Supplementary Materials

1. Introduction

The scenarios reported in this paper and Raskin *et al.* [1] were produced using the PoleStar system, an engineering-accounting integrated assessment model (IAM) that is disaggregated into 11 world regions and has detailed coverage of the following sectors: household, transportation, service, industrial, agriculture, forestry, water and energy. The base year for each scenario is 2005; future values are calculated at 2025, 2050, and 2100. Here we provide a summary of the assumptions underlying each sector in Sections 2 through 5 (see Technical Documentation [2] for full details) and the methodological details for linking the scenarios to the planetary boundaries framework in Sections 6 though 10 [3,4].

Introduced in Rockström *et al.* [3,4] the planetary boundaries framework defines thresholds of global instability for a set of global bio-physical indicators. Originally applied to existing data, the boundaries have been linked to the PoleStar system to assess whether alternative future scenarios will remain within the environmental conditions that define a "safe operating space" for Earth. This space is defined as the relatively stable Earth system conditions observed over the last 10,000 years during the Holocene, a period conducive to the introduction of settled agriculture and evolution of civilization. Our scenarios do not consider planetary boundaries that were not quantified in the original publication (aerosol loading and chemical pollution), and do not include stratospheric ozone depletion, which is expected to stay within the boundaries for all scenarios. A summary of scenario results is shown in Table S1.

Table S1. Summary of planetary boundary and social target scenario results.

Indicators		Year			
		2005	2100		
			Conventional Development	Policy Reform	Great Transition
	Boundary				
Climate change (ppm CO_2)	350	375	768	350	350
Ocean acidification (aragonite saturation)	2.75	2.77	1.85	2.99	2.99
Nitrogen cycle (Mt N)	35	181	402	35	35
Phosphorus cycle (Mt P)	11	8.4	14.5	2.7	2
Global freshwater use (km^3)	4000	2600	4000	1730	1480
Land use change (%)	15	11.6	10.3	9.4	6.4
Rate of biodiversity loss (extinction per million species-years)	10	100	1000	10	10
	Target				
Hunger (10^6 people)	56	893	517	56	0
International inequity	2	7.5	4.3	2.2	1.1
Water stress (10^6 people)	2000	1730	4680	1940	1510

As discussed in the main text, *Conventional Development* is a baseline scenario that represents the continuation of historical trends into the future. In contrast, *Policy Reform* and *Great Transition* are informed by future sustainability targets. Methodologically, they take social, economic, and technological trends in *Conventional Development* as a point-of-departure. *Policy Reform* assumes policies are enacted that alter economic growth and technological change towards sustainability. *Great Transition* assumes practically the same technological change of *Policy Reform* and also includes dramatic changes in societal values, which lead to dramatic shifts in how productivity improvements and investment are directed. In the following methods description, the reader should note that *Policy Reform* and *Great Transition* assumptions are the same unless otherwise noted.

2. Population, Economy, and Poverty

2.1. Population

In the *Conventional Development* scenario, population growth follows the UN mid-range population projections described in [5]. In the *Policy Reform* scenario, population growth in OECD regions is the same as in *Conventional Development*. For non-OECD countries, population levels are assumed to be slightly lower—2%, 5%, and 10% in years 2025, 2050, and 2100—than in *Conventional Development* as a result of reduced fertility rates associated with higher incomes and education levels in *Policy Reform*. *Great Transition* follows the low and mid-range UN projections in all regions. Global population in *Great Transition* for 2050 and 2100 is, respectively, one and two billion people less than in *Conventional Development*.

2.2. Economic Growth

In *Conventional Development* GDP per capita growth rates are computed by first adopting published growth rates for the OECD region and the World. Non-OECD growth rates are then algebraically inferred using assumed future population levels. In *Policy Reform*, policies to reduce inequity are assumed to reduce OECD growth rates by 0.5%. Aggregate World growth rates are assumed to be the same as in *Conventional Development*. Non-OECD growth rates are then recalculated using assumed future population levels and associated *Policy Reform* OECD and World GDP levels. GDP per capita growth rates for each of the 11 regions in the model are initially informed by reviews of other long-term forecasts [6,7]. For *Conventional Development*, these are then adjusted by the same factor so that in aggregate they match the OECD and non-OECD growth rates calculated previously. In *Policy Reform*, the rates are adjusted to correspond to the shift of growth from OECD to non-OECD regions. The resulting international inequity is shown in Table S1.

The changes in economic output represented in *Great Transition* constitute a fundamental break from historical trends. Through the middle of the century, growth is highly focused by diverting investment to developing regions, bringing many out of poverty and reducing international inequity. Concurrently, technological improvements and an increased focus on overall quality-of-life lead all regions to divert productivity gains to a less intensive work schedule: 6-h work days and 40 weeks of work per year. This leads all regions to eventually converge to a per capita annual income of about $30,000, which is roughly the income of Western Europe in the base year. Since demand for products and services in our model are linked to income, *Great Transition* introduces additional reductions in environmental burden over the *Policy Reform* scenario.

2.3. Sector Value-Added

Our scenarios feature a breakdown of GDP into agriculture, industrial, service, and energy sector value added. Starting year values are established from World Bank data [8]. Agricultural sector value added in OECD regions is assumed to stay at a constant fraction of GDP per capita. In non-OECD regions, the agricultural fraction of GDP per capita is assumed to converge to OECD levels as non-OECD region GDP per capita approaches base year OECD region GDP per capita. Convergence of value added (V) in region r at time t is estimated by:

$$V_{r,t} = V_{r,t-1} + \left(V_{OECD,t} - V_{r,t-1}\right)\left(\frac{i_{r,t} - i_{r,2005}}{i_{OECD,2005} - i_{r,2005}}\right) \tag{S1}$$

where $V_{OECD,t}$ is the average OECD value and i is GDP per capita. This convergence relationship is also used for many other components of our scenarios, where V is replaced by the relevant driver or variable.

Industrial sector value added has reached a post-industrial decline in OECD regions. We assume that this historical trend continues but at a slower rate. In *Conventional Development*, OECD regions' industrial fraction of GDP is decreased to 80%, 60%, and 35% of the base year value in years 2025, 2050, and 2100, respectively. In *Policy Reform*, the decline in industrial fraction of GDP is slower in order to capture balanced growth between services value added and the light industries portion of industrial value added. Consequently, OECD regions' industrial fraction of GDP is decreased to 85%, 70%, and 50% of the base year value in years 2025, 2050, and 2100, respectively. For both scenarios, non-OECD industrial fraction of GDP is determined by the convergence equation.

Energy sector value added is currently a very small fraction of overall GDP. We assume this fraction remains constant in the future. Since three of the four sectors are determined, valued added of the service sector is calculated as the balance of remaining GDP.

2.4. Poverty

Poverty is measured by the number hungry in a region. In *Conventional Development*, computing the number of hungry requires estimating the distribution of income among each region's inhabitants and the income-based hunger line. The base year distribution of income is specified by each region's Gini coefficient, which varies from 0 (equal distribution of income) to 1 (all income held by one person). In *Conventional Development*, projection of regional Gini coefficients is based on the assumption that inequity will increase under a market system with unaddressed social and environmental externalities. Therefore, we assume that from the base year to 2050 all regions' Gini coefficients will converge to towards the currently most inequitable region, Latin America. Year 2100 Gini coefficients are assumed to be 0.03 greater than 2050 values.

The income-based hunger line is a proxy for measuring hunger. It assumes that any person with an income below the hunger line is chronically hungry. Income-based hunger lines tend to be correlated with a country's GDP per capita level. As a result, we assume that the hunger line will shift upward as a region becomes wealthier. If a region reaches base year US income levels ($23,979), we assume that the hunger line remains constant at the current US hunger line, $4767.

Since the Gini coefficient can be used to construct income distributions and the hunger line defines the income below which people are considered in poverty, computing the number of hungry in *Conventional Development* follows algebraically by combining these two relationships. In *Policy Reform*, we assume that policies are put in place in each region that drastically reduces the number of hungry: 50% below base year by 2025, 25% below 2025 numbers by 2050, and 25% below 2050 numbers by 2100. Thus, projection of Gini coefficients is not needed for the *Policy Reform* scenario. The resulting numbers of hungry at the global level are reported in Table S1.

3. Energy System and Climate Policy

Energy use and supply is modeled by dividing final energy demand into five sectors: industry, transport, households, services, and agriculture. Final energy demand may be met by 8 forms of energy: coal, oil, natural gas, biomass, renewables, hydrogen, heat, and electricity. As intermediary forms of energy, heat and electricity may be produced by coal, oil, natural gas, nuclear, hydropower, biomass, or renewables (solar, wind, municipal solid waste, geothermal, wave, and tidal). The general computation strategy is to conceptualize energy demand in terms of (i) a measure of end-use activity or service, (ii) the energy intensity required to deliver the activity or service, and (iii) the final fuel mix. The measure of end-use activity, such as population or value-added, is usually determined from other parts of the scenario analysis. In *Conventional Development*—which is meant to be a continuation of the past—forecasts of energy intensity and fuel mix are typically informed by extrapolation of past trends as well as reference to other baseline scenarios in the literature. Energy intensity and fuel mix in *Policy Reform* and *Great Transition*—which are backcasts meant not to exceed the climate planetary boundary—are informed by other ambitious scenarios in the literature.

3.1. Climate policy

The climate mitigation goals of *Policy Reform* and *Great Transition* are informed by the World Energy Outlook 2007 450 ppm CO_2-equivalent [9] and SRES B1 480 ppm CO_2-equivalent scenarios [10]. *Policy Reform* is a backcasted scenario that achieves approximately 350 ppm CO_2 concentrations (450 CO_2-equivalent) by 2100. This translates into cumulative 1990 to 2100 CO_2 emissions of about 325 Gton carbon. Allocation of emissions to regions and sectors follows a five-step process based on spatial level: (i) global, (ii) macro-region, (iii) regional, (iv) sectoral, and (v) end-use fuel mix.

Global CO_2 emissions are broken into two components: (i) emissions from burning fossil fuel and from cement production and (ii) emissions from land-use change. Based on our source scenarios we set a cumulative target for fossil fuel and cement emissions at 309 Gton carbon, with the balance, 16 Gton carbon, allocated to land-use change.

The global target is then divided between the OECD and non-OECD macro-regions. First the non-OECD region's allowable emissions are determined, with OECD emissions determined by the balance of global emissions. In 2010 and 2015, non-OECD allowable emissions are set at assumed percentages—5 and 8, respectively—below each region's *Conventional Development* level of emissions. For 2025 and 2050, emission allocations are defined by a percentage cut, relative to *Conventional*

Development, of each region's emissions intensity, as measured in tons carbon per dollar of GDP PPP. In 2025 the reduction is 30%; in 2050 emission intensity is reduced by 80%.

Within non-OECD, further allocation to constituent regions is made by first calculating regional emissions per capita that result from the emissions intensity based reduction described in the previous paragraph. Guided by equity considerations, we then assume that the variance in base year emissions per capita among non-OECD regions is reduced by assumed percentages. In 2025 the reduction is assumed to be 50%; in 2050 a 90% reduction is achieved. Note that this step does not change the overall level of non-OECD emissions, only relative emissions among non-OECD regions. A similar process is used for the three OECD regions.

Recent sectoral allocations from 1995 and 2005 are used to allocate emissions among industrial, transport, households, services, and agriculture sectors. After fuel mixes are determined, sectoral allocations are further refined to better represent assumed technological changes. Assigning fuel mixes is accomplished by first setting reference fuel shares based on the literature. These fuel shares are then multiplied by fuel-specific carbon intensity factors (tons of carbon per MJ) and the total energy needed by each sector (see subsequent sections for calculation of energy demand), which yields reference sectoral emissions. Reference sectoral emissions are then compared to allowable sectoral emissions. If reference emissions are different than allowable emissions, the fuel mix is adjusted so that reference and allowable emissions are equal.

3.2. Industrial Sector

The industrial sector accounts for almost 40% of global final energy consumption and is dominated by five sub-sectors: chemicals paper and pulp; stone, glass, and clay; non-ferrous metals; and iron and steel. We use industrial sub-sector value added as a measure of end-use activity and final energy use divided by industrial sub-sector value added for energy intensity.

Sub-sector energy intensity in *Conventional Development* is informed by existing scenario literature and continuation of historical reductions in energy intensity. This trajectory leaves many opportunities for cost-effective improvement in energy efficiency unutilized. As a result, OECD regions experience a 1.0% per year reduction in energy intensity. Slower declines in non-OECD regions lead to a global average decline of 0.7% per year. The *Policy Reform* scenario implements policies that close the gap between realized and potential energy efficiency improvements. This increases the rate of decrease in OCED energy intensity to 1.4% per year. Furthermore, non-OECD countries are assumed to converge to OCED energy intensity levels, resulting in a global average reduction of 1.2% per year.

In a continuation of past trends, little fuel switching occurs in *Conventional Development*. In OECD regions coal and district heat are gradually substituted for by electricity and natural gas. Although, the direct use of carbon heavy fuels remains as the bulk of the fuel mix. Slow convergence to OECD fuel mixes is seen in non-OECD regions. More dramatic fuel switching is seen in *Policy Reform*. By 2100, industrial energy use is largely supplied by electricity and direct use of biomass.

3.3. Transportation Sector

Transportation energy use is decomposed into passenger and freight, which are further decomposed into transport modes and vehicle types. Within passenger transportation, we consider private and public road transportation, electric and non-electric rail, and air travel. Within freight transportation, we consider road transport, electric and non-electric rail, air, and water. Activity forecasts are largely informed by the Sustainable Mobility Project [11].

In *Conventional Development*, total, rail, and air passenger-km traveled per year are linked to regional GDP per capita. Road transportation is calculated as the balance of remaining passenger-km and the split between private and public transportation is linked to regional GDP per capita. *Policy Reform* utilizes the same overall relationship between total passenger-km and regional GDP per capita as *Conventional Development*. However, *Policy Reform* modal shares are adjusted by using *Conventional Development* as a point-of-departure. We assume that the decline seen in public transport systems is reversed or slowed, which leads to a less reliance on private road travel.

Current and future reduction of travel modes' energy intensities (MJ per passenger-km) are guided by the SMP model. Improvements in the transport intensities in *Policy Reform* scenarios assume the introduction of progressively stronger vehicle emissions standards, pricing reforms, investments in research and development, and a range of market-based incentives to promote more efficient vehicles. In *Conventional Development*, we assume only modest OECD market shares for alternative fuel vehicles: 5% each for biofuels, electric, and natural gas by 2050 and 13% biofuels, 14% electric, and 13% natural gas by 2100. Non-OECD market shares are assumed to gradually approach OECD patterns. *Policy Reform* envisions a very different future. In OECD regions, petroleum and natural gas private vehicles are eliminated by 2100, with 50% of energy supplied by hydrogen and 50% by renewably-supplied electricity. Biofuels are used as a transition fuel but are essentially phased out for ground vehicles by 2100. Rail transport continues past trends toward electrification, with increased switching in *Policy Reform*. Furthermore, non-electric rail is assumed to use 100% hydrogen by 2100 while air transport is assumed to use 100% biofuels by 2100.

Regional freight activity is the product of regional GDP and modal freight intensity (ton-km per $). Electric and non-electric rail freight intensity is assumed to stay at base year values over time. Water freight intensity in OECD regions also remains at base year values. Non-OECD water freight intensity is assumed to converge to the OECD average as non-OECD incomes rise. As a continuation of past trends, road freight intensity declines slightly. Although freight energy intensities have different base year values than passenger energy intensities, they decline under the same assumptions. Similar assumptions to passenger vehicles are also used for fuel switching.

3.4. Household Sector

Energy use in households is tied to a wide variety of end-uses, including cooking, lighting, space heating and cooling, water heating, and refrigeration. The nature of these end-uses is closely related to income, culture, lifestyle, climate, and access to convenient forms of energy. As a simplification, we use population in each region as the measure of end-use activity and define energy intensity in GJ per capita. Population trajectories were outlined in Supplementary Section 2.1, which leaves the exposition of energy intensity and fuel mix assumptions.

In *Conventional Development*, we assume that the adoption of increasingly efficient appliances and building shells will be largely offset by increasing dwelling size and introduction of new energy-consuming household goods. For North America, this translates into a continuation of recent trends, where energy intensity has remained roughly constant. In Western Europe and Pacific OECD regions, where household energy intensities have been increasing, we assume a continued 1.0% per year increase in energy intensity through 2025. Afterwards, it is assumed that energy intensity remains constant. In contrast, *Policy Reform* assumes that policies induce a more rapid and widespread adoption of efficient new technologies, which leads to OECD energy intensity declining at 2.0% per year for electric appliances and 1.0% per year for non-electric end-uses. Using the convergence Equation S1 for both scenarios, Non-OECD regions are assumed to converge toward energy intensity in Western Europe.

In *Conventional Development*, changes in final fuel mix—which includes electricity—follow the well-known "energy ladder". With rising incomes, households tend to switch to more convenient forms of energy: wood and dung are replaced by charcoal and other more energy dense fuels and electricity is introduced. For *Policy Reform*, this transition is accelerated and paired with substitution of more carbon-intensive fuels, such as coal and oil, for lower-carbon forms of energy, such as electricity, natural gas, and some renewable.

3.5. Service Sector

The service sector includes non-industrial activities such as retail, education, and health care. As a result, energy use is largely related to building end-uses: lighting, HVAC (heating, ventilation, and air conditioning), and other electrical appliances such as computers. Service sector energy use and supply is forecasted based on service sector value-added (see Supplementary Section 2.3), final energy demand divided by service sector value-added, and final fuel mix.

Service sector energy intensity in OECD regions has been declining since 1973. We assume this trend continues in *Conventional Development*, with service sector energy intensity declining at region-specific rates through 2050; after which, energy intensity remains constant. Policies implemented in *Policy Reform* are assumed to lead to additional improvements in energy efficiency through 2050. Using the convergence equation S1 for both scenarios, Non-OECD regions are assumed to converge toward average service sector energy intensity of the OECD. Fuel shares in *Conventional Development* are assumed to continue recent trends, which lead the final fuel mix to be more dominated by electricity and natural gas. *Policy Reform* assumes an even faster transition to low carbon energy sources in order to avoid exceeding the climate system planetary boundary.

3.6. Agricultural Sector

The agricultural sector includes farming and livestock and forestry systems. It includes activities such as field operations, irrigation, and drying. Globally, the agricultural sector accounts for 3% of final energy consumption. The measure of activity used in the computation of agricultural sector energy use is the agricultural sector value added and the energy intensity is expressed in terms of final energy divided by agricultural sector value added.

3.7. Electricity and Heat Generation

The sum of final electrical and heat demand from the five sectors must be met through generation of electricity and heat from coal, oil, natural gas, nuclear, hydropower, biomass, or renewable (solar, wind, municipal solid waste, geothermal, wave, and tidal). Calculating the change in fuel shares over time starts with determining electricity generation from solid waste and hydroelectric. Electricity generation from solid waste is linked to waste generation rates, which is discussed in the Technical Documentation. We assume that hydroelectric power increases linearly with demand. However, increases in hydroelectric gradually slow as capacity approaches maximum exploitable regional capacity. In *Conventional Development*, changes in other fuel shares reflect continued fuel switching and improvements in conversion technology seen in other baseline scenarios from the literature.

In *Policy Reform*, future electricity generation is greatly affected by the need to meet stringent CO_2 emissions targets. Hydroelectric generation is constrained to not exceed *Conventional Development* levels. Nuclear power is assumed to be completely phased out by 2050, for reasons related to cost, safety, radioactive waste disposal, and security issues. New nuclear plant capacity follows *Conventional Development* until 2010, after which no new plants are constructed. The market penetration of biomass and other non-hydro renewables increase dramatically, with intermittent renewables reaching regional shares of 60 to 95% by 2050. Electric generation shares for coal, oil, and gas continue the trend towards natural gas-fired thermal plants.

4. Agriculture, Forestry, and Land Use

Our analysis of agricultural production starts with human dietary and industrial demands for agricultural products, and then translates these demands into requirements for land, seed, water, and nutrient inputs. Agricultural products are separated into crops and animal products. Both crops and animal products are consumed for food and feed; in addition, some agricultural products are used as fuel, or as industrial feedstocks. Crops can be grown on irrigated or rainfed land and livestock can be grazed, fed on grain or fodder, or fed crop residues and wastes. In the scenarios, food demand is calculated first. Then the means of production is adjusted to match demand, management practices, and constraints, such as land use and water

4.1. Demand for Agricultural Products

Agricultural products are grouped into seven aggregate categories: wheat and coarse grains, rice, other crops, ruminant meat, non-ruminant meat, milk, and fish. In general, demand for agricultural products increases with income, although demand has begun to level out in OECD regions. In *Conventional Development*, we assume that North America and Western Europe maintain the relatively high demand seen in the base year: 3600 and 3400 kcal/cap/day, respectively. In contrast, Pacific OECD currently has a lower demand at 2800 kcal/cap/day. We assume this increases gradually to 3200 kcal/cap/day by 2100, which represents a balance of cultural convergence and persistence. In *Policy Reform*, policy changes to reduce food waste in the system are assumed to lower demand in North America and Europe to 3200 kcal/cap/day by 2100. In Pacific OECD there is still an increase in demand, but to a lower level of 3100 kcal/cap/day by 2050. For non-OECD regions, *Conventional Development* and *Policy Reform* both assume that demand asymptotically approaches 3500 kcal/cap/day. With respect to fraction of demand from animal products, both scenarios assume that regions asymptotically approach 30%.

4.2. Agricultural Practices

Changes in agricultural practices include irrigation, nutrient management, and cropping intensity. In the future, expansion of irrigated area will be constrained by the amount of land suitable for irrigation and water availability. Overall, the potential for expanding irrigated land is quite limited. In *Policy Reform*, this constraint is partially relaxed by slowing the degradation of irrigated lands and improving irrigation technology.

We assume that application of fertilizer is linked to crop yield by 0.1 multiplied by the natural log of yield. In both *Conventional Development* and *Policy Reform*, crop yield and cropping intensity are assumed to continue their historically increasing trajectories. In *Conventional Development*, the implied increase in fertilizer use is met by industrially synthesized fertilizer. *Policy Reform* assumes that a combination of alternatives to industrially synthesized fertilizer and better management practices are able to meet yield increases and significantly reduce pollution from nitrogen and phosphorus in runoff.

4.3. Demand for Forestry Products

Forest products are grouped into three categories: paper and pulp, all other industrial wood products, and biomass. Overall demand for paper and pulp is assumed to grow at the same rate as value added in the pulp and paper industry. Regional biomass fuel requirements grow with energy demand for biomass. In *Conventional Development* the fraction of pulp and paper from recycled fibers increases by 0.2% for every 1% increase in overall pulp production. In *Policy Reform* 80% of pulp and paper is produced from recycled fibers by 2050.

4.4. Land Use Change

One of the most complex constraints on food production is land use, as food production competes with other desirable uses of land. Our scenarios consider 10 types of land use: built environment, cropland, grazing land, commercially exploitable forest, non-commercially exploitable forest, plantations, protected forest, non-forested protected land, barren land, and a residual "other" category. Changes from base year land allocations are regulated by an algorithm that ensures biophysical consistency among various demands for land.

The amount of protected land is designated at the base year and is assumed not to change throughout the scenarios. Change in land dedicated to the built environment is calculated next. Demand for built environment land is estimated by multiplying regional population by a built environment coefficient (ha/cap). Per capita built environment requirements in *Conventional Development* OECD regions are assumed to grow at 0.3% per year, which is half of the historical average in the US. Non-OECD regions converge to region-specific targets. Africa and Latin America converge towards the OECD average built environment per capita as GDP per capita approaches OECD base year average GDP per capita. China+, South and Southeast Asia, Middle East, Eastern Europe, and FSU converge towards the more compact per capita built environment requires of Western Europe. In *Policy Reform*, Western Europe and Pacific OECD remain at base year built environment per capita requirements and North America converges to other OECD region values. Non-OECD regions all converge to Western Europe requirements.

If built environment land requirements exceed the current amount of land allotted, then land is switched from other categories, with a fixed fraction assumed to come from potentially arable land. First, not potentially arable land from pastures is converted, followed by unexploitable forest, barren land, and other land. Next potentially arable land from cropland is converted, followed by pasture and unexploitable forest.

Next, changes in cropland are considered. Cropland may be degraded or restored. If crop production requirements exceed available land, then additional cropland is first satisfied from pasture land, followed by unexploitable forest. Pasture needs are split into potentially and not potentially arable land, the ratio of which remains the same over time. If additional not potentially arable pasture land is needed, then unexploitable forest land is converted first, followed by barren land and then other land. If additional potentially arable pasture land is needed, then unexploitable forest is converted first, followed by other land. Finally, forestry land requirements and change is considered. If more land is needed, exploitable forest land is converted to forest plantations.

5. Water

The analysis of water composes scenarios of water withdrawals in 4 sectors and an assessment of regional water stress.

5.1. Water Stress

Since water supply issues occur at the local instead of regional level, we introduce a measure of water stress that approximates the pressures put on sustainable water resources, the reliability of water supplies, and the ability of society to cope with limited renewable freshwater supplies. The measure is a use-to-resource ratio, which is calculated by dividing withdrawals (minus desalinization and wastewater) by the regional renewable freshwater supply. Note that in using renewable supply instead of total supply, this ratio is a measure of long-term water stress as non-renewable water supply, such as from a deep aquifer, provides only short-term supply.

Following Raskin *et al.* [12], we assume that a ratio less than 0.1, between 0.1 and 0.2, between 0.2 and 0.4, and greater than 0.4 indicates, respectively, no, low, medium, and high stress. To convert ratio values to number of people in water stress, we assume that none of the population is in water stress for a ratio below 0.1. When the ratio is 0.4, 90% of the population is in water stress and 100% of the population is in water stress at a ration 1.0. For ratio values in between these points, population in water stress is linearly interpolated.

5.2. Water Withdrawals

Water withdrawals are developed for the domestic (which includes commercial), energy conversion, industrial, and agricultural sectors. As with our resource demand methods, water withdrawal by sector is computed by an activity or service level variable and an intensity variable. Activity and service level variables have been described in previous sections. Intensity variables in *Conventional Development* are usually extrapolations of past trends.

Water withdrawal for *Policy Reform* is informed by translating a water stress target (in terms of number of people) to the maximum sustainable withdrawal rate. This is accomplished by converting the water stress target to percentage of population under water stress, which is in turn related to the use-to-resource ration discussed in Supplementary Section 5.1. Given that we have an estimate of the renewable freshwater supply, maximum withdrawal rate can be found.

For each sector a "best practices" level of water withdrawal is calculated that represents the physical limit of water use reduction practices. *Policy Reform* water withdrawals are computed by first comparing *Conventional Development* withdrawals to the maximum withdrawal rate. If this rate is below the maximum rate, then *Policy Reform* rates are set equal to those from *Conventional Development*. If the *Conventional Development* withdrawal rate is greater than the maximum rate, then *Policy Reform* withdrawals rate are adjusted to equal the maximum withdrawal rate. The resulting rate as a fraction of the best practices is called the level of effort. To further constrain reform efforts, we assume that in 2025, *Policy Reform* may only approach 75% level of effort.

Domestic water use is linked to regional population. North American and Pacific OECD domestic water intensity in the *Conventional Development* scenario is assumed to decrease by 20% over the century. Western Europe domestic water intensity, which is already at significantly lower levels, is assumed to remain constant. Non-OECD domestic water intensities are assumed to converge to the average OECD level.

Water use for energy conversion is linked to thermoelectric power production. Water intensity in energy conversion has greatly improved over time as cooling systems have become less water-intensive and power plant efficiencies have increased. We assume these improvements continue in the future, with *Conventional Development* water intensities for all regions decreasing by 20% between 2005 and 2025 and by 30% between 2005 and 2050. In *Policy Reform*, the best practice water intensity level is set to the current Pacific OECD level of 0.35 m^3/GJ.

Water use for manufacturing is linked to sub-sector value added as outlined in Supplementary Section 2.3. For *Conventional Development*, OECD intensity of water use per dollar value-added is assumed to decline by 20% from 2005 levels by 2050 and by 40% by 2100. Manufacturing water intensity in non-OECD regions is assumed to converge toward the OECD average as incomes rise. Best practice water intensity levels are based on current Israeli levels, which are considered to be very efficient. We assume these current levels will drop 20% due to improvements in management and technology.

Water use in agriculture stems from irrigation, which is measured by the area of irrigated cropland. Irrigation intensity is determined by

$$\text{irrigation intensity} = \text{efficiency factor}\left(\frac{\text{yield}}{\text{crop per drop}}\right) \tag{S2}$$

Here, the efficiency factor is the ratio of the water applied to the water that reaches the plant and crop per drop is the amount of crop produced per volume of water that reaches the plant. Yields have already been determined in Supplementary Section 4.2. In *Conventional Development* the efficiency factor is left at base year levels and crop per drop is assumed to increase 0.75% for every 1.0% increase in crop yield. Best practice efficiency factors are informed by regional estimates reported in [13].

6. Climate Change

PoleStar computes annual and cumulative CO_2 emissions (*cumlE*) for each scenario. We estimate functional relationships between CO_2 concentration (C_{atm}) and cumulative CO_2 emissions using data from 11 climate scenarios provided with the MAGICC carbon cycle climate system model [14,15]. Each of these climate scenarios specifies annual CO_2 emissions (from which cumulative CO_2 emissions are determined) and the atmospheric CO_2 concentration that results from using the specified emissions as input into the MAGICC model. We use the resulting fitted equations to estimate the CO_2 concentration for *Conventional Development*. *Policy Reform* and *Great Transition* were both designed to reach 350 ppm CO_2 in 2100, as discussed in Supplementary Section 3.1.

For year 2025, we find that a power equation best fits the data with $R^2 = 1$:

$$C_{atm}\left[t=2025\right]=85.16\cdot\left(cumlE\left[t=2025\right]\right)^{0.2777} \tag{S3}$$

For year 2050, a linear equation best fits the data with $R^2 = 0.998$:

$$C_{atm}\left[t=2050\right]=0.3456\cdot cumlE\left[t=2050\right]+278.4 \tag{S4}$$

For year 2100, a quadratic equation best fits the data with $R^2 = 0.999$:

$$C_{atm}\,[t=2100] = 4.370\times10^{-5}\cdot(cumlE\,[t=2100])^2 + 0.2298\cdot cumlE\,[t=2100] + 278.0 \tag{S5}$$

7. Ocean Acidification

For ocean acidification, a simple relationship between seawater CO_2 concentration (C_{sea}) and aragonite saturation (Ω_{arag}) is derived by fitting a curve to more complex modeling results taken from the literature [16]. Aragonite is a carbonate mineral that many marine species secrete in order to produce shells. As seawater CO_2 concentration increases, ocean water becomes more acidic, which lowers oceanic aragonite concentrations. Lower aragonite concentration in seawater creates corrosive conditions for marine species' shells, which can severely impact marine ecosystems.

To relate seawater CO_2 concentration to atmospheric CO_2 concentration we make the assumption that the seawater CO_2 concentrations reported in Table 1 of Guinotte and Fabry [16] can be approximated by the atmospheric CO_2 concentrations estimated by the MAGICC model. This is a reasonable first-order approximation because the rate of gas exchange between the ocean surface and the atmosphere is fast enough that the difference between near-surface and atmospheric CO_2 concentration (by volume) is relatively small—about 8 ppm—compared to the expected changes in future CO_2 concentrations [17]. Combining this assumption with the data from Guinotte and Fabry yields ($R^2 = 0.998$):

$$\Omega_{arag,t}\cong 79.94\cdot C_{atm,t}^{-0.5610} \tag{S6}$$

8. Nitrogen

The measure of the nitrogen cycle planetary boundary is the amount of N_2 removed from the atmosphere for human use. This has three components: (1) industrial fixation of atmospheric N_2 to ammonia, (2) agricultural fixation of atmospheric N_2 via cultivation of leguminous crops and wetland rice, and (3) fossil fuel combustion.

8.1. Industrial N_2 Fixation

Based on the literature [18,19] we estimate that 23 Mt N were used globally for chemical production other than fertilizer in year 2005. This accounted for 20% of industrial nitrogen fixation with the balance belonging to fertilizer production, which yields 92 Mt N used to produce fertilizer in 2005. Global fertilizer use in year 2005 was about 87,510 kt. Therefore, a first-order estimate of the industrial N_2 fixation for fertilizer is 1.05 Mt N per Mt of fertilizer used. Assuming this ratio and that fertilizer production continues to account for 80% of global industrial N_2 fixation, then industrial N_2 fixation for region *i* is:

$$INF_{i,t} = \frac{1.05 \cdot fert_{i,t}}{0.8} \tag{S7}$$

where fert is the amount of fertilizer used.

8.2. Agricultural N_2 Fixation

Data on production for all significant leguminous crops is available from FAOSTAT [20], which includes an aggregate pulse category (chick peas, lentils, and others), carob, green beans, green peas, groundnuts (peanuts), and soybeans. In 1961, the fraction of total crop production from leguminous crops was 3.5% and the fraction of leguminous crop production attributed to soybeans was 30%. By 2009, these quantities had increased to 4.5 and 66%, respectively. Thus, as a fraction of total crop production, leguminous crops have increased in production over the past 60 years, mainly due to increases in production of soybeans.

According to FAOSTAT data, most soybeans (84% in year 2005) are processed by crushing. Of this fraction, 19% of the total mass is extracted in the form of soybean oil, while the balance (81%) is ground into soy meal, which is used as animal feed. In addition to soy meal, 4% of total soybean production was used directly as feed. Thus in year 2005, 73% of total global soybean production (156,143 kt) was used in animal feed.

PoleStar classifies crop production used for feed in three categories: wheat + coarse grains, rice, and other crops. Soybeans and other legumes are classified as other crops. In year 2005, 243,851 kt of other crops were used globally for feed, meaning that approximately 64% of this category is composed of soy-based feed. We assume that this fraction remains constant over time and applies across all regions. Since 1980, the fraction of world crop production allotted to other legumes has remained at about 1.7%. We also assume that this fraction remains constant.

Based on the literature [18,19], we estimate that in year 2005, cultivation-induced biological nitrogen fixation (C-BNF) was about 40 Mt N. Given that 328 Mt of leguminous crops were produced globally in year 2005, then ratio of C-BNF to leguminous crop production is 0.12 Mt N per Mt of leguminous crop produced. As a first-order approximation, we assume that this ratio holds in the future even though the fraction of soybeans in total leguminous crop production will likely increase due to greater levels of meat consumption.

Combining the above assumptions yields the final expression for C-BNF in region *i*,

$$CBNF_{i,t} = 0.12\left(\frac{0.64}{0.73} \cdot FOC_{i,t} + 0.017 \cdot TC_{i,t}\right) \tag{S8}$$

where FOC is the feed requirement provided by other crops and TC is total crop production.

8.3. Fossil Fuel Combustion

To estimate the contribution to nitrogen fixation from fossil fuel combustion, we apply emissions factors from Table 1-8 for N_2O and Table 1-9 for NO_x from the IPCC Guidelines for National Greenhouse Gas Emissions Inventories Reference Manual [21] to the fossil fuel use variables in PoleStar. We estimate the level of NO_x controls by taking the level of N fixation from fossil fuel combustion reported in Rockström [4] and dividing into the base-year NO_x emissions calculated from emissions factors. This yields a base year fraction of uncontrolled emissions of 0.485. As a baseline, we assume this fraction holds steady over time.

8.4. Management of Reactive Nitrogen

Over the course of the 21st century, the pathways of inert nitrogen from the atmosphere to reactive nitrogen change quite dramatically. Even though the planetary boundary is specified as nitrogen removed from the atmosphere, the pathway taken from inert to reactive nitrogen has important implications for nitrogen management and ultimate transport to the environment. At the base year of 2005, 63% of fixed nitrogen is fixed by industrial processes, of which 80% goes to fertilizer. By 2100 in *Conventional Development*, 49%, 33%, and 18% of nitrogen is fixed through industrial processes, in leguminous crops, and through energy production. In contrast, nitrogen fixation through industrial processes is reduced to 20% and 26% in *Policy Reform* and *Great Transition*, respectively, with almost the entire balance of nitrogen fixed into leguminous crops. Thus although the overall flow of nitrogen in these scenarios at 2100 (178 and 108 Mt N) is larger than the planetary boundary for nitrogen fixation, the amount of reactive nitrogen in a form that may easily enter the environment is much smaller. As a result, keeping the flow of reactive nitrogen into the environment below its planetary boundary is well within the capabilities of management and control technologies, such as improved management of soil and runoff water, and improved treatment of waste and storm water. We therefore assume that in *Policy Reform* and *Great Transition*, society deploys the strategies necessary to not exceed 35 Mt of reactive N entering the environment.

9. Phosphorus

The key stressor here is the quantity of phosphorous (P) inflow to oceans. The primary source is the P lost from fertilizer applied to cropland. According to Rockström *et al.* [4], in the year 2000, 20 Mt P was extracted for human use (almost entirely for fertilizer), 10.5 Mt P was lost from the worlds cropland, and 9 Mt P was added to the world's oceans above the background input of 1.1 Mt P.

The computational strategy is to link P input to oceans to the mass of fertilizer used (*fert*; in units of kt N) as computed in PoleStar. This requires the derivation of two relationships: (i) the ratio of P consumed in fertilizer to P inflow to the ocean, which we label the inflow ratio, and (ii) the ratio of

P used in fertilizer to N used in fertilizer, which we label the nutrient ratio. N fertilizer used, the inflow ratio, and the nutrient ratio relate to P input to oceans in region *i* by:

$$P_{i,t} = (inflow\ ratio) \cdot (nutrient\ ratio) \cdot fert_{i,t} \tag{S9}$$

To account for extracted P being used in products other than fertilizer, we first convert the P extracted for human use (20 Mt P) from year 2000 to P consumed in fertilizer. From 2002–2008 global-level data [22] on fertilizer production and use, we estimate the average ratio of P consumed to P extracted to be 0.945. Applying this ratio to 20 Mt P extracted for human use yields an approximation of P consumed in fertilizer in year 2000 of 19 Mt P. The inflow ratio is calculated by dividing year 2000 P inflow to the ocean (9 Mt P) by P consumed in fertilizer, yielding a value of 0.48.

The nutrient ratio is estimated from year 2005 data [22] on global production of N and P fertilizers, resulting in a nutrient ratio of 0.18 kt P per kt N. As a first-order approximation, we assume that the inflow and nutrient ratios remain constant across regions and over time.

10. Rate of Biodiversity Loss

The base year rate of biodiversity loss, 100 extinctions per million species-years (E/MSY), is taken from Rockström *et al.* [4]. Under the *Conventional Development* scenario, we assume that the rate of biodiversity loss will increase to 1000 E/MSY by 2100, which is line with more detailed analysis of biodiversity loss under a business-as-usual scenario [23]. Under the *Policy Reform* and *Great Transition* scenarios, we assume that concerted and sustained international efforts to preserve habitats and conserve biodiversity lead to a fundamental transformation of land use practices that, along with mitigation of climate change, reduces the rate of biodiversity loss to 10 E/MSY by 2100. This target is at the low end of biodiversity scenarios [24].

References

1. Raskin, P.D.; Electris, C.; Rosen, R.A. The century ahead: Searching for sustainability. *Sustainability* **2010**, *2*, 2626–2651.
2. Electris, C.; Rosen, R.A.; Raskin, P.D. *The Century Ahead: Four Global Scenarios*; Tellus Institute: Boston, MA, USA, 2011.
3. Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S., III; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; *et al.* A safe operating space for humanity. *Nature* **2009**, *461*, 472–475.
4. Rockstrom, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S.I.; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; *et al*. Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc*. **2009**, *14*, Article 32.
5. United Nations (UN). *Population, Resources, Environment, and Development: The 2005 Revision*; UN: New York, NY, USA, 2006.
6. Organization for Economic Cooperation and Development (OECD). *Environmental Data Compendium Online Datasets*; OECD: Paris, France, 2008.
7. World Bank. *Global Economic Prospects*; World Bank: Washington, DC, USA, 2008.
8. World Bank. *World Bank Country Statistics*; World Bank: Washington, DC, USA, 2008.

9. International Energy Agency (IEA). *World Energy Outlook 2007: China and India Insights*; IEA: Paris, France, 2007.
10. International Institute for Applied Systems Analysis (IIASA). *Greenhouse Gas Initiative Version 1.0.9*; IIASA: Laxenburg, Austria, 2006.
11. International Energy Agency and World Business Council on Sustainable Development (IEA/WBCSD). *Sustainability Mobility Project Model Documentation and Reference Case Projection*; IEA/WBCSD: Paris, France, 2004.
12. Raskin, P.; Gleick, P.H.; Kirshen, P.; Pontius, R.G., Jr.; Strzepek, K. *Water Futures: Assessment of Long-Range Patterns and Problems*; Stockholm Environment Institute: Stockholm, Sweden, 1997.
13. Seckler, D.; Barker, R.; Amarasinghe, U. Waster scarcity in the twenty-first century. *Int. J. Water Resour. Dev*. **1999**, 15, 29–42.
14. Meinshausen, M.; Raper, S.C.B.; Wigley, T.M.L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. *Atmos. Chem. Phys*. **2011**, *11*, 1417–1456.
15. Meinshausen, M.; Wigley, T.M.L.; Raper, S.C.B. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 2: Applications. *Atmos. Chem. Phys*. **2011**, *11*, 1457–1471.
16. Guinotte, J.M.; Fabry, V.J. Ocean acidification and its potential effects on marine ecosystems. *Ann. N. Y. Acad. Sci*. **2008**, *1134*, 320–342.
17. Siegenthaler, U.; Sarmiento, J.L. Atmospheric carbon dioxide and the ocean. *Nature* **1993**, *365*, 119–125.
18. Galloway, J.N.; Cowling, E.B. Reactive nitrogen and the world: 200 years of change. *Ambio* **2002**, *31*, 64–71.
19. Gruber, N.; Galloway, J.N. An Earth-system perspective of the global nitrogen cycle. *Nature* **2008**, *451*, 293–296.
20. United Nations Food and Agricultural Organization (FAO). *FAOSTAT Online Database*; FAO: Rome, Italy, 2011.
21. Intergovernmental Panel on Climate Change (IPCC). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual*; Cambridge University Press: Cambridge, UK, 1996.
22. United Nations Food and Agricultural Organization (FAO). *ResourceSTAT Online Database*; FAO: Rome, Italy, 2011.
23. Mace, G.; Masundire, H.; Baillie, J. Biodiversity. In *Ecosystems and Human Wellbeing: Current State and Trends*; Hassan, H., Scholes, R., Ash, N.J., Eds.; Island Press: Washington, DC, USA, 2005.
24. Pereira, H.M.; Leadley, P.W.; Proença, V.; Alkemade, R.; Scharlemann, J.W.; Fernandez-Manjarrés, J.F.; Araújo, M.B.; Balvanera, P.; Biggs, R.; Cheung, W.W.L.; *et al.* Scenarios for global biodiversity in the 21st century. *Science* **2010**, *330*, 1496–1501.