The Empirical Bases for the Earth3 Model: Technical Notes on the Sustainable Development Goals and Planetary Boundaries

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This technical note contains supplemental material to the report by Randers et al (2018) *Transformation is Feasible, How to achieve the Sustainable Development Goals within Planetary Boundaries, a report to the Club of Rome*, Stockholm: SRC., as well as to the scientific paper Randers et al (2018) "Achieving the Sustainable Development Goals within Planetary Boundaries", in preparation to *Global Sustainability*.

Abstract
This technical note presents the bases for the Earth3 model system with a focus on how SDGs and Planetary Boundaries are assessed in the model. This includes data selection, sources, analysis and forecasting methods. We also present the threshold levels that have been chosen for the respective SDGs and Planetary Boundaries.

Key words:
Sustainable Development Goals, Agenda 2030, Planetary Boundaries, Safe Operating Space, Doughnut Economics

1. Introduction: Data selection, sources, analysis and forecasting methods

Our starting point is the 17 Sustainable Development Goals agreed by the UN in 2015. Table 1 lists the modelled indicators we have used to track the degree to which the 17 SDGs are achieved, by region. The indicators were chosen based on goal formulations in the resolution[1], data availability and compatibility with the processes in our model system, the SDG Index and Dashboards Report 2016 and 2017[2], and further modified by the project team. Details on each SDG are presented in section 2 below. Details on the planetary boundaries are presented in section 3. We use the seven world regions as specified in section 4, and weight by population size when aggregating (the primary) national data to regional levels.

In general, the following procedure has been followed with some alterations for the different SDGs as specified under each goal:

- We present the historical data as a function of GDP per person (GDPpp, measured in 2011 Purchase Power Parity adjusted US$ with data from the Penn World Tables). Country data has been averaged over five-year periods. As there are shortages of historical data for many countries, we have averaged the numbers based on the population sizes of countries where data is available, as part of the respective regions.

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- We have then regressed the indicator (y) on GDP per person (x) – fitting the curve by using a suitable functional form based on soft knowledge and the data analyzed. Normally the formula is y=a+b*exp(-cx). The reasoning behind this functional form is that we assume that social and economic indicators of progress will initially improve fast as GDPpp grows. Eventually, however, this effect will be balanced by different forms of saturations such as that the whole population has been lifted out of poverty (SDG1) or that electricity access is approaching 100% (SDG7).
- We use the resulting regressed equations to forecast future values of the indicators.
- In most cases, we use different functions for the seven different regions. We do this based on the assumption that there are characteristics of the regions, such as institutions and distribution, that have been stable over time and will continue to coevolve with GDP per person in a similar way.

Later we may try to improve the regression fit by adding other independent variables (like inequity, government spending per person, or time) to the mathematical formula, to improve the model's forecast (but this would perhaps be at the expense of some of its simplicity).

Sustainable Development Goals		**Indicator**	**Historical data**	**Forecasting method**	**Threshold value - green to yellow**	**Threshold value - yellow to red**
The 17 goals for humanity agreed by the UN in 2016		*Indicator for the achievement of each Sustainable Development Goal*	*Source of the historical data*	*Method used to forecast the indicator value towards 2050*	*The 'target'*	*'Halfway target' - it's yellow if :*
1	No poverty	Fraction of population living below 1.90$ per day (%)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	< 2%	< 13%
2	Zero hunger	Fraction of population undernourished (%)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	< 7%	< 15%
3	Good health	Life expectancy at birth (years)	Worldbank - f(GDPpp,t), by region	In SDG module - as f(GDPpp, t), by region	> 75 years	> 70 years
4	Quality education	School life expectancy (years)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	> 12 years	> 10 years
5	Gender equality	Gender parity in schooling (1)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	> 0,95	> 0,8
6	Safe water	Fraction of population with access to safe water (%)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	> 98%	> 80%
7	Enough energy	Fraction of population with access to electricity (%)	Worldbank - f(GDPpp), by region	In SDG module - as f(GDPpp), by region	> 98%	> 80%
8	Decent jobs	Job market growth (%/y)	Earth3 core - f(GDPpp), by region	In Earth3 core (= Growth in GDPpp - 2%/y, by region)	> 1% / year	> 0% / year
9	Industrial output	GDP per person in manufacturing & construction (2011 PPP US$/p-y)	Earth3 core - f(GDPpp), by region	In Earth3 core (= GDPpp in 2. sector, by region)	>6.000 2011 PPP US$/p-y	>4.000 2011 PPP US$/p-y
10	Reduced inequality	Share of national income to richest 10% (%)	World Inequality Report - f(t), by region	In Earth3 core (= Manual forecast, by region)	< 40%	< 50%
11	Clean cities	Urban aerosol concentration (µg 2.5M /m3)	Worldbank - f(GDPpp), by region	In SDG module, f(GDPpp), by region	< 10 µg 2.5M /m3	< 35 µg 2.5M /m3
12	Responsible consumption	Ecological footprint per person (gha/p)	Earth3 core - f(GDPpp), by region	In Earth3 core (= Ecological footprint pp, by region)	< 1.4 gha/p	< 2 gha/p
13	Climate action	Temperature rise (deg C above 1850)	ESCIMO - global f(t)	In ESCIMO - as is	< 1 deg C	< 1.5 deg C (by 2050)
14	Life below water	Acidity of ocean surface water (pH)	ESCIMO - global f(t)	In ESCIMO - as is	> pH 8.15	> pH 8.1
15	Life on land	Old-growth-forest area (Mkm2)	ESCIMO - global f(t)	In ESCIMO + new old growth forest sector	> 25 Mkm2	>19 Mkm2
16	Good governance	Government spending per person (2011 PPP US$/p-y)	Earth3-core - f(GDPpp), by region	In Earth3-core (= Government spending pp, by region)	>3.000 2011 PPP US$/p-y	>2.000 2011 PPP US$/p-y
17	More partnership	Exports as fraction of GDP (%)	Earth3-core - f(t), by region	In Earth3-core (= Manual forecast, by region)	> 15%	> 10%

Table 1: The SDGs, the chosen indicator, data source, forecasting method and threshold values.

2. Data analysis of the 17 SDGs

Below we present and briefly discuss the indicators of the respective SDGs and from where data has been retrieved.

SDG1 – No poverty

For SDG1 – No poverty we use the commonly used definition *Fraction of population living below 1.90$ per day*. This indicator is included in the *SDG Index and Dashboards Report* 2017[3] in relation to SDG1. Also, data availability is good. We have retrieved data per region from the World Bank DataBank[4] for the following years for the respective regions (displayed in Figure 1):

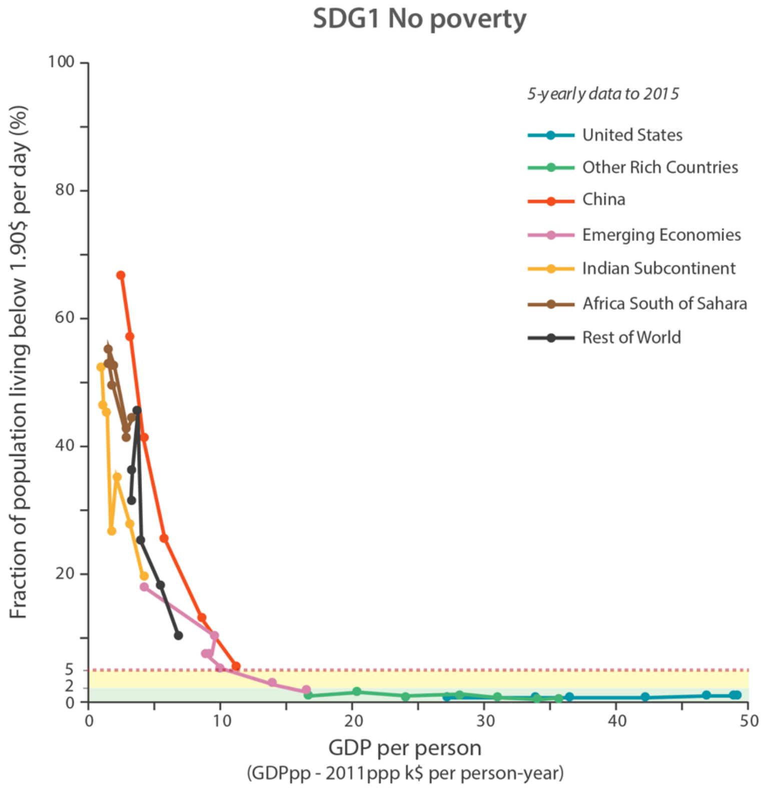

Figure 1: Historical levels of SDG1 No poverty.

- 1980–2015:
    - United States
- 1985–2015:
    - Other Rich Countries
    - Emerging Economies
    - Indian Subcontinent
    - Africa South of Sahara
- 1990–2015
    - China
    - Rest of World

The threshold levels of 2 and 13 are based on the *SDG Index and Dashboards Report* 2017[5].

The data on SDG1 is performing well around our proposed functional formula:

$$y = 100 * \exp\,(-x/b).$$

for all regions except China.

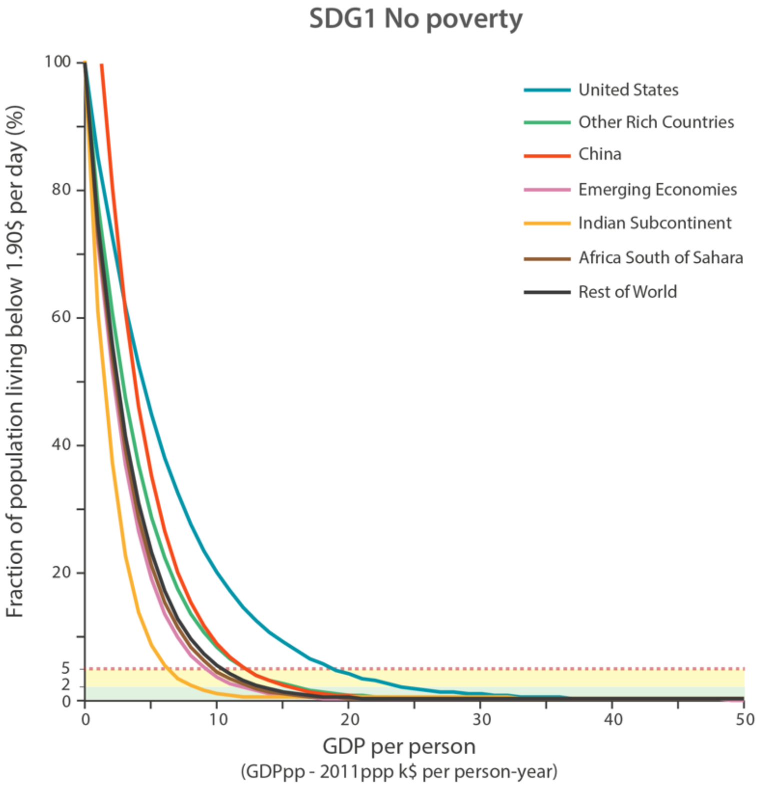

Figure 2: Functions for SDG1 No poverty.

By analyzing the Chinese data, we deemed the functional formula to project unreasonable high levels of poverty and adjusted the formula to:

$$y = a * \exp\left(-x/b\right)$$

resulting in an a value of 140. The resulting functions are plotted in Figure 2. Figure 3 portrays the development when we run the model in Scenario 1 to 2050. Notice that Figure 1 and Figure 2 have GDPpp on the horizontal axis, while Figure 3 has time on the horizontal axis.

In the graph one can see, for instance, the rapid decline in Chinese poverty (red line) to reach the “green” zone (<2%) by 2025. From that year on, China gets a “1” score on this SDG1 (summed up for all regions in the SDG success scores). The regions that are in the yellow area (boundary condition), get “0.5” score on this SDG1. Africa South of Sahara gets a 0.5 SDG score on this from 2035 and beyond.

By adding up the number of regions that are in 1, 0.5 or 0 (red) territory, weighted by population, we get the world’s SDGs score for any given year. The same procedure has been performed for all SDGs, but we will only present the data and functional formula derived for the rest.

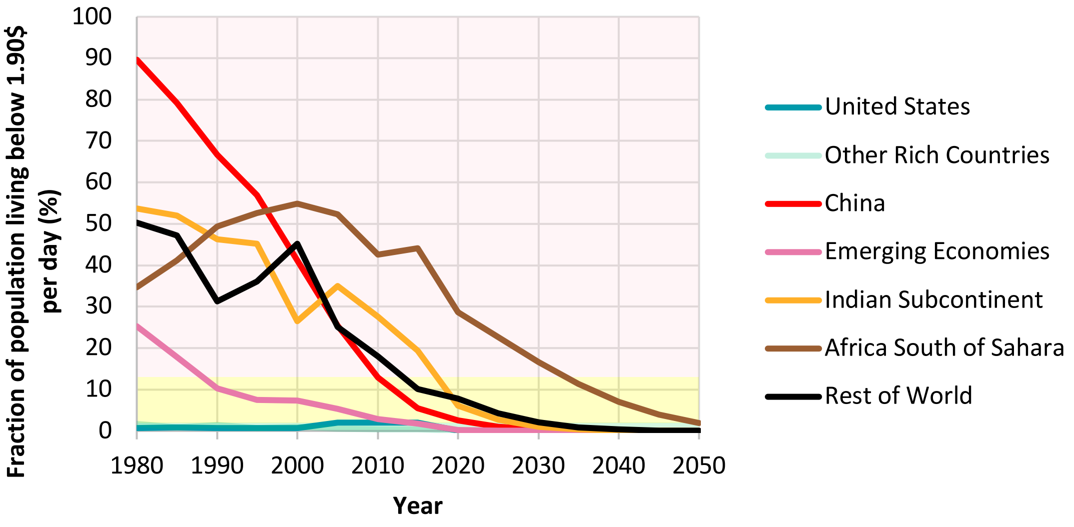

Figure 3: Simulated development on SDG1 in scenario 1.

SDG2 – Zero hunger

For SDG2 – Zero hunger we use the indicator *Fraction of population undernourished*. Undernourishment is also used as one of the indicators in the *SDG Index and Dashboards Report* 2017[6]. We have obtained three data points for all regions, for 2000–2015, from the World Bank[7]. The threshold levels of 7 and 15 are based on the *SDG Index and Dashboards Report* 2017[8].

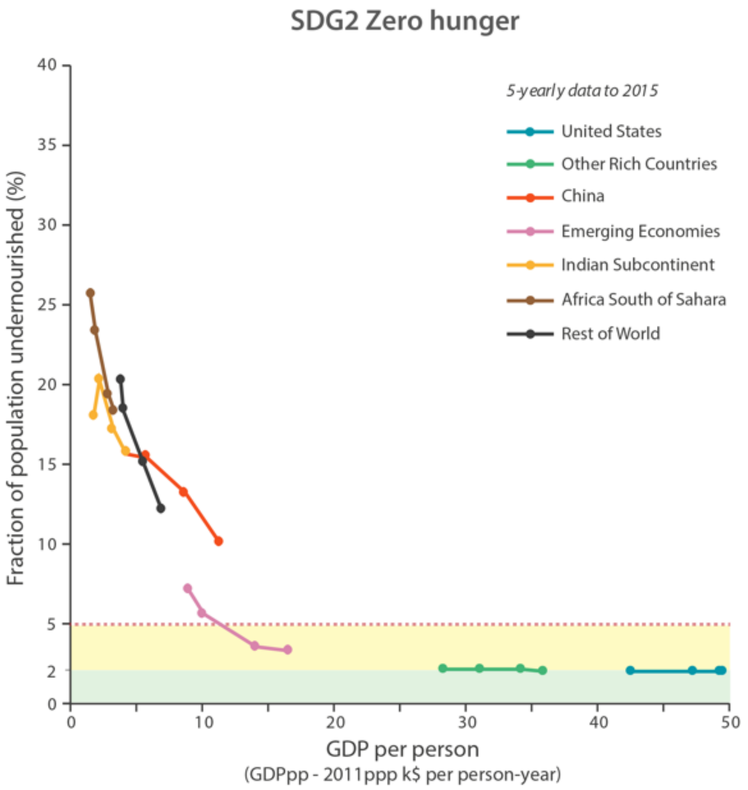

Figure 4: Historical levels of SDG2 Zero hunger.

Looking at the data on SDG2 portrayed in Figure 4, we found that all regions behave in quite a similar way to SDG1. The data indicates that a function that crosses the y-axis at around 35 seems to be reasonable in predicting the future behavior of the variable. The two rich regions – United States and Other Rich Countries – have undernourishment levels of around 2.5% for recent years. We have therefore chosen the functional formula for all regions to be:

$$y = 2.5 + 32.5 * \exp\left(-x/b\right)$$

The resulting functions are plotted in Figure 5.

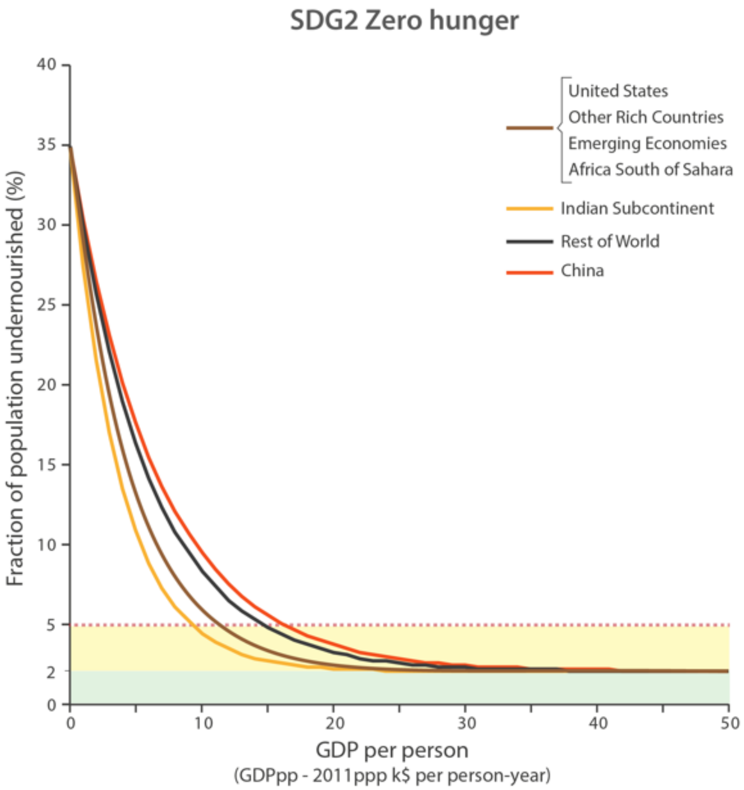

Figure 5:Functions for SDG 2 Zero hunger

SDG3 - Good health

For SDG3 – Good health we use the indicator *Life expectancy at birth*. Data is retrieved from the UN Population Statistics from 1965[9] and portrayed in Figure 6. The SDG Index and Dashboard Report 2017[10] includes a similar variable, *Healthy life expectancy at birth*. We found data availability for *healthy life expectancy* not as good as for *life expectancy*. Our threshold values of 70 and 75 years are based on *SDG Index and Dashboards Report* 2017 and the average difference between data for *Life expectancy* and *Healthy life expectancy* for different countries.

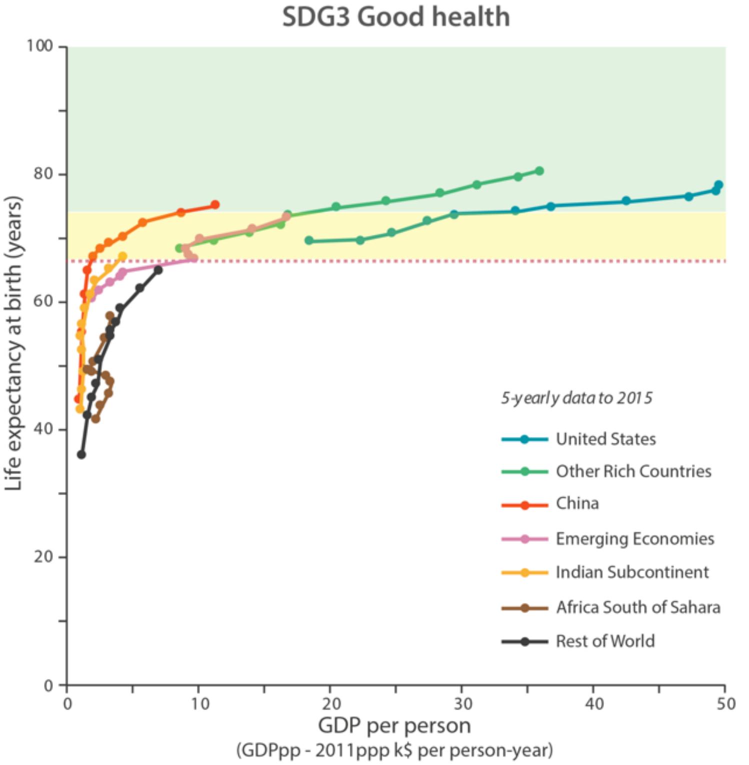

Figure 6: Historical levels of SDG3 Good health

For SDG3 we assume both a GDP per capita effect and a technology effect. We have therefore used a function with two parts. The functional formula used:

$$y = \left(70 + 0.18 * (years\ since\ 1965)\right) * \left(1 - c * EXP(-x / d)\right)$$

The first part of the equation:

$$(70 + 0.18 * (time - 1965))$$

represents the maximum life expectancy and depends on technological advancement, assumed to have a linear effect per year on life expectancy. Parameters *a* and *b* where parameterized using all five-year regional data for all countries 1965 to 2015. The *c* and *d* parameters were derived by regressing all data points for which life expectancy is higher than 60 years, to prevent the strong catching-up effect at low levels of life expectancy affecting our long-term forecasts.

As no data point is above 60 years for Africa South of Sahara, the same parameter values as for Rest of World are used. The resulting function is plotted for 2015 and displayed in Figure 7.

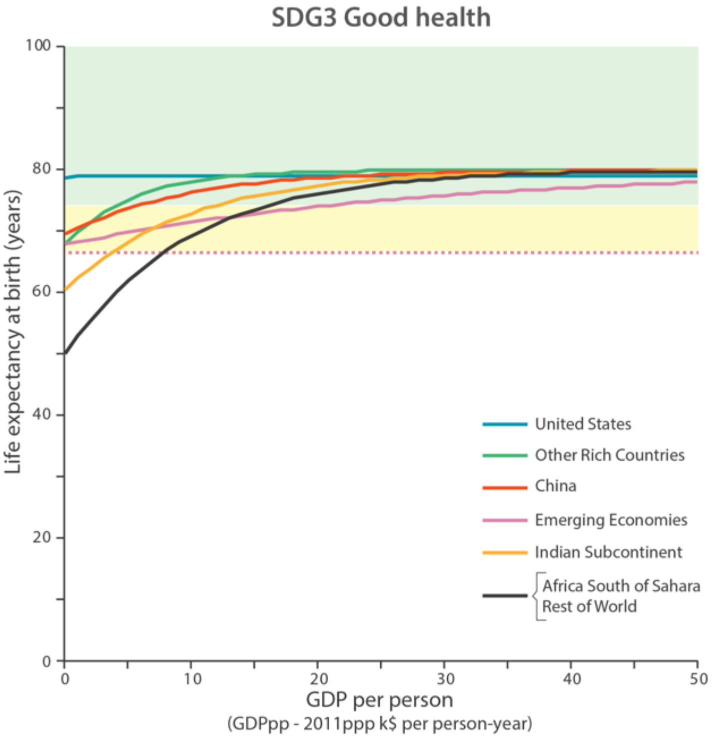

Figure 7: Functions for SDG3 Good health, excluding the technological advance that is part of the full equation, see text.

SDG4 – Quality education

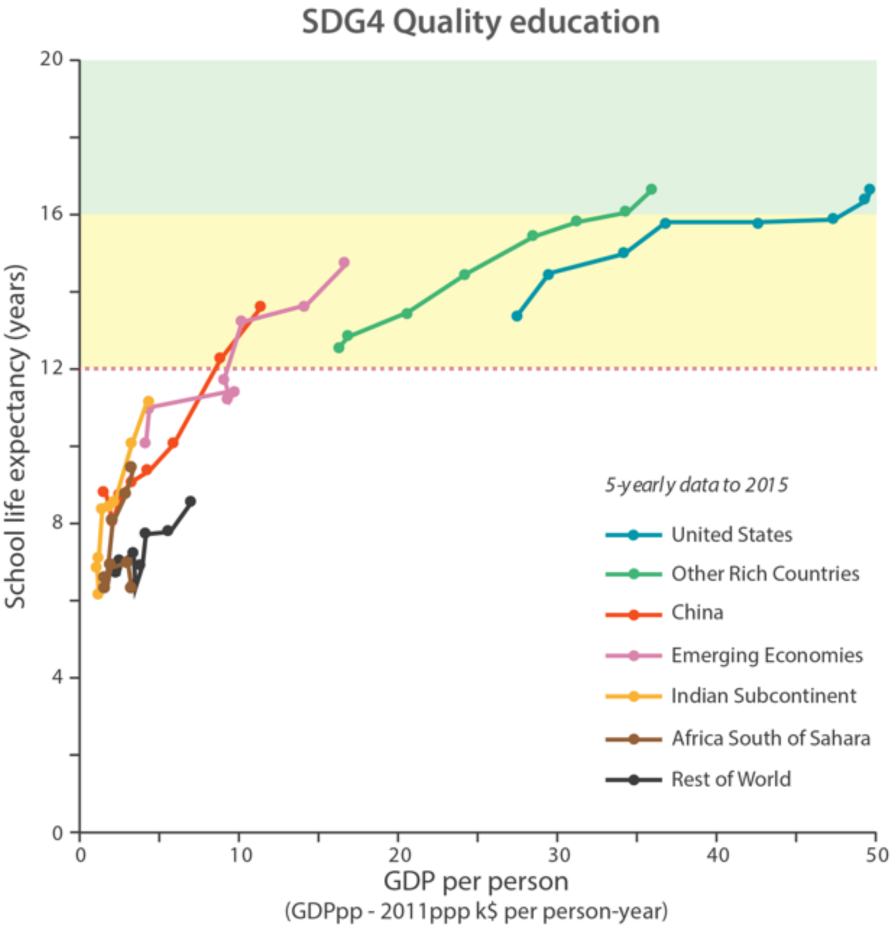

Figure 8

For SDG4 – Quality education we use the indicator *School life expectancy, primary to tertiary, both sexes* as our indicator. *School life expectancy* is included in the calculations of the Human Development Reports[11] and the *SDG Index and Dashboards Report* 2017[12]. The threshold levels of 10 and 12 are consistent with the *SDG Index and Dashboards Report* 2017. It also corresponds well with the explicit mentioning of secondary education in the Agenda 2030 resolution[13]. We retrieved the data from the World Bank[14] for 1980–2015 for all world regions.

Looking at our data on SDG4 we found that all regions behave in quite a similar ways. The data indicates that a function that crosses the y-axis at around six seems to be reasonable in simulating future behavior of the development. It also seems reasonable to believe that education will not grow forever but may saturate at a level of around 18 years.

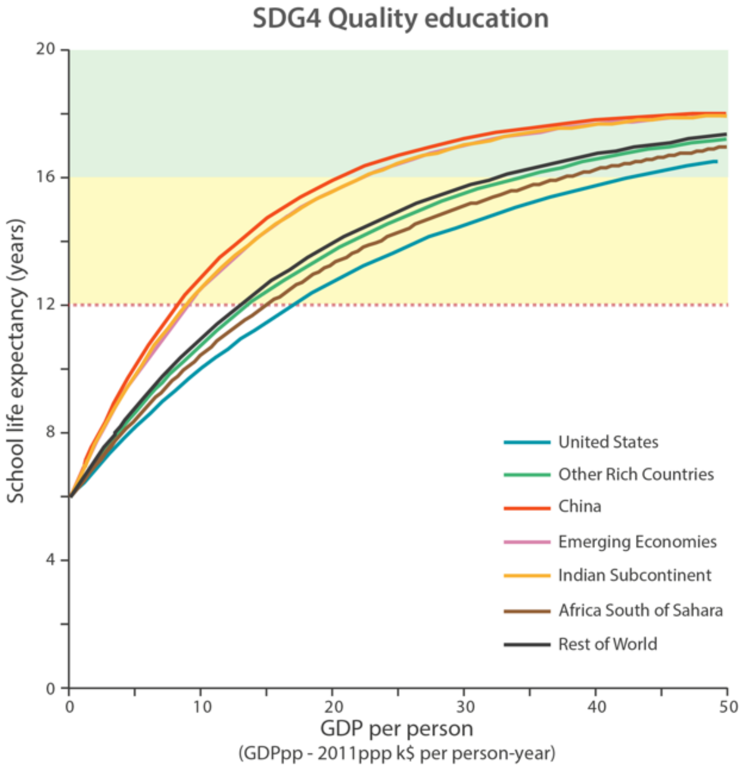

Figure 9

We have therefore chosen the following functional formula for all regions:

$$y = 18 - 12 * \exp\,(-x/a)$$

a was adjusted for the Indian Subcontinent to the same value as for Emerging Economies as we found the value retrieved from the regression unreasonably low.

We also adjusted *a* for Rest of World as the data points for this region were so low (just above six) that the *a* value retrieved from the regression would give unreasonably low predictions for the region’s future development.

SDG5 - Gender equality

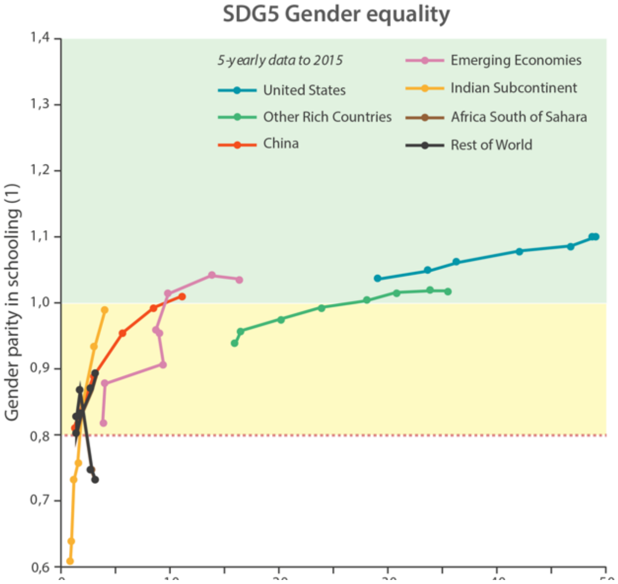

Figure 10

For SDG5 – Gender equality we use *School life expectancy, primary to tertiary, gender parity index (GPI)* as our indicator. The data was retrieved from the World Bank DataBank[15] for 1980–2015 for all world regions except United States (1985–2015) and Rest of World (1995–2015). Note that we use the indicator *expected years of schooling* and *not* years of schooling for both SDG5 and SDG4. Gender parity of expected years of schooling is the expected years of schooling for women, divided by the expected years of schooling for men. A value of 1 indicates that both men and women have the same expected years of schooling, a value below 1 indicates that men have higher expected years of schooling and a value above 1 that women have higher expected years of schooling.

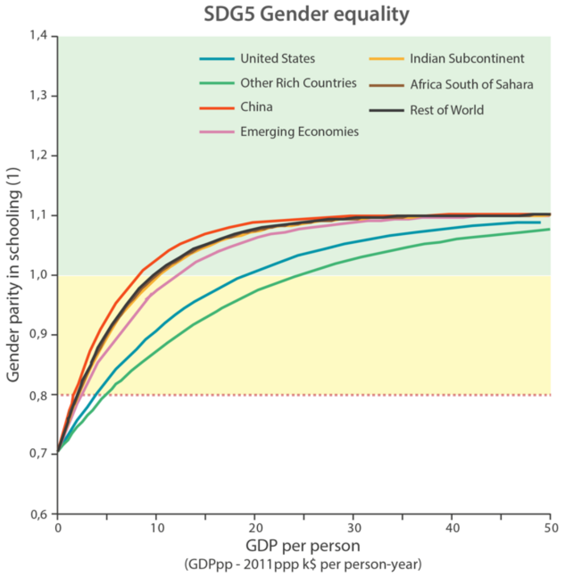

Figure 11

The *SDG Index and Dashboards Report* 2017 includes the similar variable *Female years of schooling (% male)* and suggests the threshold values of 75% and 98% (corresponding to the gender parity index of 0.75 and 0.98 respectively). We use 0.80 and 0.95. Looking at the data, it seems like the gender parity index grows above 1 for high levels of GDPppp. Also, the data indicates that a function that crosses the y-axis at around 0.7 seems to be reasonable in predicting the future behavior. We therefore chose the following functional formula for all regions:

$$y = 1.1 - 0.4 * \exp\left(-x/a\right)$$

The resulting functions are plotted in Figure 11.

SDG6 – Safe water

For SDG6 – Safe water we use *People using at least basic drinking water services (% of population)* as our indicator. The data was retrieved from the World Bank[16] for 2000–2015 for all regions except United States and Rest of World (both 2005–2015), plotted in Figure 12. The *SDG Index and Dashboards Report* 2017 includes the similar indicator: *Access to improved* *water*. We use the threshold values that the *SDG Index and Dashboards Report* 2017 suggests for this indicator, 80% and 98%.

We have used the functional formula

$$y = 100 - a * \exp{(-x/b)}$$

for predicting future values of safe-water access.

Because of the poor data availability (especially when it comes to historical levels for the richer regions), we chose to group similar regions. We use the *a* and *b* values that we retrieved from the regression of Emerging Economies for United States, Other Rich Countries and China as well. Also, we used the same parameters for Rest of World as we derived from the regression for Africa South of Sahara, as the *a* value becomes unreasonably low with a regression of Rest of World alone. The resulting functions are portrayed in Figure 13.

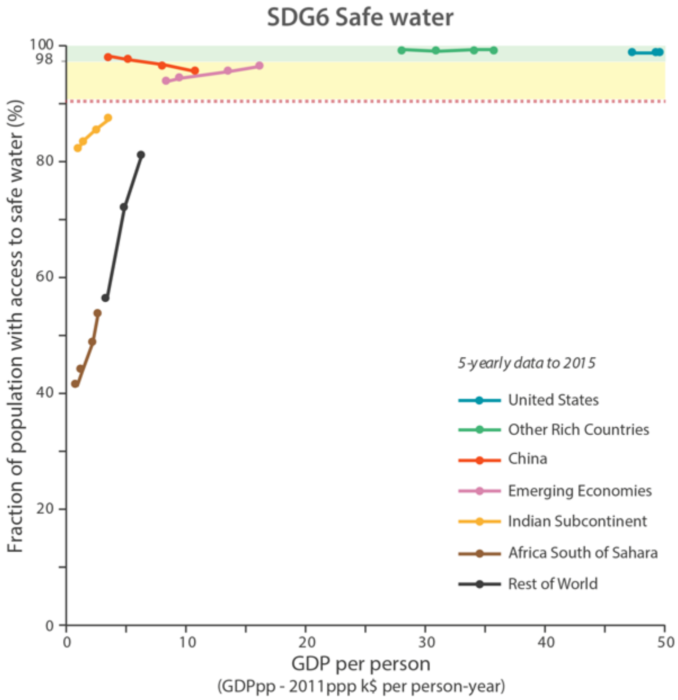

Figure 12

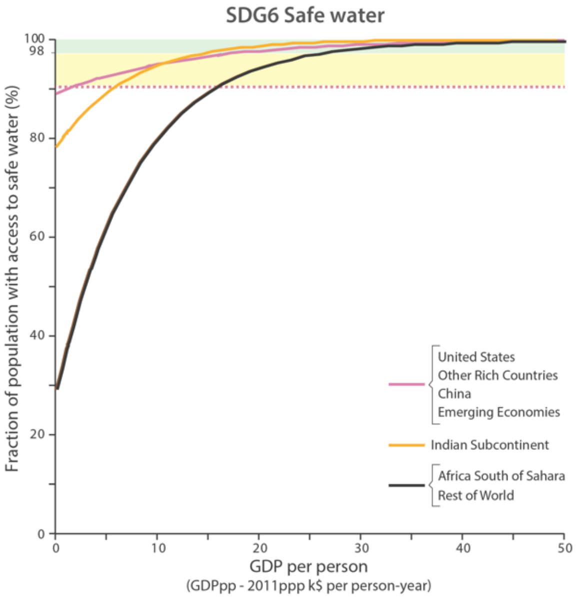

Figure 13

SDG7 – Enough energy

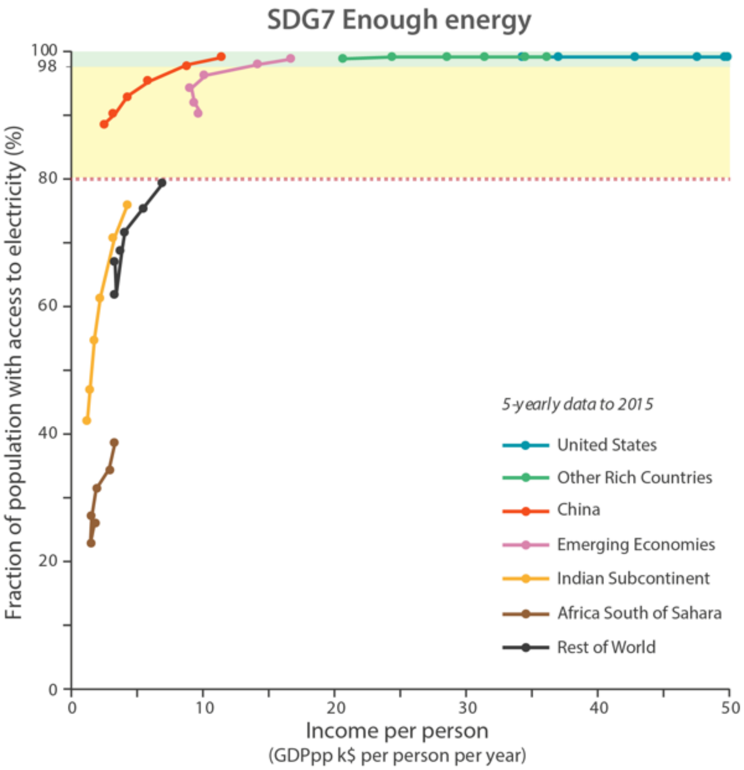

Figure 14

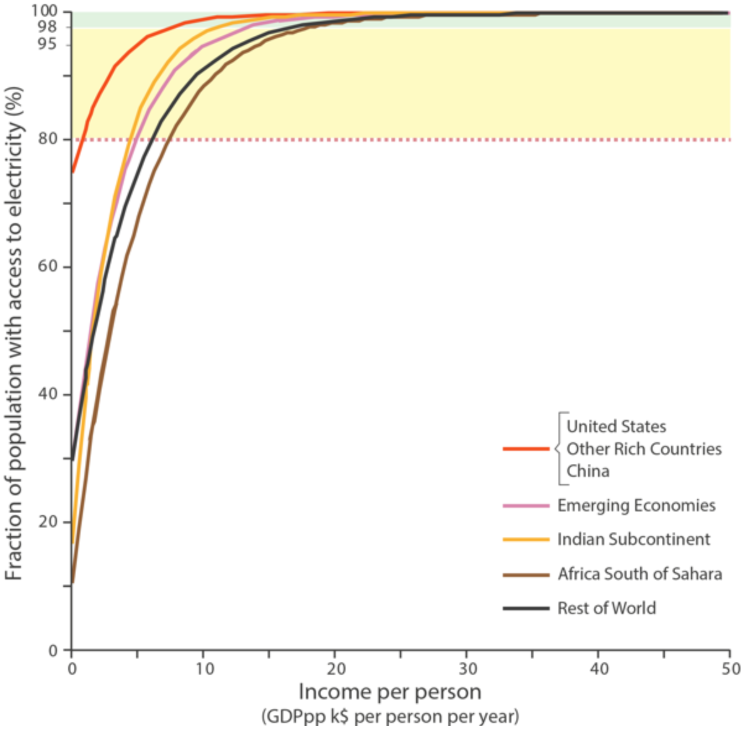

Figure 15

For SDG7 we use the indicator *Access to electricity (% of population)* that we retrieved from the World Bank[17] for 1990–2015 for all our regions, Figure 14. Access to electricity is also included as an indicator for SDG7 in the *SDG Index and Dashboards Report* 2017. We use the same threshold values as in the *SDG Index and Dashboards Report* 2017[18], 80% and 98%.

We decided to use the following functional formula:

$$y = 100 - a * \exp(-x/b).$$

As all data points for United States and Other Rich Countries are 100%, we use the same parameter values for these regions as for China, while the rest of the parameters were derived through regressions of the respective regions. The resulting functions are plotted in Figure 15.

SDG8 – Decent jobs

For SDG8 – Decent jobs we use job-market growth as our indicator. The *SDG Index and Dashboards Report* 2017[19] suggests various employment indicators and we deem job market growth to be compatible and relevant to these. We assume that job growth is one percentage point less than the rate of change in GDP per person, as we assume that the very long-term productivity increase amounts to this percentage. We calculate the historical rate of change by using GDP values from Penn World Tables in 2011PPP$ per year[20] and divide that by historical population from the UN[21]. For the future, we forecast the rate of change in GDP as a function of GDP per person in the previous period using the formula:

$$\mathrm{y} = \mathrm{a} \cdot \mathrm{e}^{(-\mathrm{b} * \mathrm{x})} - \mathrm{c} \cdot \mathrm{e}^{(-\mathrm{d} \cdot \mathrm{x})}$$

We have set a = 9, b = 0.07, c = 6 and d = 0.3

Future population is calculated by forecasting the birth and death rate. For the birth rate, we use the formula:

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

with a = 0.8, b = 3 and c = 5 and x being the GDP per person in the previous period. This is our global guideline; future values are then adjusted from the previous actual data point with an adjustment time of 20 years. The death rate is forecast by:

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

with a = 0.8, b = 1.5 and c = 2 This is our global guideline, future values are then adjusted from the previous data point with an adjustment time of 30 years. Since our formula is trained on data from a time period where the age pyramid was indeed a pyramid, we introduce an aging multiplier on the death rate to represent the changing of the shape of the pyramid that is not yet in the data. This multiplier is:

$$\mathrm{y} = \mathrm{a} \cdot \mathrm{e}^{(\mathrm{t} - 2015)}$$

where a is calculated as the annual rate of change in the fraction of the population 65 and older between 1995 and 2015. The resulting job-market growth is portrayed in Figure 16 together with the historical data. In the Figure 16 we use moving averages for the historical data to smooth the function.

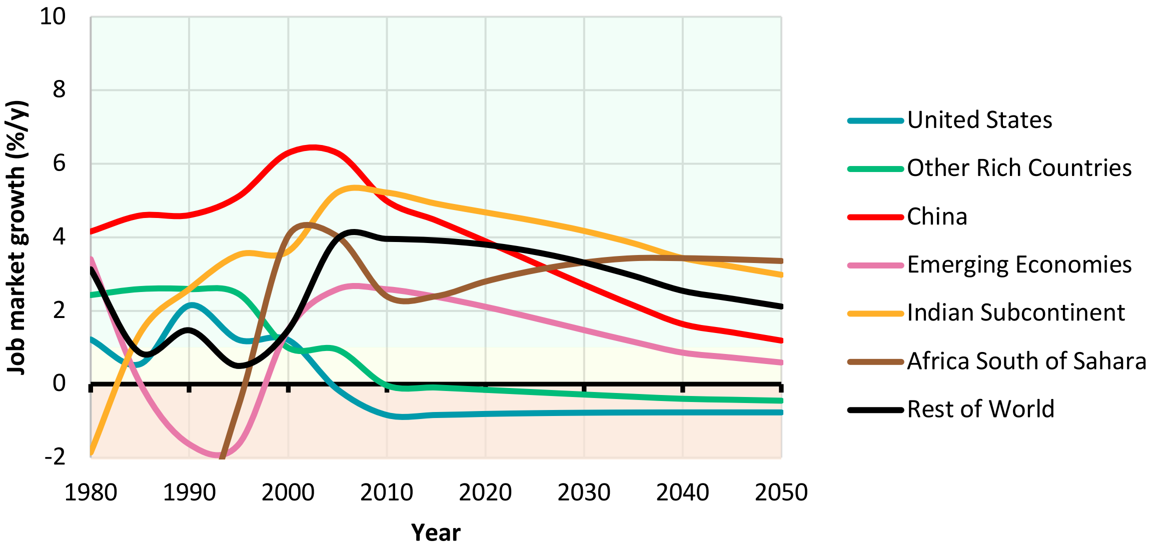

Figure 16

We have chosen the target value of 1% increase and the halfway target 0 (see green and yellow areas respectively in Figure 16).

SDG9 – Industrial output

For SDG9 – Industrial output we use the indicator GDP per person in manufacturing and construction measured in k$/person-year. We have calculated the historical values from using GDP and fractions of GDP in the primary, secondary and tertiary sectors (see SDG8 above for source). Data on the size of the sectors (as % of GDP) is retrieved from the World Bank[22]. For the future values we forecast the rate of change in GDP as a function of GDP per person in the previous period using the formula:

$$y = a \cdot e^{(-b*x} - c \cdot e^{(-d*x)}$$

We set a = 9, b = 0.07, c = 6 and d = 0.3. We forecast future shares of agriculture by

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

with a = 1, b = 37 and c = 5 and x being the GDP per person in the previous period. This is our global guide; actual values are then adjusted to the previous data point with an adjustment time of 20 years. We forecast future shares of services by:

$$y = a + b \cdot e^{\left(-\frac{x}{c}\right)} + \left(1 - e^{\left(-\frac{x}{d}\right)}\right)$$

with a = 15, b = 60, c = 1 and d = 15 and x being the GDP per person in the previous period. This is our global guide; actual values are then adjusted to the previous data point with an adjustment time of 20 years. The share in industry is:

y = 1 – *share in agriculture – share in services*

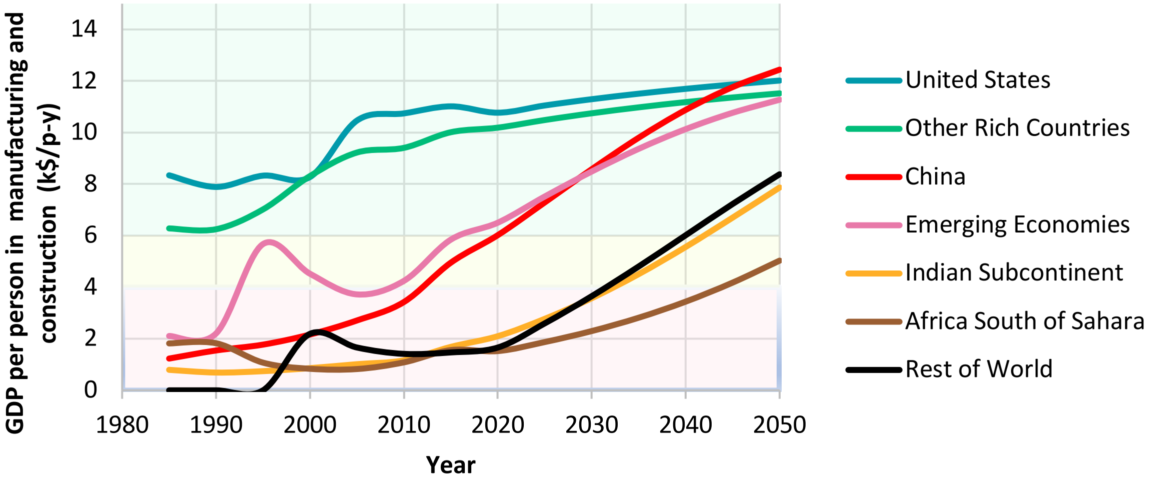

Figure 17

We have chosen the target values of above 6 k$/person-year and set the halfway target at 4 k$/person-year. The resulting behavior of Scenario 1 of the different regions is portrayed in Figure 17 together with the historical data.

SDG 10 – Reduced inequality

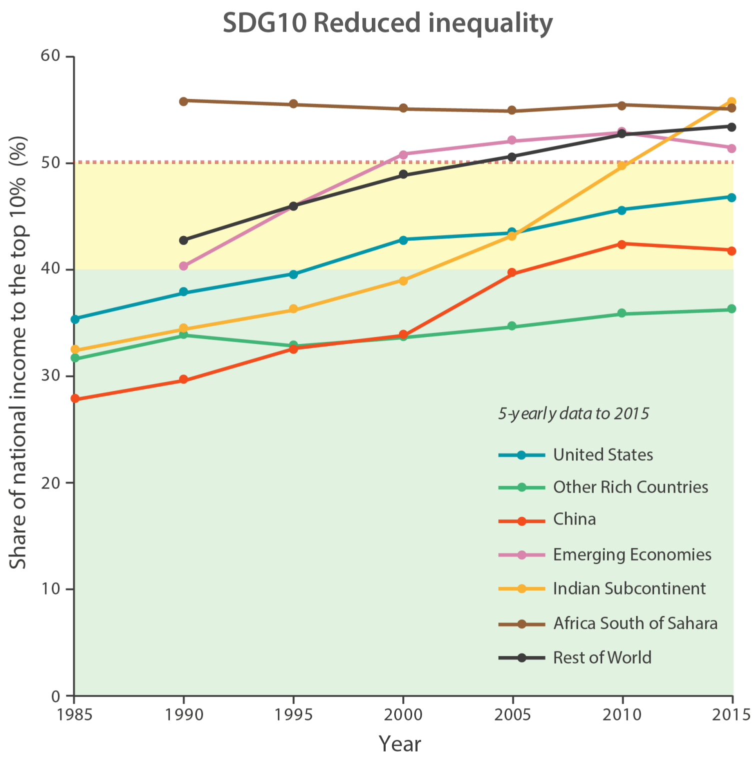

Figure 18

As our indicator for inequality, we use the share of incomes of the top 10% of the population. The *SDG Index and Dashboards Report* 2017[23] uses the Palma Ratio which includes the top 10% (and the bottom 40%) of incomes. History is calculated from the World Inequality Database, the percentage of annual pre-tax national income accruing to the top 10% income earners[24]. World Inequality Database includes data from 1980 for some of the regions, and 1990 for others. We apply their regional differences to derive reasonable values for our regions. We forecast the future manually (ie. exogenously), portrayed in Figure 18

SDG11 – Clean cities

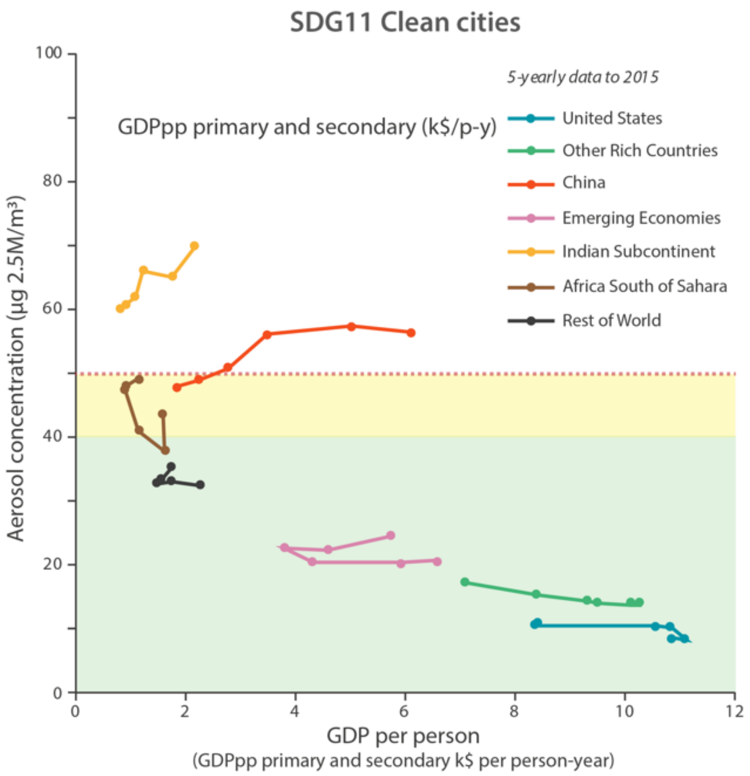

Figure 19

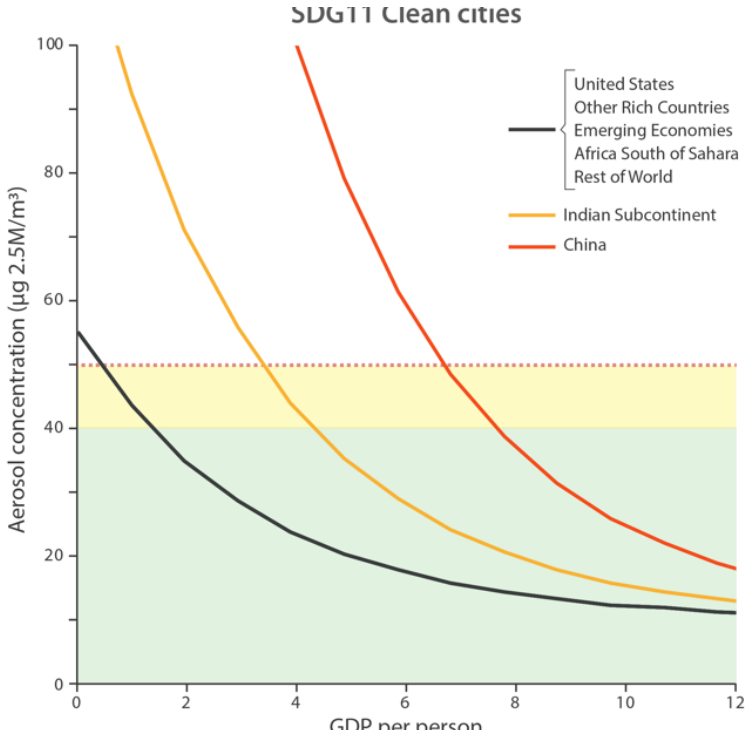

Figure 20

For SDG11 – Clean cities we use the indicator *PM2.5 air pollution, mean annual exposure (micrograms per cubic metre)* which is the “average level of exposure of a nation’s population to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter”[25]. The data was retrieved from the World Bank for 1990–2015 for all world regions, and portrayed in Figure 19. The similar variable, PM2.5 in urban areas, is included in the *SDG Index and Dashboards Report* 2017. We have chosen the threshold levels 10 and 35 based on the World Health Organization’s recommendations[26] and expert judgement of the planetary boundary on aerosols.

There are diverse sources of air pollution. We have assumed that industrial development is the main driver, and we have chosen to plot it against GDP per person in the primary and secondary sectors. Figure SDG11 indicates an overall decline in aerosol concentrations as the GDP per person in the primary and secondary sectors increases, for all regions except China and the Indian Subcontinent. Also, the lowest concentration values of all countries are around five (for Sweden and Australia). Therefore, we use the following functional formula:

$$y = 5 + a * \exp\,(-x/b)$$

We regressed the data for United States, Other Rich Countries, Emerging Economies, Africa South of Sahara and Rest of World together. We then adjusted the *b* value so that we got curves close to the latest values for the Indian Subcontinent and China as we judge that the behavioral patterns of these regions will be similar to the rest of the regions. The functions are portrayed in Figure 20.

SDG12 – Responsible consumption

As indicator for SDG12 – Responsible consumption we use the *ecological footprint per person* (gHa/p). The historical values are calculated from the total ecological footprint[27], divided by population data from the UN (see SDG8 for source). For the future we forecast the rate of change in GDP as a function of GDP per person in the previous period using the formula

$$y = a \cdot x \cdot e^{\left(-\frac{(t-2015)}{c}\right)}$$

where a is set regionally, c = 40 and x is the GDP per person in the agricultural and industrial sector. Values are for a range from 0.5 to 1.0. This is a proportion between x and y controlled by the slope a, modified with a rate of technological progress.

Historical values together with the forecast for Scenario 1 are portrayed in Figure 21.

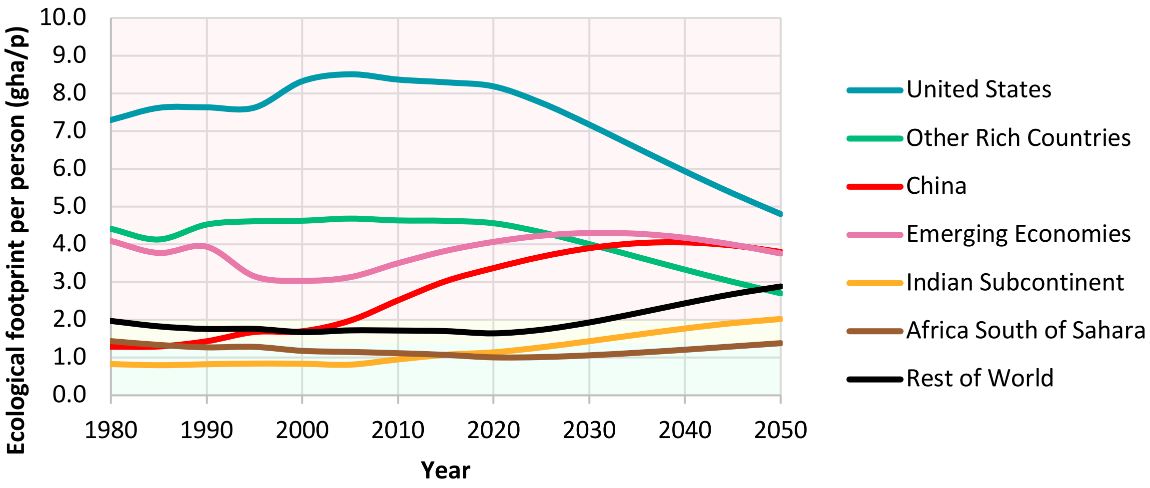

Figure 21

SDG13 – Climate action

We measure SDG13 – Climate action in global mean temperatures as *temperature rise in Celsius degrees above 1850 levels*. This is a global indicator, which means that it is the same for all regions. History is given by the National Centers for Environmental Information[28]. The raw data is the anomaly to the base "the 20th century". For the future forecast we use ESCIMO, a climate-change model described and fully available here: http://www.2052.info/ESCIMO/ To generate the forecast we drive the model with assumptions about greenhouse-gas emissions. See the Planetary Boundary on Climate Change for data and the forecast for Scenario 1. We use the same threshold value as for the planetary boundary, 1 degree and 1.5 degrees.

SDG14 – Life below water

As an indicator for SDG14 – Life below water we use *acidity of ocean surface water (pH)*. It is a global indicator, which means that it is the same for all regions. This indicator is also the same as the one used for Planetary Boundary Ocean Acidification. Historical data is from the WHOI Hawaii Ocean Time-series Station[29] and the Bermuda Institute of Ocean Science[30]

For the future forecast we use ESCIMO, a climate-change model described and fully available here: http://www.2052.info/ESCIMO/ To generate the forecast we drive the model with assumptions about greenhouse-gas emissions. Also, we use the same thresholds as the safe territory and high-risk zone for the planetary boundary, using above pH 8.15 as target and above 8.10 as a halfway target.

SDG15 – Life on land

As our indicator for SDG15 – Life on land we use *old-growth-forest area measured in Mkm^2*. It is a global indicator which means that it is the same for all regions. This indicator is also the same as the one used for Planetary Boundary Forest Degradation. Historical data is retrieved from the FAO's Forest Resource Assessment, various years[31]. For the future forecast we use ESCIMO, a climate-change model described and fully available here: http://www.2052.info/ESCIMO/ To generate the forecast we drive the model with assumptions about greenhouse-gas emissions. Threshold values are set to 17 as target and 25 as the halfway target.

SDG16 – Good governance

For SDG16 – Good governance we use the indicator *government spending per person as measured in 2011 PPP US$/p-y*. The historical data is calculated from GDP (see SDG8 for source) and fraction of GDP in government spending, also from the Penn World Tables.
How we forecast GDP is detailed in the section on SDG8 above. We forecast future shares of government spending by

$$y = a + b \cdot e^{\left(-\frac{x}{c}\right)} + \left(1 - e^{\left(-\frac{x}{d}\right)}\right)$$

with a = 20, b = 10, c = 2 and d = 25 and x being the GDP per person in the previous period. This is our global guide; actual values are then adjusted to the previous data point with an adjustment time of 20 years. The forecast for Scenario 1 is presented in Figure 22 together with historical data.

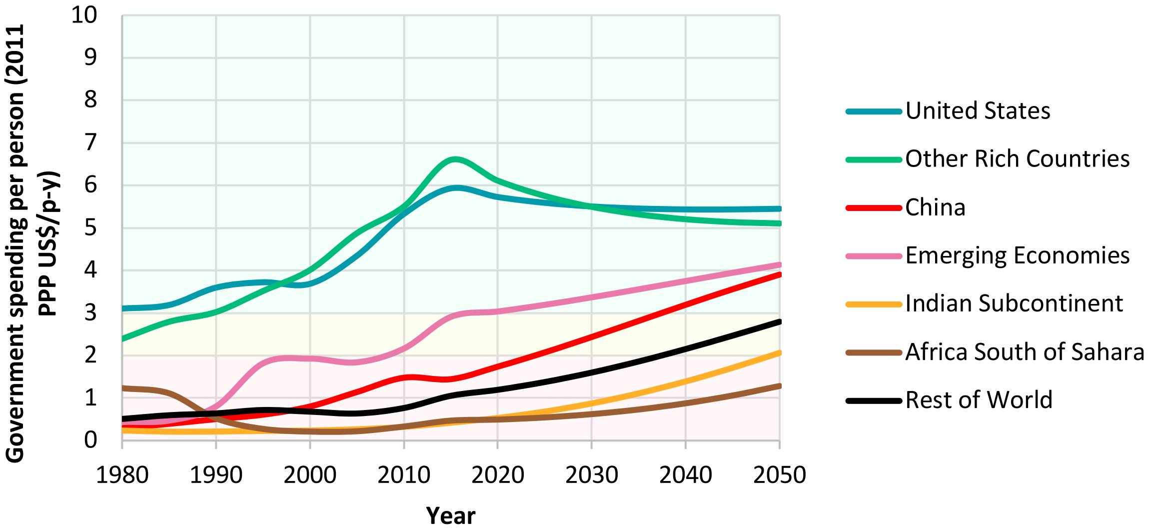

Figure 22

SDG17 – More partnership

For SDG17 – More partnership we use the indicator *exports as fraction of GDP (%)*. History is calculated from GDP (see SDG8 for source) and fraction of GDP in exports, also from the Penn World Tables. How we forecast GDP is the description for SDG8. We forecast future export fractions manually. Historical data and future forecast is presented in Figure 23.

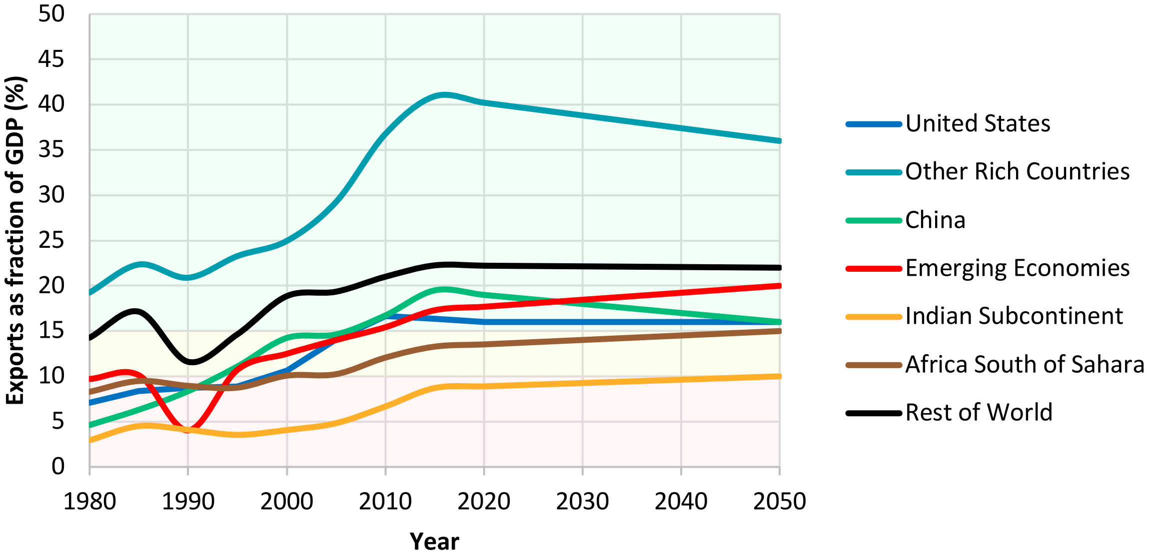

Figure 23

3. Planetary boundaries

We measure the different effects of human activities on the nine planetary boundaries in terms of the production and consumption activities that are included in the Earth3-core module, supported by the environmental system dynamics model ESCIMO (full high-level description, model equations and documentation and input data available at www.2052.info/ESCIMO).

We have used the planetary boundaries processes as presented in Steffen et al. (2015) [32] and Rockström et al. (2009)[33]. Where possible, we retain their indicators. In some cases, we have had to use other indicators for which historical data are available back to 1980. For these, we have chosen indicators that have widespread real-world application, especially in policy contexts, and that are sensitive to changes over the time frame to 2050. In setting the safe and high-risk zones for these indicators, we have focused on the points where scientific assessment coincides with multilateral and international policy concern about large-scale systemic environmental change.

We present the planetary boundaries together with a rationale behind our thresholds and graphs that includes historical development and our forecasted Scenario 1 values.

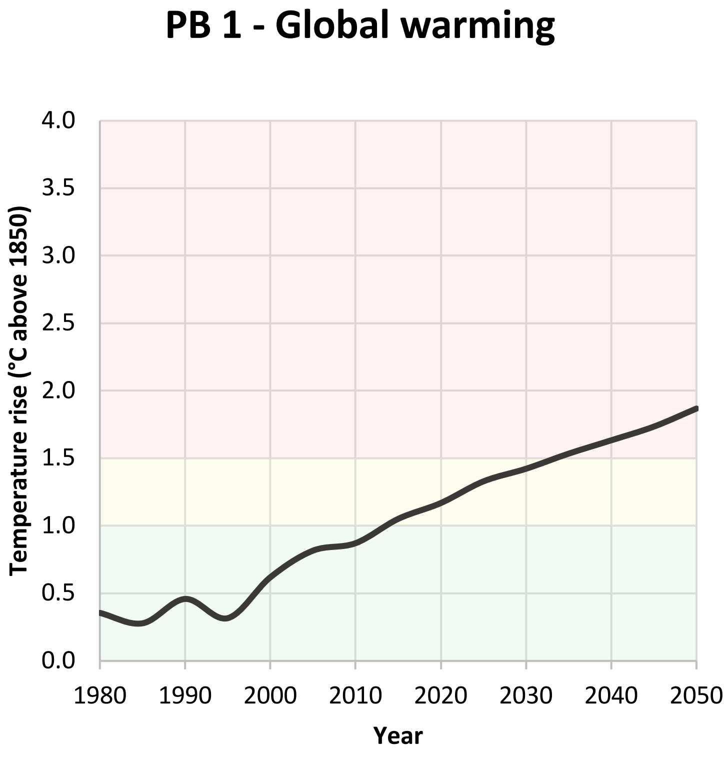

Figure 24

Global warming

For our analysis of the climate-change planetary boundary, we use temperature rise as the indicator. ESCIMO[34] calculates global average temperature rise, and this is the same indicator that we use for SDG13 – Climate action. Global temperature is a good indicator for measuring climate change because it is both intuitive and it is the basis of political negotiations on climate change.

The safe zone is set to below 1 degree Celsius above pre-industrial levels. This encompasses the long-term temperature variability of the previous few millennia, during which the world's civilizations established themselves. The high-risk zone is set above 1.5 degrees Celsius, where there is broad scientific and policy consensus that climate-change risks to societies and ecosystems will be globally severe. Note that we run the model until 2050, and a 1.5-degree temperature rise until 2050 may be consistent with a 2-degree increase to 2100. See Figure 24.

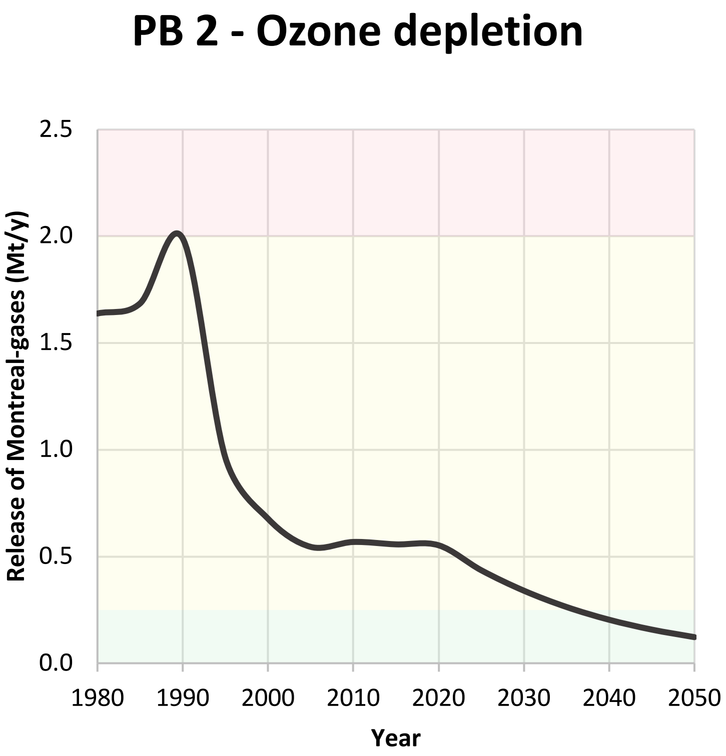

Figure 25

Ozone depletion

We measure ozone depletion as the release of Montreal gases. This indicator gives a measure of the emissions derived from human activities that drive the growth of the ozone hole. The Montreal gases are powerful greenhouse gases that contain stratospheric ozone-depleting chlorine and bromine atoms. We have set the safe zone to below 0.25 Mt/year, and the high-risk zone above 2 Mt/year corresponding to emission levels driving the emergence and large-scale expansion of the ozone hole. For the future we forecast Montreal gas emissions as a function of GDP per person in the previous period using the formula:

$$y = a \cdot x^{-b} \cdot e^{\left(-\frac{(t-2015)}{c}\right)}$$

where a = 2.2322, b = 2.269 and c = 40. x is the GDP per person. The resulting figure is then multiplied by the total GDP to get the total gases. The exponential term reflects our assumption that Montreal gases will be phased out with a half-life of 40 years (less in scenario 4). See Figure 25.

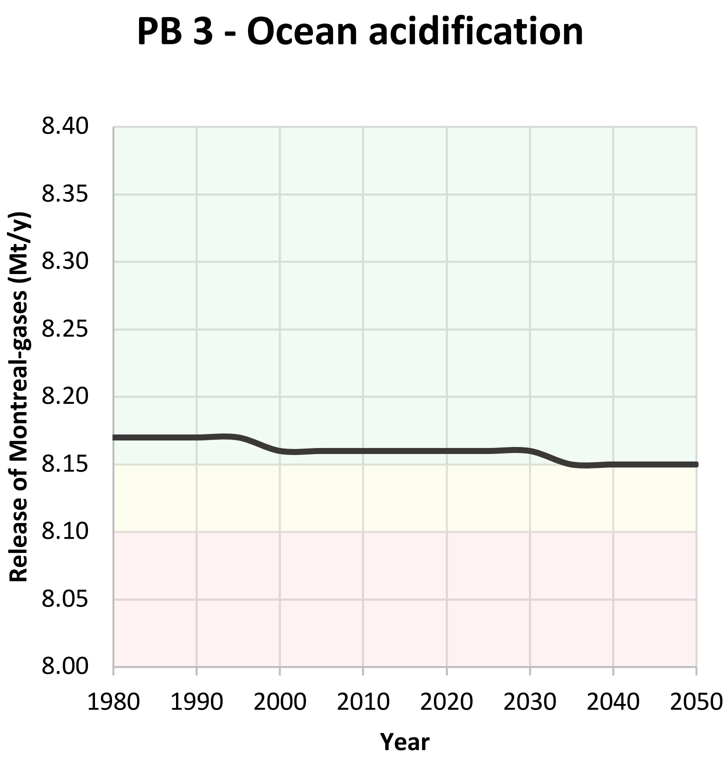

Figure 26

Ocean acidification

Ocean acidification is the decrease in the pH value of the oceans, caused when carbon dioxide from the atmosphere dissolves in sea water. Since the industrial revolution, the ocean has absorbed about one-quarter of anthropogenic carbon emissions[35]. The lowered pH alters the ocean carbon cycle, and has severe impacts on marine organisms, especially corals, plankton and shellfish. We have set the safe zone for ocean acidification as pH values above 8.15, corresponding approximately to pre-industrial levels of atmospheric CO_2. We set the high-risk zone to pH values below 8.10, which is the same as for SDG14. History is from the WHOI Hawaii Ocean Time-series Station[36] and the Bermuda Institute of Ocean Science[37]. For the future forecast we use ESCIMO, a climate-change model described and fully available here: http://www.2052.info/ESCIMO/. The results are portrayed in Figure 26.

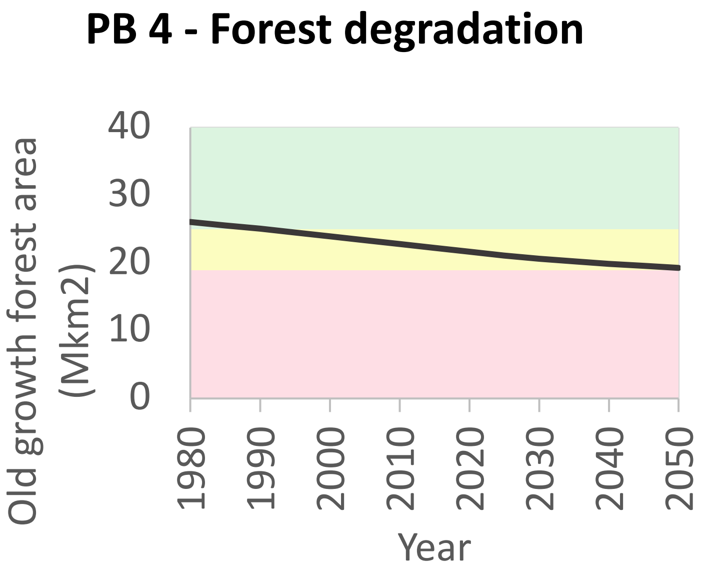

Figure 27

Forest degradation

As the indicator for the planetary boundary on land use, we have used old-growth-forest area measured in Mkm^2. Old growth forest is especially important in the maintenance of biodiversity, and deforestation also affects the Earth system through changes in the water cycle, CO_2-emissions and long-term carbon storage. Tropical forests support at least two thirds of the world's biodiversity[38]. Our safe zone is a forested area above 25 Mkm^2 and the high-risk zone is below 19 Mkm^2. History is from the FAO's Forest Resource Assessment, various years[39]. For the future forecast we use ESCIMO, a climate-change model described and fully available here: http://www.2052.info/ESCIMO/.

Nutrient overloading

We measure the change in biogeochemical flows of nutrient elements in terms of the environmental release of bioactive nitrogen from human activities. The overloading of nutrient elements (particularly nitrogen and phosphorus compounds applied as fertilizers) has severe environmental consequences, including losses of water quality, increases in algal blooms and more extensive ecosystem changes. We have set the safe zone of nitrogen release at less than 100 Mt N/year and the high-risk level at more than 200 Mt N/year, in line with Rockström et al. (2009) and Steffen et al. (2015) values on fixation rate.

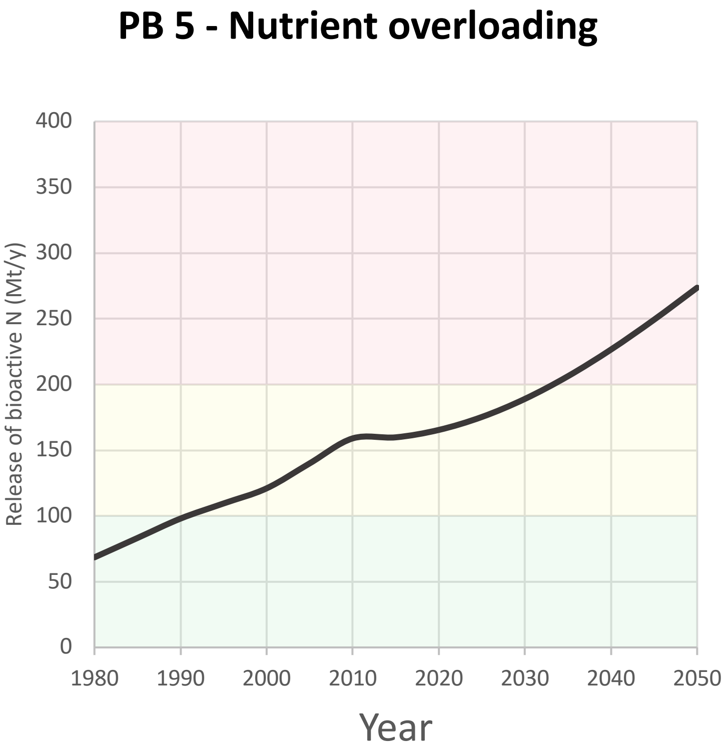

Figure 28

For the future we forecast nitrogen flow as a function of GDP per person in the previous period using the formula:

$$y = (a \cdot x + b) \cdot e^{\left(-\frac{(t-2015)}{c}\right)}$$

For N: a = 1.1704, b = 52.524 and c = 20. x is the GDP in T\$/y. In the Earth3-core, we have included a similar function calculating release of bioactive phosphorus, but this is not included in this version's calculation of the safety margin. See Figure 28.

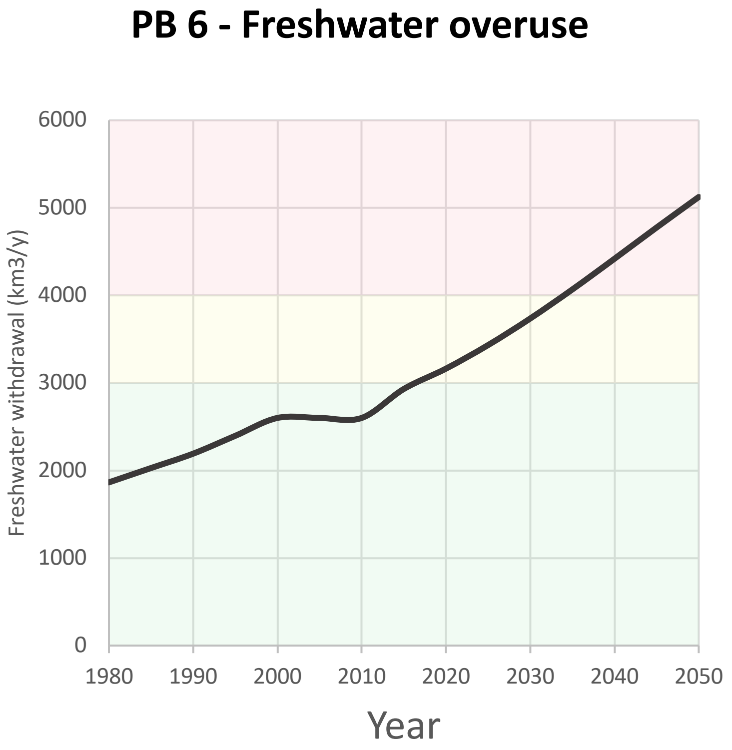

Figure 29

Freshwater overuse
For the planetary boundary on freshwater, the indicator we use is freshwater withdrawal measured in km^2/year. Human pressure on worldwide water resources is becoming increasingly severe. As in Steffen et al. (2015), the high-risk zone is set to freshwater withdrawal above 4000 km^2/year. The safe zone is set to below 3000 km^2/year. For the future we forecast water use as a function of GDP per person in the previous period using the formula:

$$y = a \cdot x + b$$

where a = 13.972 and b = 1613.3 Data is retrieved from Steffen et al. (2015)[40] and Rockström et al. (2009).[41]

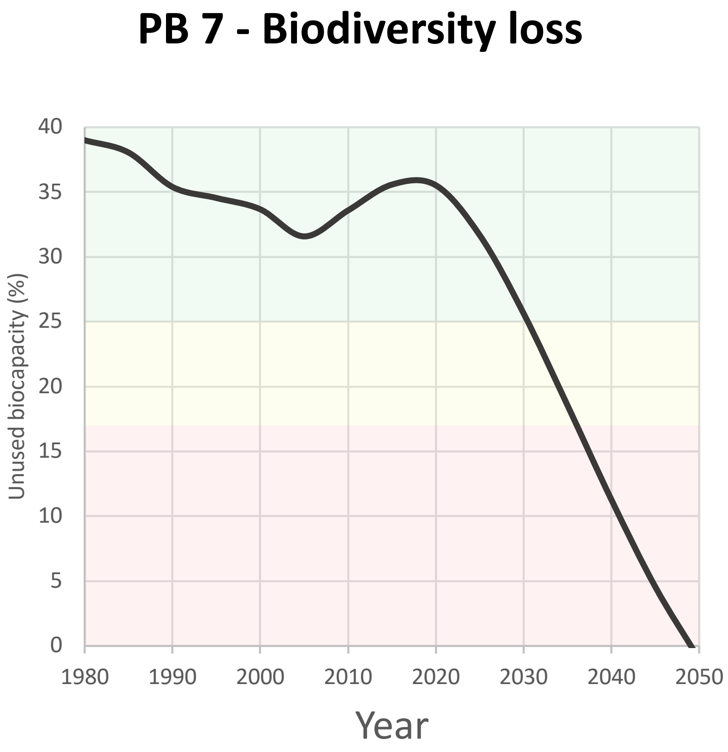

Figure 30

Biodiversity loss

For the planetary boundary on biodiversity loss we use unused biocapacity as our indicator. The worldwide erosion of biosphere integrity reduces nature's resilience to disturbances and its capacity to contribute to human wellbeing. The biocapacity metric is a departure from the count of extinctions proposed in Rockström et al. (2009). We chose it because it can represent both gains and losses in biosphere integrity on the time frame of our analysis. It is also widely used as part of ecological footprinting by countries, businesses and other groups and individuals. The safe zone is set to above 25% of the biocapacity and the high-risk zone to below 12%. History is calculated from data from the Global Footprint Network[42]. From their data we calculate a non-energy footprint as the difference between their total ecological footprint and their carbon footprint. We divide our non-energy footprint with their biodiversity.

We forecast our non-energy footprint as a function of GDP per person in the previous period using the formula:

$$y = a \cdot x \cdot^{\left(\frac{-(t-2015)}{c}\right)}$$

where a is set regionally, c = 60 and x is the GDP per person in the agricultural and industrial sectors. Values are for a range from 0.12 to 0.3. This is a proportion between x and y controlled by the slope a, modified with a rate of technological progress. We also assume an adjustment time to the previous data point of 20 years. Finally, we assume a biodiversity loss of 5% in 2050 over 2015. See Figure 30.

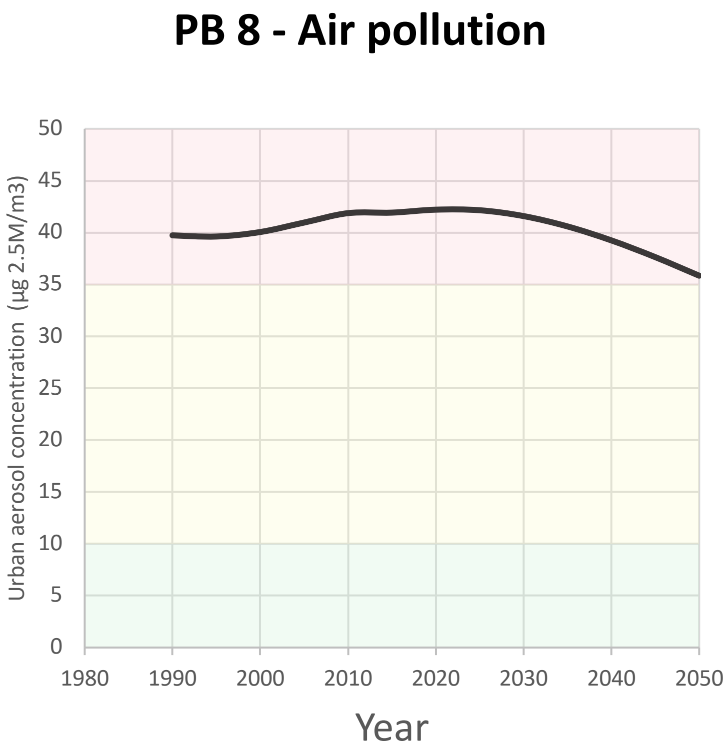

Figure 31

Air pollution

Our indicator for atmospheric aerosols is the concentration of fine particulate matter in air (PM2.5), measured as µg per m^3. This is the same indicator as for SDG11. Fine particles in the atmosphere are a consequence of emissions from transport, industrial processes and agriculture. They have effects on the water cycle, climate and ecosystem health. The safe zone is set to less than 10 µg per m^3 and the high-risk zone set to above 35µg per m^3. Although Steffen et al. (2015) did not provide a globally quantified aerosols boundary, they demonstrated that large-region climate changes associated with intense air pollution are already a cause for concern. For the future we forecast air pollution as a function of GDP per person in the previous period using the formula:

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

where a = 5, b = 46 (100 for the Indian subcontinent) and c = 5. We also assume an adjustment time to the previous data point of 15 years. The data is retrieved from the World Bank[43]. See Figure 31.

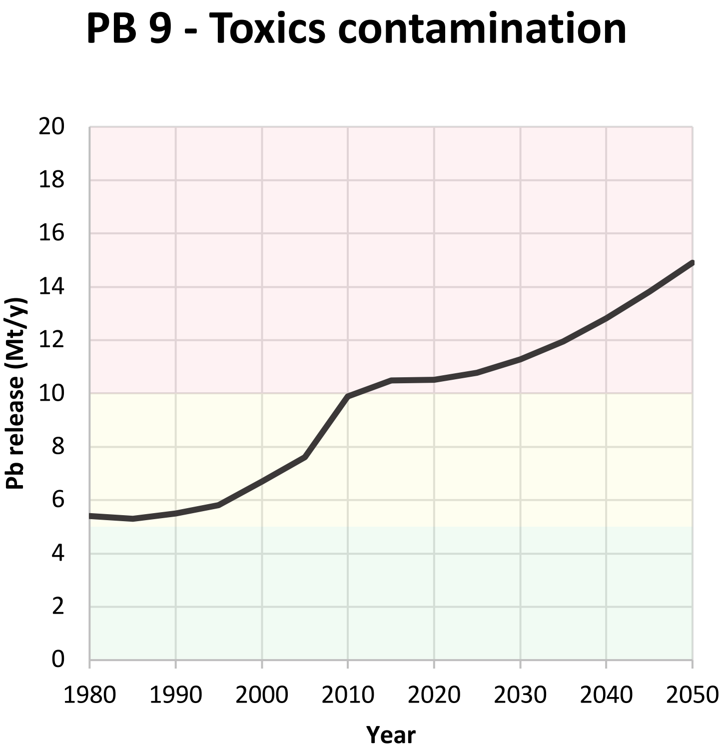

Figure 32

Toxics contamination

There is not a globally quantified novel entities boundary, although Steffen et al. (2015) explain the precautionary rationale, emphasising the long-term persistence and global distribution of harmful substances. We have used the total production of lead (which has the elemental symbol Pb) as an indicator for the planetary boundary on novel entities. Historical data trace the drivers, impacts and societal responses to lead emissions, linked to its long-term use as a vehicle fuel additive. The safe zone of Pb production is set to below 5 Mt/year and the high-risk zone above 10 Mt/year.

For the future we forecast Pb production as a function of GDP per person in the previous period using the formula:

$$y = (a \cdot x + b) \cdot e^{\left(-\frac{(t-2015)}{c}\right)}$$

where a = 0.0544, b = 4.4918 and c = 20. x is the GDP in T$/y. The data for Pb production is retrieved from the International Lead Association[44]. We measure total metal production. However, in future development of the model it may be useful to differentiate between mine production of lead and recycled lead. See Figure 32.

4. Specification of the seven regions

We have divided the world's countries into economic regions. The source of the national economic data we have used is the Penn World Tables, version 9[45] available for download at www.ggdc.net/pwt. All GDP data are in 2011 PPP $, in the table below 2011 PPP G$/y. (1 G$ = 1 billion $ = 1000 million $.) Population data is from UN Population Division: https://esa.un.org/unpd/wpp/DataQuery/

We have used seven regions for our analysis: United States, Other Rich Countries, Emerging Economies, China, Indian Subcontinent, Africa South of Sahara and Rest of World. The sequence in Table 2 follows an order of descending GDPpp per region average.

We have disregarded "region 8", which consists of a few super-rich countries outside the OECD. This cluster of countries is small (<1% of world population), and they are statistical outliers that distort the analysis. The global messages about SDG implementation from our analysis nevertheless also apply to these countries.

Table 2

REGION	Country	Population	GDP	GDPpp
		2015	2015	2015
		Mp	G$/y	$/p-y
		UN	PWT	(=D/C)
1. United States (USA)				
	US, Including Puerto Rico and US Virgin Islands	327	16 705	*51 100*
	SUM USA	***327***	***16 705***	***51 100***
2. Other Rich Countries (ORC)				
	Australia	23,8	1 017	*42 700*
	Austria	8,7	407	*46 800*
	Belgium	11,3	490	*43 400*
	Canada	36,0	1 507	*41 900*
	Chile	17,8	383	*21 500*
	Czech Republic	10,6	336	*31 700*
	Denmark	5,7	254	*44 600*
	Estonia	1,3	38	*29 200*
	Finland	5,5	221	*40 200*
	France	64,5	2 603	*40 400*
	Germany	81,7	3 707	*45 400*
	Greece	11,2	286	*25 500*

	Hungary	9,8	256	*26 100*
	Iceland	0,3	14	*46 700*
	Israel	8,1	264	*32 600*
	Italy	59,5	2 141	*36 000*
	Japan	128,0	4 483	*35 000*
	Luxembourg	0,6	53	*88 300*
	Netherlands	16,9	797	*47 200*
	New Zealand	4,6	156	*33 900*
	Norway	5,2	331	*63 700*
	Poland	38,3	972	*25 400*
	Portugal	10,4	296	*28 500*
	Slovakia	5,4	155	*28 700*
	Slovenia	2,1	63	*30 000*
	South Korea	50,6	1 758	*34 700*
	Spain	46,4	1 567	*33 800*
	Sweden	9,8	433	*44 200*
	Switzerland	8,3	480	*57 800*
	UK	65,4	2 589	*39 600*
	SUM ORC	***748***	***28 057***	***37 500***
3. Emerging Economies (EE)				
Characteristic: big mid-income countries				
	Argentina	43,4	869	*20 000*
	Brazil	206,0	3 064	*14 900*
	Iran	79,4	1 215	*15 300*
	Kazakhstan	17,8	407	*22 900*
	Malaysia	30,7	692	*22 500*
	Mexico	125,9	1 988	*15 800*
	Russia	143,9	3 448	*24 000*
	Romania	19,9	409	*20 600*
	Thailand	68,7	946	*13 800*
	Turkey	78,3	1 491	*19 000*
	Ukraine	44,7	465	*10 400*
	Venezuela	31,2	434	*13 900*
	SUM EE	**890**	**15 428**	***17 300***
4. China				
	Taiwan	23,5	1 039	*44 200*
	China	1 397,0	17 080	*12 200*
	Hong Kong	7,3	374	*51 200*
	SUM CHINA	**1 428**	**18 493**	***13 000***

5. Indian Subcontinent				
Characteristic: poor and populous				
	Bangladesh	161,2	459	*2 800*
	India	1309,0	6 767	*5 200*
	Pakistan	189,4	860	*4 500*
	SUM INDIAN SC	**1 660**	**8 086**	***4 900***
6. Africa South of Sahara (ASoS)				
Characteristic: poor and resource rich				
	Angola	27,9	193	*6 900*
	Cameroon	22,8	61	*2 700*
	Congo	76,2	91	*1 200*
	Cote d'Ivoire	23,1	74	*3 200*
	Ethiopia	99,9	128	*1 300*
	Ghana	27,6	96	*3 500*
	Kenya	47,3	124	*2 600*
	Madagascar	24,2	29	*1 200*
	Mozambique	28,0	31	*1 100*
	Nigeria	181,2	976	*5 400*
	Sudan	38,6	190	*4 900*
	South Africa	55,3	655	*11 800*
	Tanzania	53,9	112	*2 100*
	Uganda	40,1	69	*1 700*
	SUM AFRICA SoS	**746**	**2 829**	***3 800***
7. Rest of the World – 120 (RoW)				
Sum world (from other data)		7 383	103 866	*14 100*
Sum of regions 1–8		5 847	92 380	*15 800*
=	***SUM ROW 120***	**1 536**	**11 486**	***7 500***
8. Super-rich outside OECD				
Characteristic: “authoritarian wealth”				
	Quatar	2,5	314	*125 600*
	Saudi Arabia	31,6	1 483	*46 900*
	Singapore	5,5	400	*72 700*
	UAE	9,2	585	*63 600*
	SUM SUPER-RICH	**49**	**2 782**	***57 000***
MEMO				

The following countries have more than .3% of total population or GDP. That is >22Mp or >300G$/y				
But have still been left in the Rest of World category				
	Afghanistan	33,7		
	Algeria	39,9	499	*12 500*
	Colombia	48,2	602	*12 500*
	Egypt	93,8	888	*9 500*
	Indonesia	258,2	2 470	*9 600*
	Iraq	36,1	427	*11 800*
	Morocco	34,8	243	*7 000*
	Myanmar	52,4	286	*5 500*
	Nepal	28,7	61	*2 100*
	North Korea	25,2		
	Philippines	101,7	660	*6 500*
	Uzbekistan	31,0	241	*7 800*
	Vietnam	93,6	495	*5 300*
	Yemen	26,9	88	*3 300*
	SUM BIG in ROW120	**904**	**6 960**	***7 700***

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