP US$/p-y)	>6.000 2011 PPP US$ / p-y	< 4.000 2011 PPP US$ / p-y
10	Reduced inequality	Share of national income to richest 10 % (%)	< 40 %	> 50 %
11	Clean cities	Urban aerosol concentration (µg 2.5M /m3)	< 10 µg 2.5M /m3	> 20 µg 2.5M /m3
12	Responsible consumption	Total footprint per person (gha/p)	< 1.5 gha/p	> 2 gha/p
13	Climate action	Temperature rise (deg C above 1850)	< 1 deg C	> 1,5 deg C
14	Life below water	Acidity of ocean surface water (pH)	> 8,15 pH	< 8,1 pH
15	Life on land	Old-growth forest area (Mkm2)	>25 Mkm2	< 17 Mkm2
16	Good governance	Government spending per person (2011 PPP US$/p-y)	>3.000 2011 PPP US$ / p-y	< 2.000 2011 PPP US$ / p-y
17	More partnership	Exports as fraction of GDP (%)	> 15 %	< 10 %

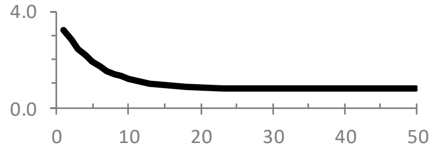
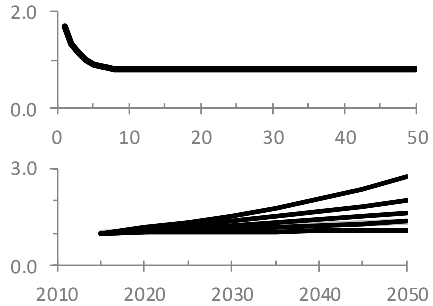
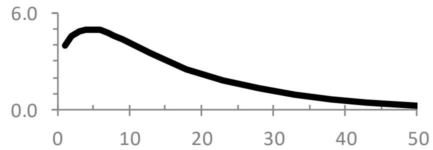
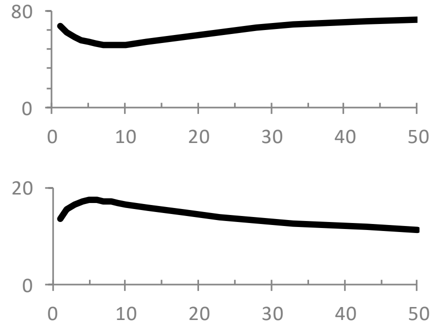
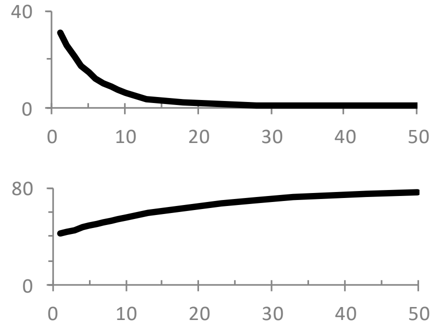
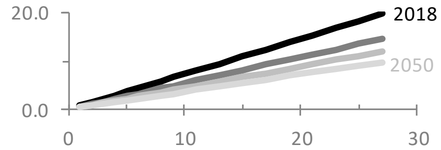
Table 2. The 17 sustainable development goals (SDGs) in Earth3. Indicators, units, targets and half-way targets.
Details in The Empirical Bases for the Earth3 model https://doi.org/10.31223/osf.io/ephsf.

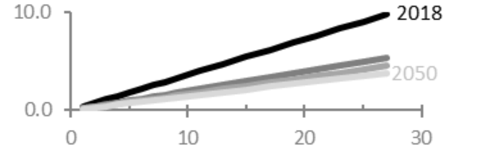
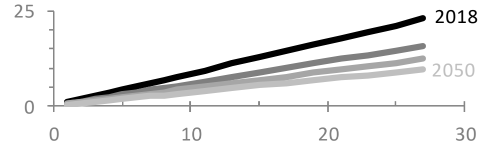
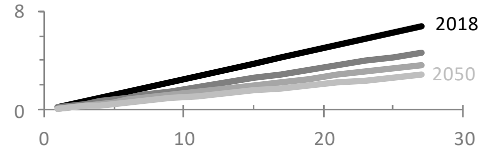
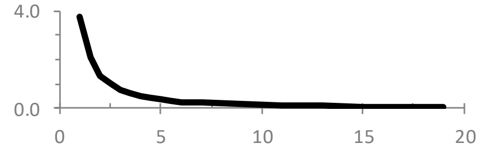
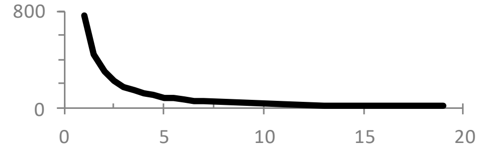
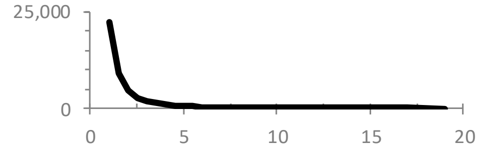
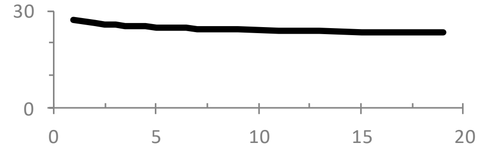
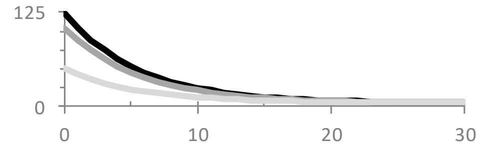
	Planetary boundary	**Indicator**	**Limit of safe zone**	**Limit to high-risk zone**
	Man-made processes that threaten to exceed a planetary boundary in 21st century	*Indicator of the current pressure on each planetary boundary*	*Threshold value for green zone*	*Threshold value for red zone*
1	Global warming	Temperature rise (deg C above 1850)	< 1 deg C	>= 2 deg C
2	Ozone depletion	Montreal-gas emissions (Mt/y)	< 0,25 Mt/y	>= 2 Mt/y
3	Ocean acidification	Acidity of ocean surface water (pH)	>pH 8.15	<=pH 8.1
4	Forest degradation	Old-growth forest area (Mkm2)	> 25 Mkm2	<= 17 Mkm2
5	Nutrient overloading	Release of bioactive nitrogen (Mt/y)	< 100 N Mt/y	>=200 Mt/y
6	Freshwater overuse	Freshwater withdrawal (km3/y)	< 3.000 km3/y	>= 4.000 km3/y
7	Biodiversity loss	Unused biocapacity (% of biocapacity)	> 25 %	<= 18 %
8	Air pollution	Urban aerosol concentration (µg 2.5M/m3)	< 10 µg 2.5M/m3	>= 35 µg 2.5 M/m3
9	Toxics contamination	Release of lead (Mt/y)	< 5 Mt/y	>= 10 Mt/y

Table 3. The 9 planetary boundaries (PBs) in Earth3. Indicators, units, limits and half-way limits. Details in The Empirical Bases for the Earth3 model https://doi.org/10.31223/osf.io/ephsf.

Average Wellbeing Index				
Component		**Rationale**	**Indicator**	**Ambition**
Five aspects that influence the wellbeing of an average citizen		*Explanation of what the component is meant to capture*	*Indicator chosen to quantify the situation, measured relative to the satisfactory level*	*The level seen as satisfactory*
1	Consumption	The private consumption of goods and services per inhabitant	Consumption per person (2010 PPP US$ / person-year)	>10.000 2011 PPP US$ / p-y
2	Public services	The supply of public services available to each inhabitant	Public services per person (2010 PPP US$ / person-year)	>1.500 2011 PPP US$ / p-y
3	Equity	The satisfaction arising from a more even distribution of income	Share of national income to richest 10% (%)	<40 %
4	Environmental quality	The satisfaction arising from a good physical environment	Urban aerosol concentration (µg 2.5M/m3)	<10 µg 2.5M/m3
5	Hope	The satisfaction arising from believing in a better future	Recent temperature rise (deg C above 1850)	<0,05 deg C in 20 years

Table 4. The 5 Average Wellbeing Index consists of 5 components with equal weights.
The AWI is calculated by region from 1980 to 2050.

Correlations in Earth3-core		
Dependent variable		
Birth rate (%/y) Adjustment time 20 years		f(GDPpp) in thousand 2011 PPP $ per person-year
Death rate (%/y) Adjustment time 30 years		f(GDPpp) times age pyramid multiplier
Rate of growth of GDPpp (%/y) Adjustment time 20 years		f(GDPpp)
Demand fractions of GDP (%) Adjustment time 20 years Consumer spending (top) + government spending (bottom) + capital formation = 100 %		f(GDPpp)
Output fractions of GDP (%) Adjustment time 20 years Primary sector (top) + secondary sector + tertiary sector (bottom) = 100%		f(GDPpp)
Electricity use per person (kWh/p-y) Adjustment time 20 years		f(GDPpp in 1st and 2nd sector) times tech. progress

Direct use of fossil fuels per person (toe/p-y) Adjustment time 20 years		f(GDPpp in 1st and 2nd sector) times tech. progress
Total footprint per person (gha/p) Adjustment time 10 years		f(GDPpp in 1st and 2nd sector) times tech. progress
Non-energy footprint per person (gha/p) Adjustment time 10 years		f(GDPpp in 1st and 2nd sector) times tech. progress
Man made methane emissions ($GtCO_2e$ /T$) Phase out time: none		f(GDPpp)
N_2O gas emissions ($GtCO_2e$ /T$) Phase out time: 200 years		f(GDPpp) times policy progress
Montreal gas emissions ($GtCO_2e$ /T$) Phase out time: 40 years		f(GDPpp) times policy progress
Kyoto-Flour gas emissions ($GtCO_2e$/T$) Phase out time: 40 years		f(GDPpp) times policy progress
Urban aerosol concentration (µg 2.5M/m^3) Phase out time = 50 years for US and emerging economies, 10 years for all other regions		f(GDPpp in 1st and 2nd sector) times policy progress
Freshwater withdrawal (km^3/y) = 416 m^3 per person-year times population		
Forest degradation (km^2/y) = output from ESCIMO-plus		

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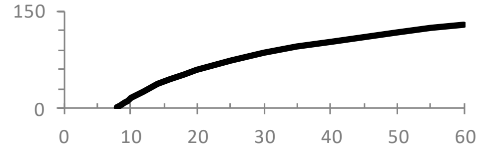
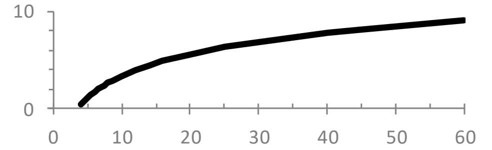
Release of bioactive nitrogen (Mt/y) World Adjustment time = 150 years		f(World GDP) in trillion 2011 PPP $ per year
Release of lead (Mt/y) World Adjustment time = 150 years		f(World GDP) in trillion 2011 PPP $ per year

Table 5. Important correlations in Earth3-core.
For detailed formulae and parameters,
see http://www.2052.info/wp-content/uploads/2018/correlations.pdf

Functions in SDG-module			
Dependent variable		**Independent variable**	**Formula**
1	Fraction of population living below 1.90$ per day (%)	= f(GDPpp)	= a * exp (-GDPpp / b) by region
2	Fraction of population undernourished (%)	= f(GDPpp)	=a + b*exp(-GDPpp/c) by region
3	Life expectancy at birth (years)	= f(GDPpp)	= (a+b*(year since 1965))*(1 – c * exp(-GDPpp / d)) by region
4	School life expectancy (years)	= f(GDPpp)	=a-b*exp(-GDPpp/c) by region
5	Gender parity in schooling (1)	= f(GDPpp)	=a-b*exp(-GDPpp/c) by region
6	Fraction of population with access to safe water (%)	= f(GDPpp)	=a-b*exp(-GDPpp/c) by region
7	Fraction of population with access to electricity (%)	= f(GDPpp)	=a-b*exp(-GDPpp/c) by region
8	Job market growth (%/y)	= f(GDPpp)	= Rate of change of GDPpp less 1%
9	GDP per person in manufacturing & construction (2011 PPP US$/p-y)	= f(GDPpp)	See Table 5
10	Share of national income to richest 10 % (%)		= manual forecast
11	Urban aerosol concentration (µg 2.5M /m3)		See Table 5
12	Total footprint per person (gha/p)		See Table 5
13	Temperature rise (deg C above 1850)		output from ESCIMO-plus
14	Acidity of ocean surface water (pH)		output from ESCIMO-plus
15	Old-growth forest area (Mkm2)		output from ESCIMO-plus
16	Government spending per person (2011 PPP US$/p-y)	= f(GDPpp)	See Table 5
17	Exports as fraction of GDP (%)		= manual forecast

Table 6. Important functions in SDG-module.
For more detail, see Empirical basis of Earth3 on web.

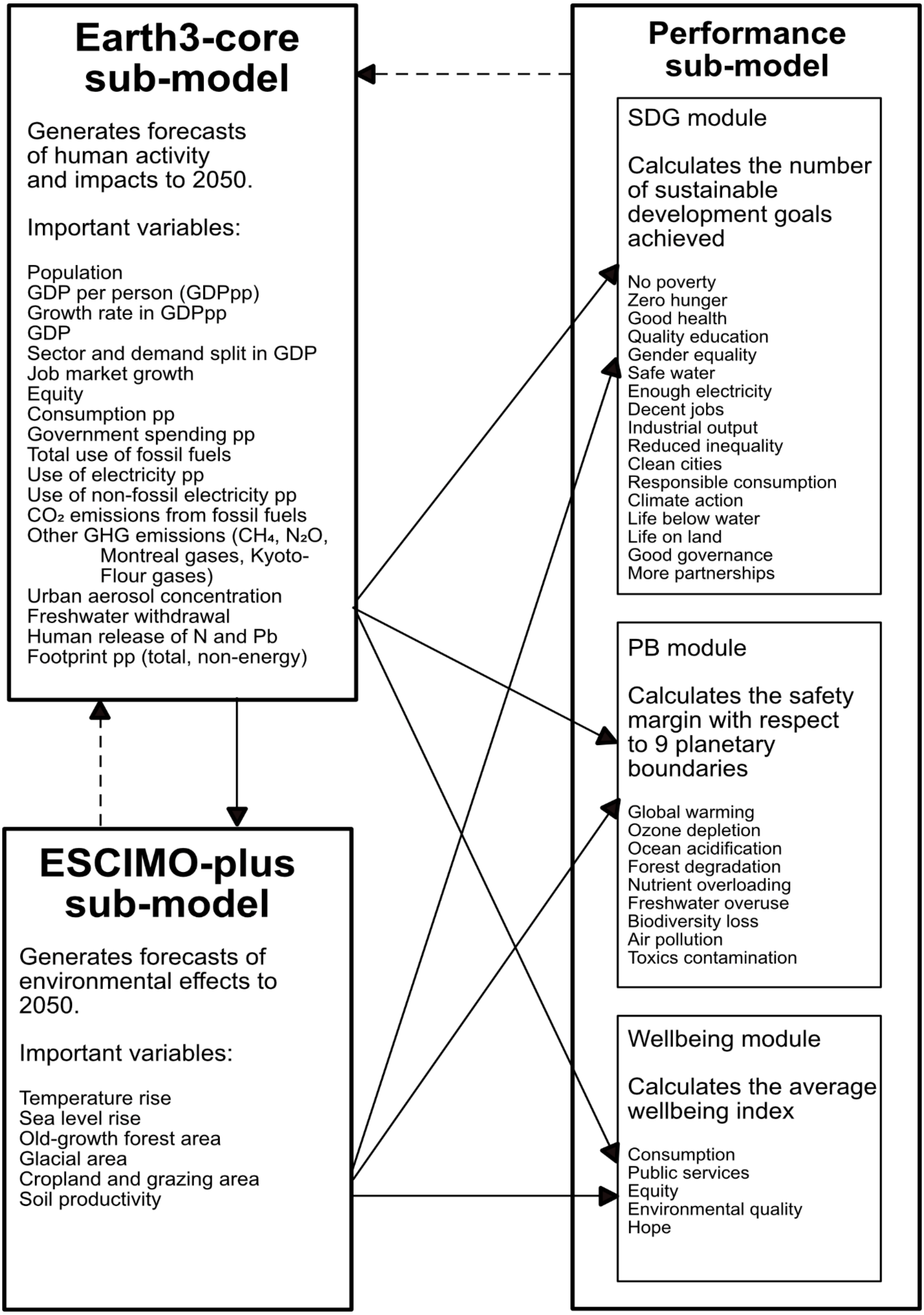


Figure 1. The Earth3 model system.
The dashed feedbacks are not yet included.

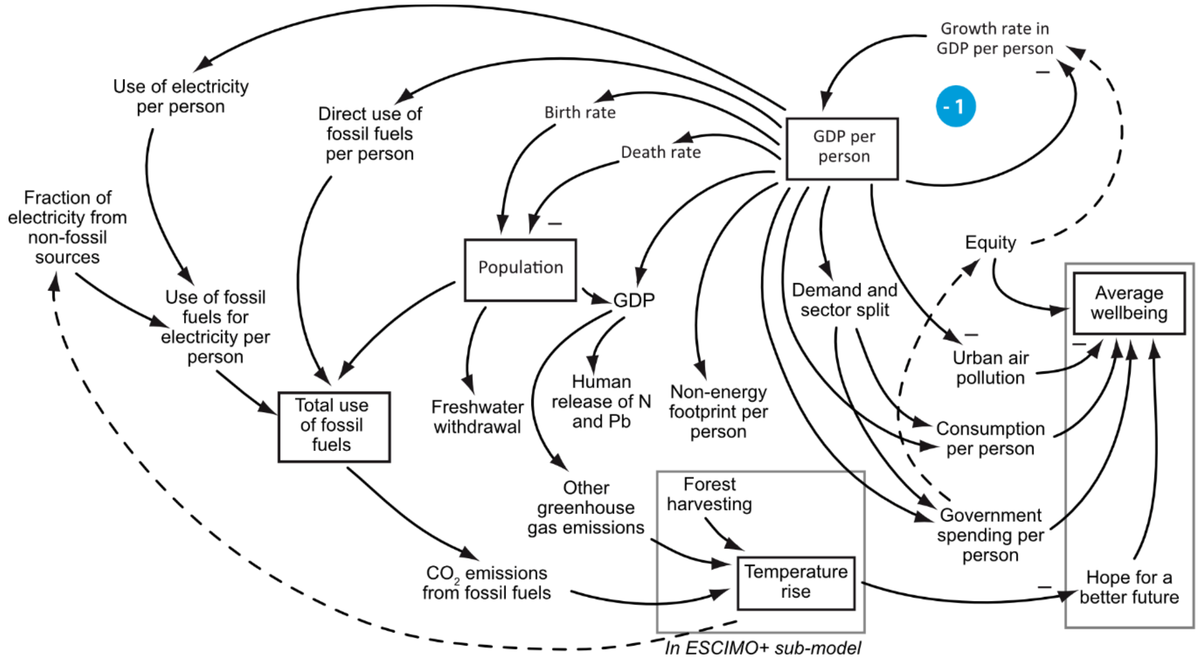


Figure 2. The causal structure of the Earth3-core sub-model.
The dashed feedbacks are not yet included

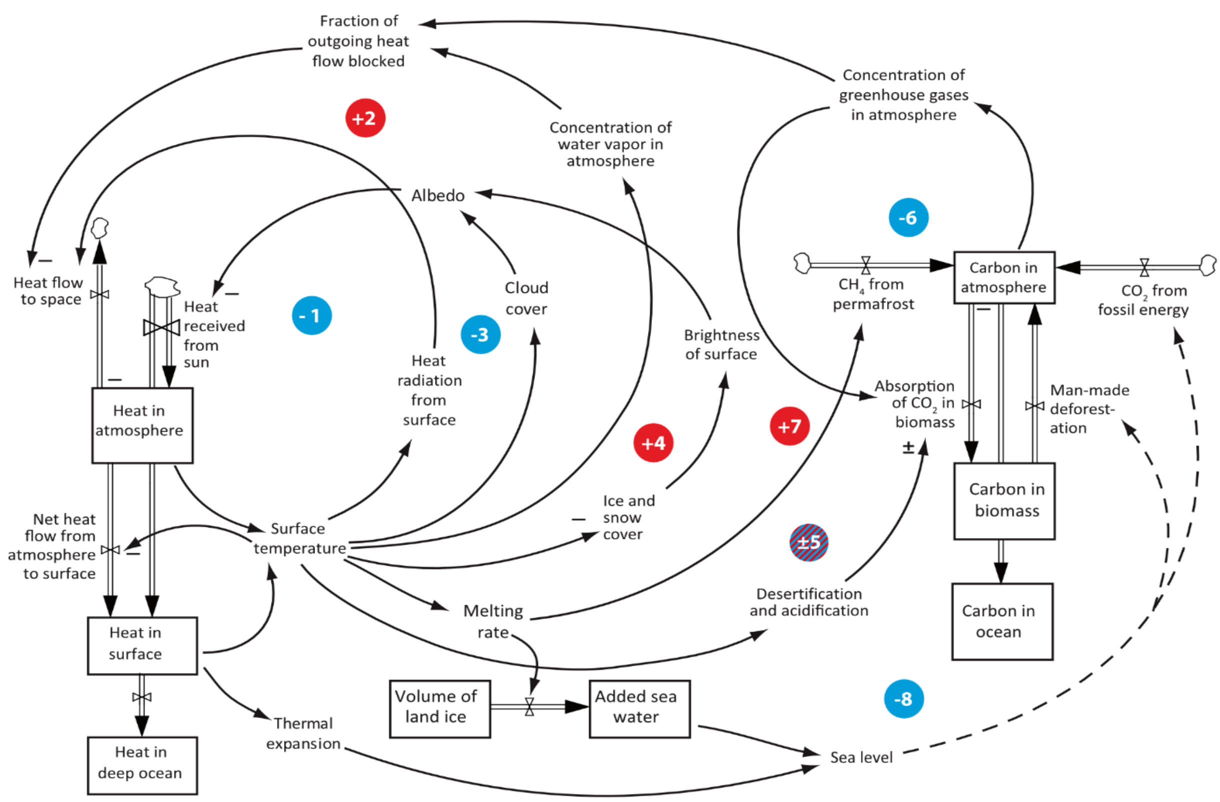


Figure 3. The causal structure of the ESCIMO-plus sub-model.
The dashed feedbacks are not yet included.

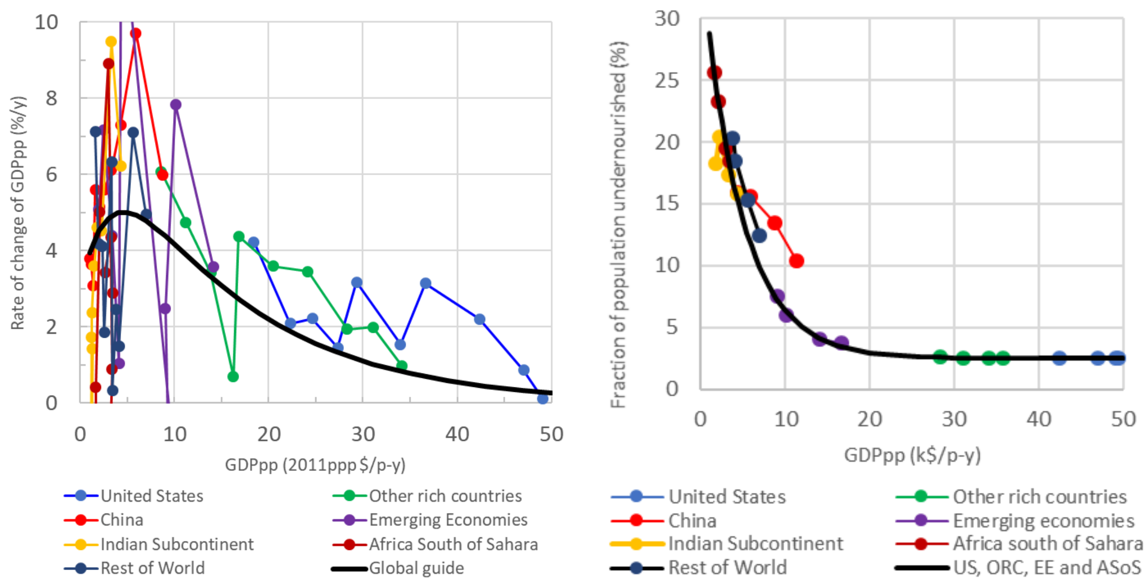


Figure 4. Examples of correlations used in Earth3-core (left) and SDG-module (right).

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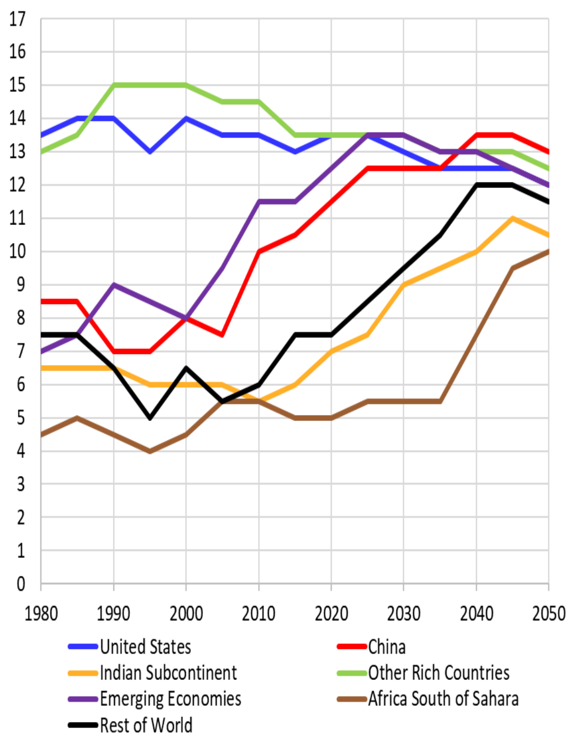

Figure 5. Number of SDGs achieved. Business-as-usual scenario, by region, 1980-2050.

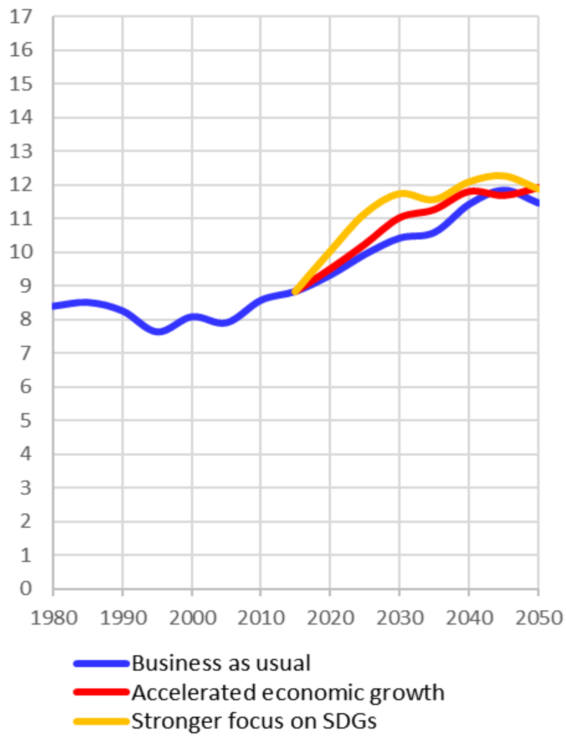

Figure 6. Number of SDGs achieved. Three scenarios, world average, 1980-2050.

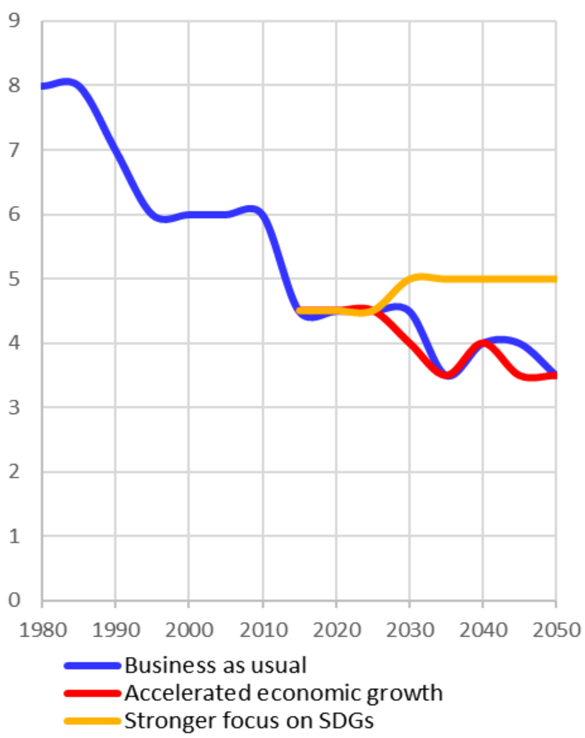

Figure 7. The global safety margin. Three scenarios, world, 1980-2050.

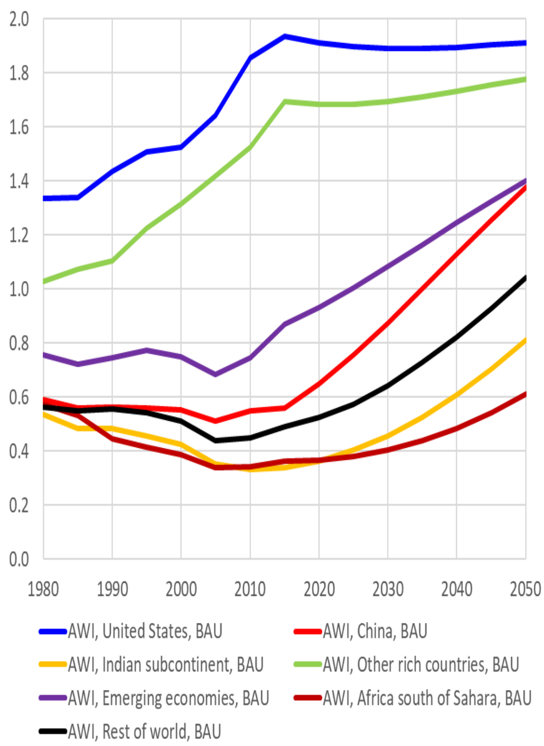

Figure 8. The average wellbeing index. Business-as-usual scenario, by region, 1980-2050

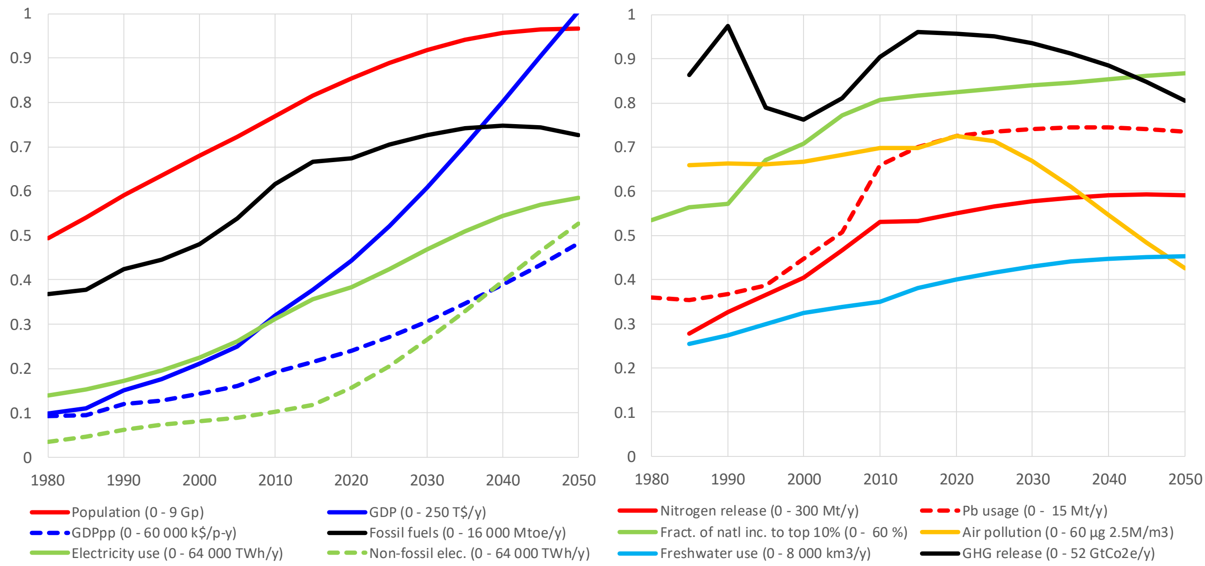

Figure 9. Outputs from Earth3-core. Business-as-usual scenario, world, 1980-2050.

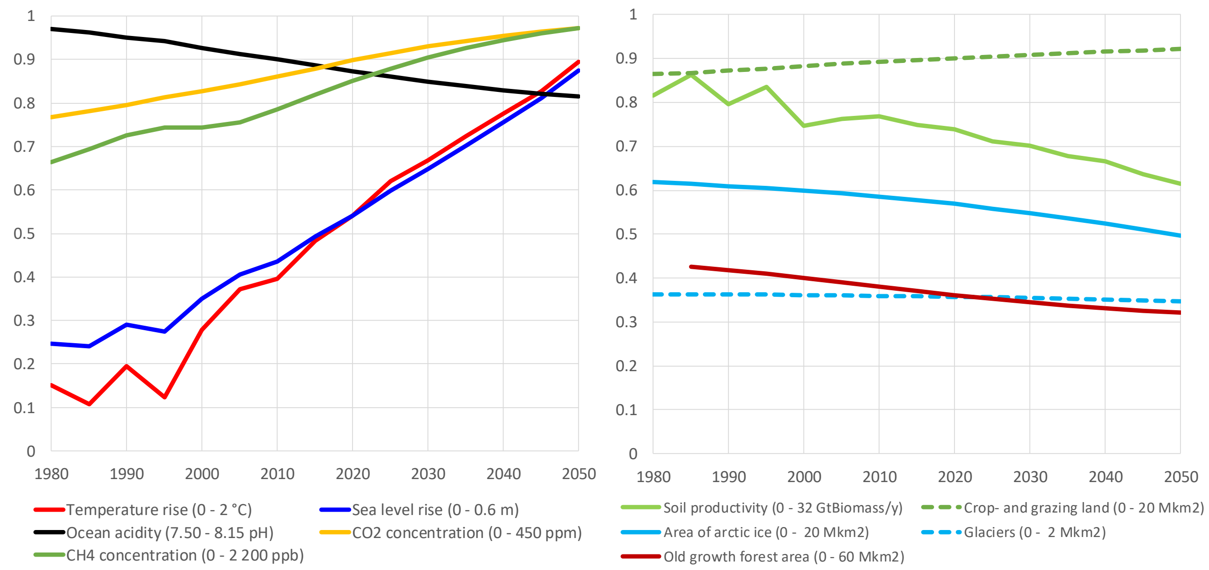

Figure 10. Outputs from ESCIMO-plus. Business-as-usual scenario, world, 1980-2050.

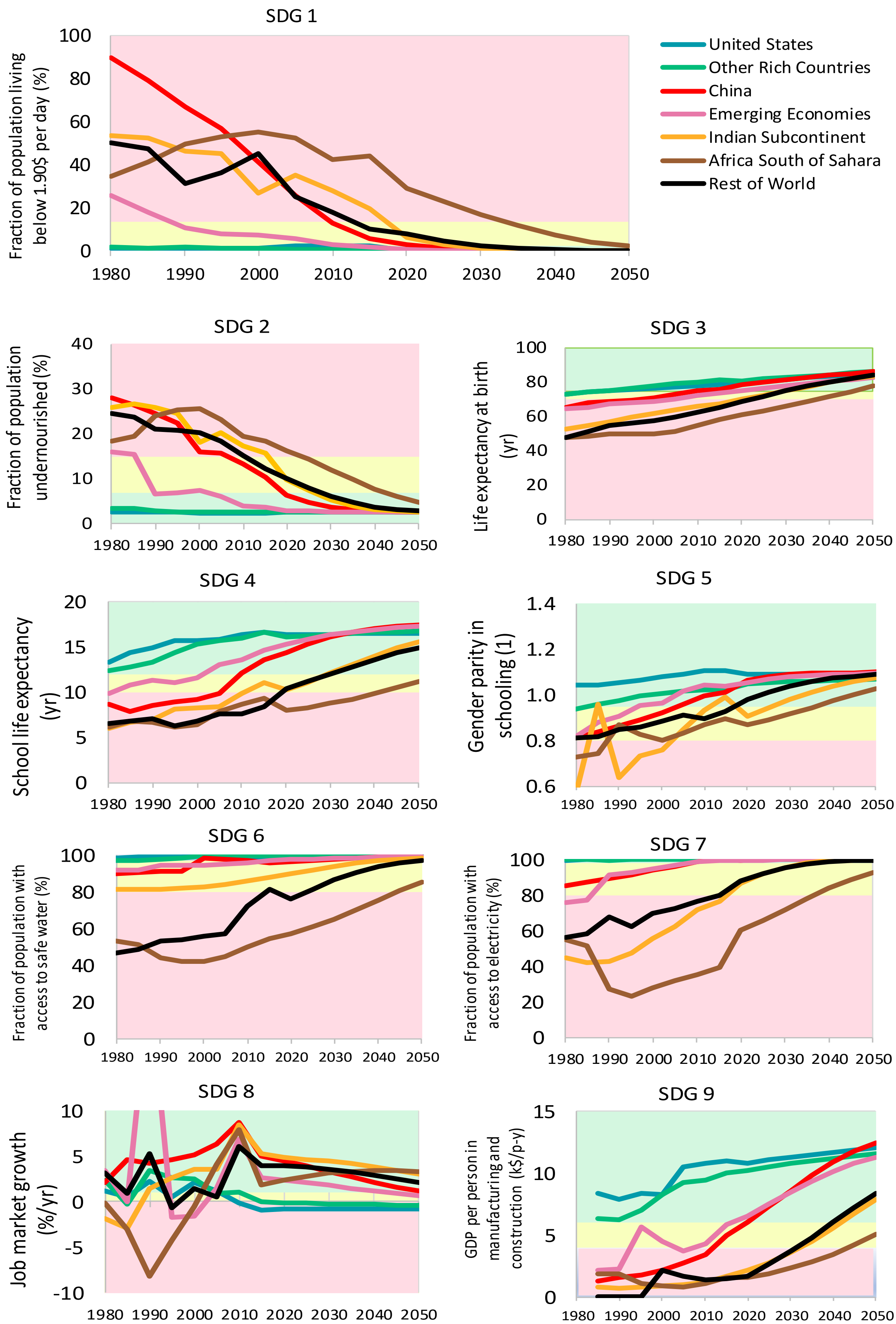

Figure 11. (page 1 of 2) Achievement of individual SDGs. Business as usual scenario, by region, 1980-2050.

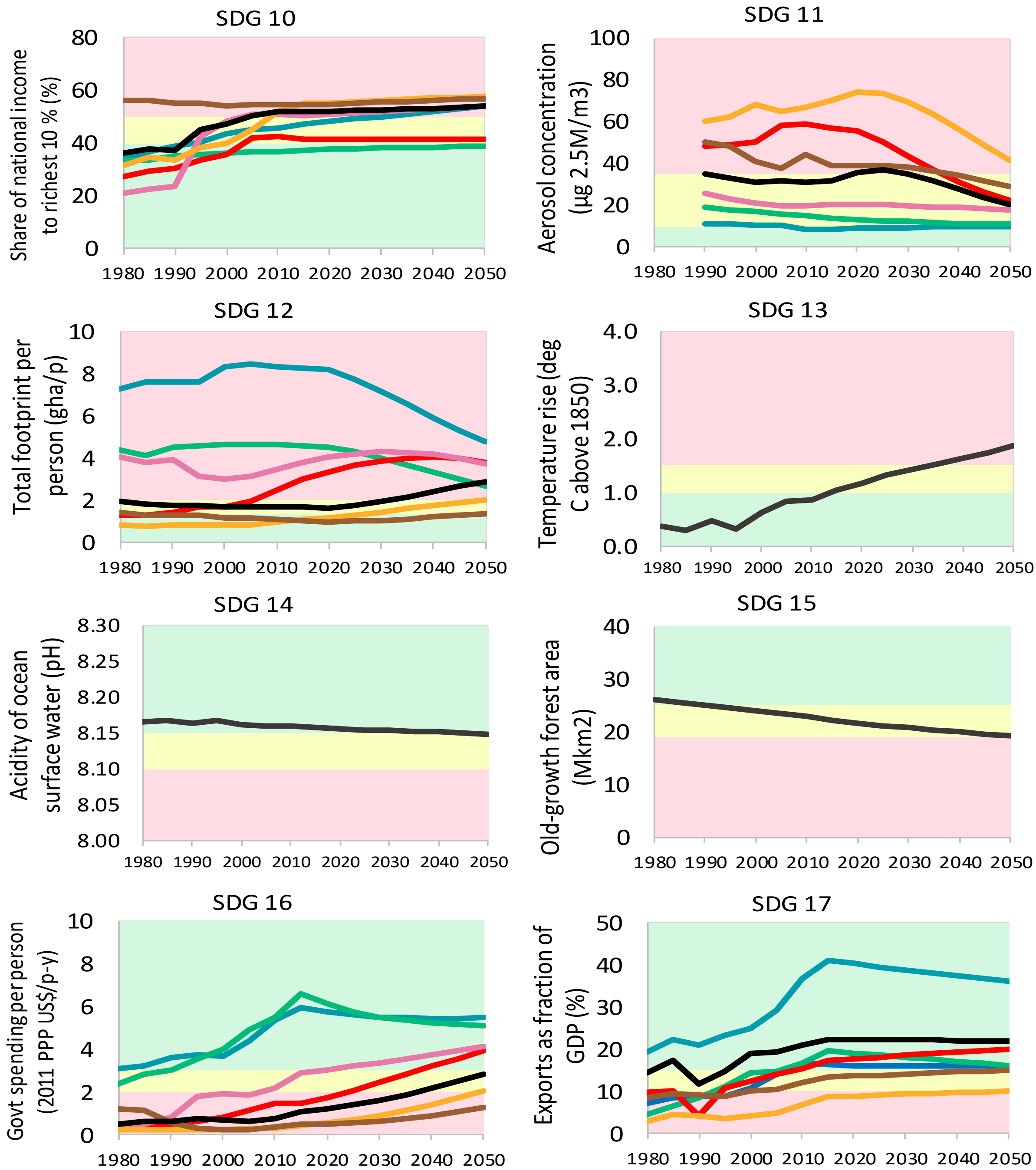

Figure 11. (page 2 of 2) Achievement of individual SDGs. Business as usual scenario, by region, 1980-2050.

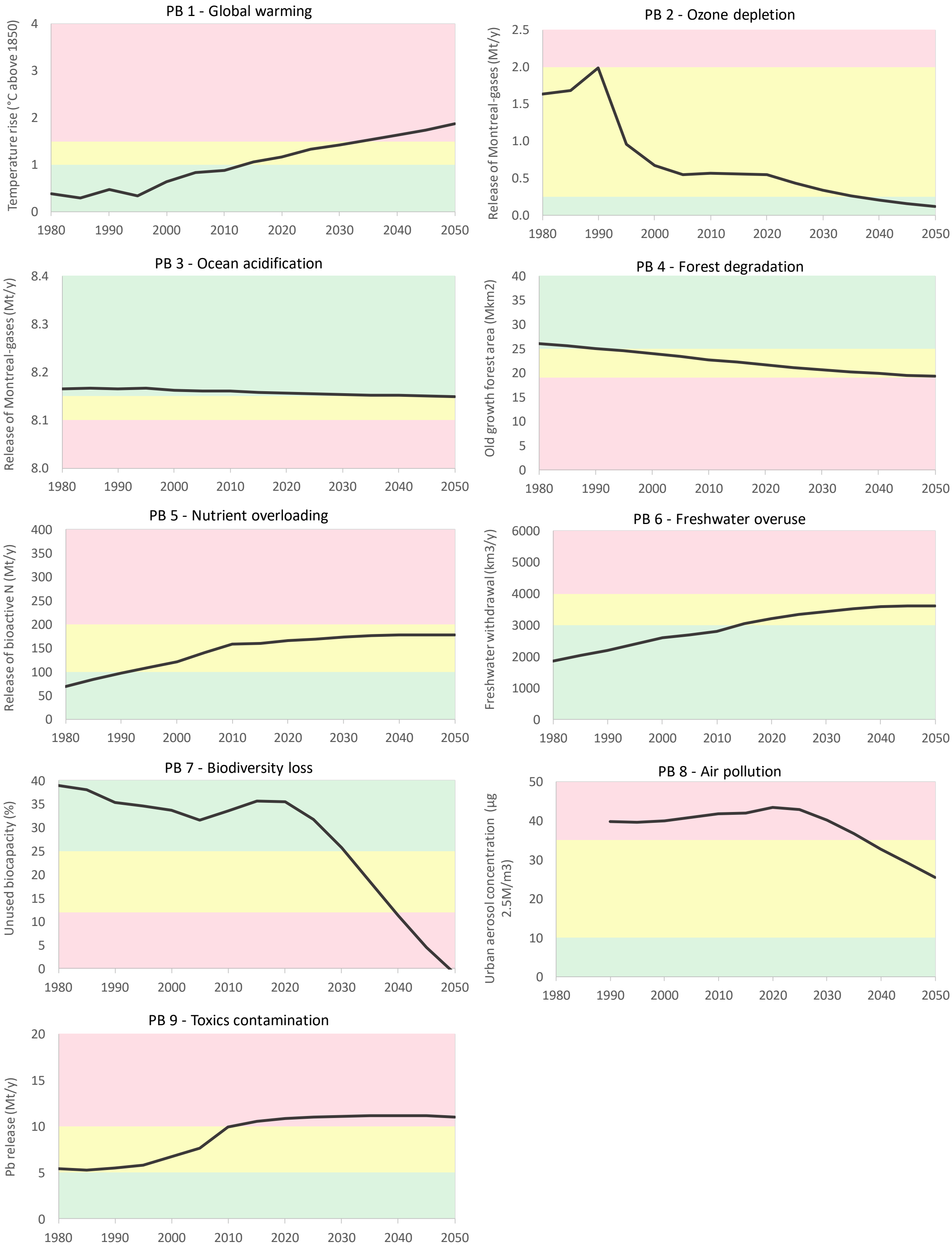

Figure 12. The pressure on individual PBs. Business-as-usual scenario, world, 1980-2050.

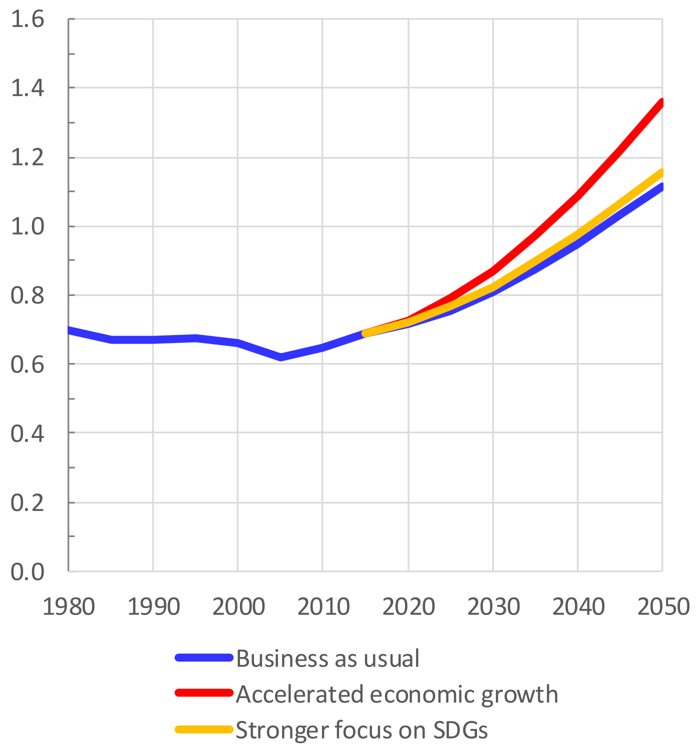

Figure 13. The average wellbeing index. Three scenarios, world average, 1980-2050.