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Tracking sustainable development with a national barometer for South Africa using a downscaled "safe and just space" framework

Megan J. Cole[a,b,1], Richard M. Bailey[a], and Mark G. New[a,b]

[a]School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, United Kingdom; and [b]African Climate and Development Initiative, University of Cape Town, Rondebosch 7000, South Africa

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Nations in the 21st century face a complex mix of environmental and social challenges, as highlighted by the on-going Sustainable Development Goals process. The "planetary boundaries" concept [Rockström J, et al. (2009) *Nature* 461(7263):472–475], and its extension through the addition of social well-being indicators to create a framework for "safe and just" inclusive sustainable development [Raworth K (2012) *Nature Climate Change* 2(4):225–226], have received considerable attention in science and policy circles. As the chief aim of this framework is to influence public policy, and this happens largely at the national level, we assess whether it can be used at the national scale, using South Africa as a test case. We developed a decision-based methodology for downscaling the framework and created a national "barometer" for South Africa, combining 20 indicators and boundaries for environmental stress and social deprivation. We find that it is possible to maintain the original design and concept of the framework while making it meaningful in the national context, raising new questions and identifying priority areas for action. Our results show that South Africa has exceeded its environmental boundaries for biodiversity loss, marine harvesting, freshwater use, and climate change, and social deprivation is most severe in the areas of safety, income, and employment. Trends since 1994 show improvement in nearly all social indicators, but progression toward or over boundaries for most environmental indicators. The barometer shows that achieving inclusive sustainable development in South Africa requires national and global action on multiple fronts, and careful consideration of the interplay between different environmental domains and development strategies.

sustainable development | South Africa | planetary boundaries | social deprivation | sustainable development goals

Human impact on the Earth's biophysical processes and resources is a global concern. It is seen by many as a new geological era, the Anthropocene (1), with natural resource consumption accelerating in the past 50 y—food, freshwater, and fossil fuel use have more than tripled (2)—and these trends are likely to continue as global population grows to 9.6 billion by 2050 (3). This concern has led to international treaties that seek to address global environmental challenges through negotiation and agreement among the nations of the world, such as the United Nations (UN) Convention for the Protection of the Ozone Layer, the UN Convention on Biological Diversity (UNCBD), and the UN Framework Convention on Climate Change (UNFCCC). This impact has also led to the proliferation of sustainable development indicators (SDIs). The outcome of the 1992 UN Conference on Environment and Development, Agenda 21, calls for SDIs to "provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development system" (4). Over 900 SDI initiatives have been undertaken to date (5), in recognition of the fact that indicators provide a quantitative and rational basis for decision making (6), simplify a complex reality to a manageable level (7), create a body of knowledge and comparable data for policy applications, measure progress (8), and allow the public to evaluate society and its leaders (9). Individual indices, such as the Human Development Index and the Ecological Footprint, have been used to compare countries, and sustainability frameworks, such as Ostrom's framework for social-ecological systems (10) and the "ecosystems approach" adopted by the UNCBD (11), have been developed to better understand the relationships between social and ecological systems.

In 2009 a new conceptual framework, "planetary boundaries," was proposed by Rockström et al. (12, 13) as "a bid to reform environmental governance at multiple scales" (14). The planetary boundaries are an estimated "safe distance" from thresholds associated with nine global environmental change processes that, when crossed, will take humanity into unchartered environmental territory (13). The nine processes (or dimensions) are: climate change, ocean acidification, freshwater use, land-use change, biodiversity loss, nutrient cycles (nitrogen and phosphorous), ozone depletion, atmospheric aerosol loading, and chemical pollution. Three of these global boundaries (climate change, biodiversity loss, and nitrogen fixation) have been transgressed and several others are in danger of being exceeded. Rockstrom et al. proposed there should be a global goal to stay within the "safe operating space for humanity" defined by these boundaries.

Despite a mixed reaction from the academic community, who have raised concerns about the existence of global tipping points for some of the dimensions (15–17) and the specific metrics used (18–23), the planetary boundaries concept has been used in proposals for defining the UN Sustainable Development Goals (SDGs) (24–26). The SDGs will guide the international sus-

Significance

We have downscaled planetary boundaries and applied the "safe and just space for humanity" framework at the national scale, for the first time, creating a "barometer" for inclusive sustainable development for South Africa. The barometer presents the state and trajectory of a broad but manageable set of indicators for environmental and social priorities, and highlights the country's proximity to environmental boundaries and the distance from eradication of social deprivation. This creates a monitoring and communication tool for national government for thinking in an integrated manner about environmental and social-development issues. Our case study provides insight into the challenges and complexities of developing indicators and targets for the proposed global Sustainable Development Goals that that are globally, regionally, and nationally relevant.

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[1]To whom correspondence should be addressed. Email: megan.cole@ouce.ox.ac.uk.

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tainable development agenda after 2015 and they represent an opportunity for science to inform policy making (27–29), for the UN to implement the lessons from the Millennium Development Goals (MDGs) and to expand them to include all countries, and for greater integration of environmental and social metrics in decision-making. In this context, the planetary boundaries concept was extended by Raworth (30, 31) to include a set of 11 social dimensions, defining "a social foundation" below which exists unacceptable human deprivation. This approach highlighted the notion that access to the benefits of natural resources is also of global concern, and Raworth (30) argued that ending current global deprivation could be achieved with a minimal impact on the planetary boundaries. Raworth reframed Rockström et al.'s (12, 13) planetary boundaries concept as a "safe and just space for humanity"; this new framework brought together the dual objectives of poverty eradication and environmental sustainability as socio-economic priorities (30).

Raworth's safe and just space (SJS) framework has gained interest from the UN General Assembly (32), policy think tanks (e.g., ref. 33), and development agencies (e.g., ref. 34) because it provides a platform for integrated analysis and debate about global goals. The framework appears in the Worldwatch Institute's latest State of the World report (35) and Griggs et al. (25) have since developed a similar framework to reframe the UN paradigm of three pillars of sustainable development as a nested concept.

However, social and environmental concerns are intrinsically scale-dependent and need to take local circumstances into account if they are to be acted upon by national governments, which are ultimately responsible for taking action. The downscaling of the SJS to subglobal spatial scales, with heterogeneity of biophysical and social conditions and the instruments of governance, is not straightforward. The particular challenges for the biophysical dimensions are highlighted by Nykvist et al. (36), who assessed national "environmental performance" on four planetary boundaries (climate change, water, land, and nitrogen) for 60 countries. Because the chief aim of the SJS is to influence public policy, and this happens largely at the national level, our objective in this report is to assess whether the SJS concept can be used at the national scale, using South Africa as a test case.

In this report we first review the SJS concept and explore how it might be applied at the national scale. We then present a decision-based methodology and results for our case study on South Africa. Finally, we discuss the applicability of the tool in South Africa, the local-regional-global links and the SDGs, and the data limitations, scientific challenges, and further research needs.

A Safe Operating Space

The focus of the planetary boundaries concept is staying within the safe operating space in which human civilizations have developed: that is, the relatively stable biophysical conditions of the Holocene (the past approximately10,000 y). The concept combines global environmental change and resilience science, which focuses on understanding the effects of and response to abrupt change in social-ecological systems (SES) in the context of sustainable development (37). Resilience can be defined as the "capacity of a SES to continually change and adapt yet remain within critical thresholds" (38). Crossing a planetary boundary represents a risk of moving from the current known state to a new, unknown, and possibly dangerous state. These boundaries could be (but are not necessarily) critical thresholds or tipping points beyond which systemic planetary-scale regime shifts [the Earth system processes involved being referred to as "tipping elements" (39)] may occur or dangerous levels of environmental change may be reached. Critical transitions are often referred to as abrupt (in that the rate of response is considerably greater than the rate at which the driving factors change), but many unfold slowly in absolute terms after a threshold is transgressed (40). An important potential property of such shifts is "hysteresis," which describes the need to reduce forcing back beyond threshold-crossing levels to return the system to its previous state (41).

Barnosky et al. (42) identified global-scale critical transitions in the Earth's past and pointed out that the current global-scale forcing mechanisms, such as resource consumption, far exceed the rate and magnitude of the most recent global-scale state shift of the last glacial–interglacial transition. The authors also argued that local-scale drivers have accumulated to the extent that global-scale drivers have emerged; 38% of Earth's terrestrial surface has been converted to agricultural land (43), CO_2 concentrations are 35% higher than preindustrial times (44), rates of nitrogen fixation have more than doubled (45), and ocean acidity has increased by a pH of 0.05 (46).

For the planetary boundaries, Rockström et al. (12, 13) distinguish between thresholds driven by systemic global-scale processes impacting subsystems "top-down," such as climate change, and thresholds that may arise at the local scale that become a global concern when aggregated, impacting the global system "bottom-up," such as freshwater use. The authors (12) defined 10 indicators to measure the state of their nine dimensions, noting that determining a safe boundary involves "normative judgements of how societies choose to deal with risk and uncertainty" (12, 13). As Cornell (47) pointed out, these indicators actually comprise a mix of system properties, which results in conceptual tensions. Nykvist et al. (36) used the driving forces-pressures-states-impact-response framework to categorize the dimensions as one driver (nitrogen), three pressures (phosphorous loading, freshwater use, chemical pollution), five states (ozone depletion, climate change, ocean acidification, aerosol loading, land-use change), and one impact (biodiversity loss). Each indicator has an associated (safe) boundary, defined using the precautionary principle given the notorious difficultly in predicting where critical thresholds lie in natural systems. Hughes et al. (48) have subsequently defined the boundaries as safe levels of drivers of environmental change. Because all drivers of environmental change are essentially driven locally, boundaries could be determined at scales other than global, including the national scale, which is the focus of the present work.

A Just Space

In Raworth's (30) SJS framework, the term "just" describes the avoidance of unacceptable human deprivation and extreme global inequality in the context of human rights. The term focuses on the opportunities component of justice and supports Rawl's "Difference Principle" (which promotes propoor distribution of social and economic benefits) as described by Sen (49). The SJS highlights the multidimensional nature of deprivation, thus it builds on work by Townsend (who pioneered the relative deprivation approach) and Sen's capabilities approach (50). Townsend defined deprivation as "a state of observable and demonstrable disadvantage relative to the local community or the wider society" (51), and thus the local, national, and global contexts are important when selecting deprivation indicators. International agreements for human needs are more clearly articulated and institutionalized than environmental needs (52) and date back to the 1948 Universal Declaration of Human Rights. The MDGs, which represent voluntary time-bound targets that developing countries are evaluated on until 2015 (53), have created global awareness for extreme poverty and mobilized funds and established new organizations to promote basic human rights (54).

Raworth's (30) global "social foundation" has 11 dimensions of well-being: food security, energy, water and sanitation, education, health care, income, jobs, voice, resilience, social equity, and sex inequality. These dimensions were drawn from the national social development priorities in 80 government submissions to the UN Rio+20 Conference in 2012, and therefore are both global and national in nature. The dimensions are measured with deprivation indicators largely taken from the MDGs, although Raworth specifically selected indicators that measure the percentage of the total population who are deprived. The boundary for each indicator is argued to be zero deprivation, based on human rights, thus the selection of the indicator determines the just boundary of unacceptable deprivation. As the social foundation measures the well-being of a population, it can be scaled to any level, including the national scale, which we will show in this report.

National Case Study: South Africa

We chose South Africa as our case study for testing the SJS framework at the national scale for three reasons. First, it has large, good quality environmental and social datasets and established national research institutes, which enables rigorous analysis and debate. Second, as the largest economy in Africa (55), it is influential both on the continent and globally as part of the BRICS group of emerging economies (Brazil, Russia, India, China, and South Africa), and research is more likely to be shared through South–South cooperation. Third, it is ecologically megadiverse (56), has widespread poverty and extreme inequality (57), and this heterogeneity will provide a stringent test for the framework.

South Africa is one of the youngest democracies in the world, with elections in 1994 marking the end of white minority rule. Twenty years on, its planned development pathway is described in the "National Development Plan" (58), which has two overarching goals: to eliminate income poverty and to reduce inequality by 2030. The National Climate Change Response Strategy has been a catalyst for mainstreaming environmental issues in South Africa and is supported by the National Strategy for Sustainable Development (59), which promotes stewardship of limited natural resources, and the Green Economy Accord (60), which focuses on technology and job creation to meet development goals in a sustainable way. South Africa is a signatory to a number of international environmental treaties, including the Montreal Protocol, the UNCBD and the UNFCCC.

Summary of Methodology

To apply the SJS framework at the national scale, we developed a decision-based methodology (Fig. 1) to assess the environmental and social dimensions, indicators and boundaries in a repeatable and consistent way. Details are provided in the *Supporting Information* (sections A and B) and are summarized here. Our criteria for selecting the dimensions were: "Is this relevant at the national scale?" and "Does the set of dimensions include the main environmental and social concerns in South Africa?" Our criteria for indicator selection were: "Is the indicator the best available direct measure of that dimension?", "Are there sufficient reliable data that are measured on a regular basis?" and "Can a national boundary be determined?" If the existing dimension or indicator did not meet the criteria then it was removed or replaced with a more appropriate national-scale choice. The data were taken from relevant national databases and reports, international databases, and academic papers, and we sought expert judgment through semistructured interviews with 43 South African experts from national, provincial, and metropolitan government, national research institutes, universities, and international nongovernment organizations (*Supporting Information*, section C). The experts were identified based on their experience, academic or professional credibility, and involvement in national policy-making, as well as through recommendations by other experts.

Environmental Stress. We used the Environmental Sustainability Indicators technical report (61) published by the Department of Environmental Affairs (DEA) as a starting point for our analysis because it was developed based on a comprehensive review of potential national indicators, Yale's Environmental Performance Index, and the driving forces-pressures-states-impact-response framework. We then reviewed relevant national policies, reports, and assessments, as well as academic literature to identify the most suitable dimensions, indicators, and boundaries. Although we changed only two of Rockström et al.'s (12, 13) global dimensions—ocean acidification became marine harvesting and aerosol loading became air pollution—we adjusted all of the indicators and boundaries to suit national circumstances. The current status is a national average or aggregation of local data

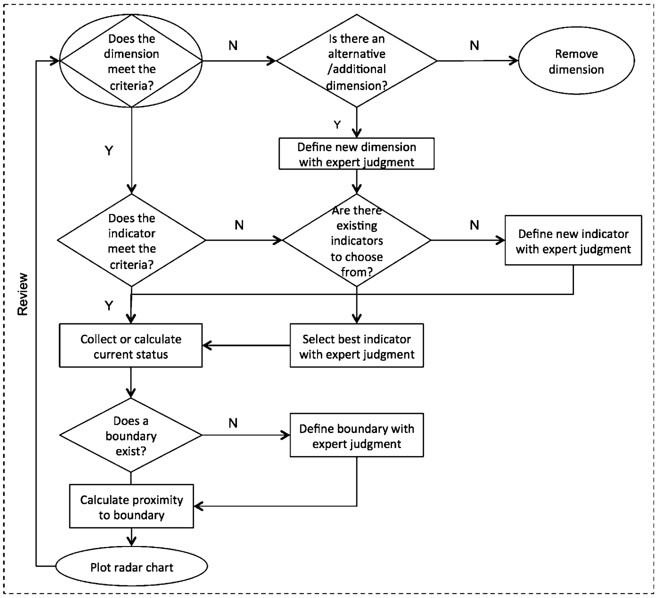

Fig. 1. Decision-based methodology for selecting national dimensions, indicators and boundaries for the national barometer for inclusive sustainable development.

points and in most cases this calculation had already been done in the source documents. In three cases (phosphorous, biodiversity loss, and marine harvesting) no preexisting calculation was available and was performed by the authors (details in *Supporting Information*). Environmental baselines were not used because of very limited information on preindustrial conditions.

Determining national environmental boundaries was challenging because of the novelty of defining local equivalents to planetary boundaries, the uncertainty in the data, and because ideally safe boundaries should combine expert scientific opinion and societal acceptance. We identified three types of environmental boundaries, which arise from differences in the nature of the biophysical dimensions. The first type (Type A) is used for dimensions that are inherently global in nature: climate change and ozone depletion. Boundaries are based on global biophysical thresholds but necessarily incorporate some measure of multilateral political agreement to ensure that they take differences in national capability and responsibility into account. They can either be internationally agreed targets that set out national actions (Type A1), which is the case for ozone depletion, or national interpretations of a globally accepted threshold in the absence of agreed targets (Type A2), which is the case for climate change. The second type of boundary (Type B) represents national limits for land and freshwater resources. These can be purely natural limits (Type B1) or natural limits combined with human intervention, such as infrastructure, technology, and imports (Type B2). The third type (Type C) combines local biophysical thresholds and a national safe boundary based on established research and expert judgment. These can be based on a single local biophysical threshold (Type C1), such as phosphorous concentrations in freshwater, or aggregations of biophysical thresholds of different components (Type C2), such as ecosystem types for biodiversity loss.

Type A: Global boundaries—climate change and ozone depletion. Global CO_2 and stratospheric ozone concentrations cannot be disaggregated to the national scale; however, emissions are reported at the national scale. The Montreal Protocol contains internationally agreed phasing out schedules for the production and consumption of 96 ozone-depleting (ODP) substances. South Africa has phased out all ODP substances except hydrochlorofluorocarbons (HCFCs) (62), producing 262 ODPt in 2013 (63). Our indicator "Annual HCFC consumption," has a boundary based on the government's commitment to freeze HCFC consumption and limit it to the baseline of 370 ODPt by 2013 (64). South Africa is 29% below its ODP boundary. Although no internationally agreed CO_2 emissions targets exist, South Africa has committed to reduce its emissions by 30–40% by 2050 from 2003 levels, after peaking at 650 $MtCO_2$ in 2020, based on the long-term mitigation scenarios (65). Our indicator, "Annual direct CO_2 emissions," had a status of 461 $MtCO_2$ in 2010 (66) and we based our boundary on the emissions trajectory of the "Required by Science" scenario in the long-term mitigation scenarios, which sets the 2010 target at 451 $MtCO_2$. South Africa exceeds its climate change boundary by 2%.

Type B: National limits—freshwater use and arable land use. Freshwater and land are limited natural resources. We estimated that freshwater use in South Africa was 18,895 $Mm^3 \cdot yr^{-1}$ in 2013 based on the Department of Water Affairs (DWA) Water Authorization and Registration Management System database (67), and used this as our indicator. The DWA (68, 69) calculate that the country has 14,319 $Mm^3 \cdot yr^{-1}$ total available yield for human use, which accounts for the "ecological reserve," the minimum in stream flow needed to support ecological functioning (70), and assurance of supply. We used this as our safe boundary, which was exceeded by 34%, showing that human freshwater use is given priority over the ecological reserve. Although Rockström et al. (12, 13) focused on land-use change, land cover in South Africa has been stable since 1961 (71). Instead we used "rain-fed arable land converted to cropland" (11.9% in 2005) (72) as our indicator, because South Africa is a largely semiarid country with limited land capable of supporting sustainable crop production. Only 12.1% is classified as rain-fed arable land (73); hence, South Africa is 2% below its land use boundary.

Type C: Local thresholds.

Nutrient cycles. Although nitrogen (N) and phosphorous (P) cycles (essential for food production) are global in scale, the local negative impacts of N and P use pose the main challenge. Eutrophication of freshwater resources is widespread in South Africa and is a national concern (74), with P levels in major reservoirs used as a national indicator. We obtained the latest data from the National Eutrophication Monitoring Program to calculate the current status of 0.098 mg/L in 2013 (75) and used Oberholster and Ashton's (76) critical threshold of 0.10 mg/L P in freshwater as the safe boundary. South Africa is 2% below its P loading boundary. The negative impact on the N cycle in South Africa is largely through N removed from the soil by crop production, despite fertilizers being applied. Maize production uses nearly two-thirds of N (77) and is the staple crop. On average, maize removes 27 kg N from the soil per ton of marketable product (78), thus in 2011/2012 an estimated 102 kg N/ha were removed from the soil. The average maize N application rate (our indicator) was 85 kg N/ha in 2012 (77), indicating that N is not being fully replaced. Rockström et al. (12, 13) identified the overapplication of N as the main global concern and we therefore used Brentrup and Palliere's (79) N use efficiency threshold of 70%, which would translate to an N application rate of 144 kg N/ha for maize in South Africa, as our safe boundary. South Africa is 41% below its N boundary.

Biodiversity loss. Although Rockström et al. (12, 13) used rate of extinction to measure biodiversity loss, the more common indicator is threat of extinction (80). South Africa has undertaken biodiversity assessments since 1980 and in 2004 expanded from a species approach to an ecosystem approach. The 2011 National Biodiversity Assessment (56) reported the ecosystem threat status of 1,763 ecosystem types across six categories: terrestrial, rivers, wetlands, estuaries, coastal and inshore, and offshore. The assessment has four threat status classes: critically endangered, endangered, vulnerable, and least threatened, which incorporate biophysical thresholds. Our indicator, "endangered and critically endangered ecosystems" (37% in 2011), is based on expert opinion and our safe boundary is set at zero (i.e., no ecosystems should be endangered or critically endangered). South Africa exceeds its biodiversity loss boundary by 37%.

Marine harvesting. South Africa is at a very early stage in understanding ocean acidification (81) and the national priority for oceans is the sustainability of marine resources. Although the biodiversity-loss dimension measures marine ecosystem stress, marine harvesting is better measured by the stock status of commercial fisheries. Seventeen fishery sectors and 45 species (or subspecies) are reported in the *Status of South African Marine Fishery Resources 2012* (82), published by the Department of Agriculture, Forestry, and Fisheries (DAFF). Stock status is based on the present biomass level (population size) and the biomass level at which maximum sustainable yield (the target for optimal utilization) is obtained. Our indicator, the "depleted marine fisheries stocks" (45% in 2011), is based on expert judgment and our safe boundary was set at zero (i.e., no marine fisheries are depleted). South Africa exceeds its marine harvesting boundary by 45%.

Air pollution. Aerosol loading, a driver of regional climate change, is not a major concern in South Africa; hence, we changed the dimension to address the national issue of air pollution that affects human health. The government (83) has identified particulate matter (PM_{10}) and SO_2 as problem pollutants at a national scale, and uses the annual average concentration of each to calculate a National Air Quality Indicator. The latest "State of Air" results for 2012 (83) show that PM_{10} is the "greatest national cause for concern in terms of air quality"; hence, we chose PM_{10} concentration as our indicator (46.9 $\mu g/m^3$ in 2012) and the government's PM_{10} threshold of 50 $\mu g/m^3$ as our safe boundary. South Africa is 6% below its air pollution boundary.

Chemical pollution. Similarly to Rockström et al. (12, 13), we did not identify an indicator for this dimension because of the lack of detailed and accurate data. Although South Africa's National Waste Information Baseline Report (84) provides an estimated baseline of over 1.3 Mt of hazardous waste (most of which is landfilled), reporting is voluntary and measurement is incomplete.

Social Deprivation. We used the South African Index of Multiple Deprivation (SAIMD) (85, 86), developed by the national Department of Social Development, the Human Sciences Research Council and Oxford University, and the annual Development Indicators report (87), published by the Presidency, as guidelines for selecting social dimensions and indicators. Both have been informed by international good practice and adapted to South African conditions, and the latter uses aggregate data from a range of sources covering the post-Apartheid period (1994–2013) and supplied most of the data for our barometer. Where it did not contain the required data, we used the latest General Household Survey (GHS) (88). We grouped the dimensions into four domains—basic services, public goods, livelihoods, and living standards—to facilitate the analysis.

We made a number of changes to the original Raworth (30) dimensions. Water and sanitation were separated into individual dimensions; housing, household goods, and safety were added; and resilience, social equity, and sex equality were removed. The experts we consulted saw resilience as a cumulative effect that is dependent on the other dimensions, and therefore an indirect measure. Experts also felt that both social equity and sex inequality should be incorporated into the other dimensions, as they are cross-cutting. The Gini coefficient only measures income inequality and Palma (57) argues that it hides the homogeneity in the middle half of the population and the great heterogeneity between the top 10% and the bottom 40% of the population. As the five indicators of the UN's Sex Inequality Index (89) shows, sex equality could be addressed under the dimensions of health, education, voice, and employment. Ideally, social equity and sex equality should be measured for all of the dimensions of the barometer in future iterations.

We had to choose social boundaries from three types of indicator sets. The first type (Type 1) represents a range of levels of deprivation, which are commonly found in household surveys. For example, choosing "access to piped water within 200 m of the dwelling" rather than "access to piped water in the dwelling" sets a lower boundary. The second type of indicator set (Type 2) is a range of definitions of the same indicator. For example, unemployment can be defined as narrow or broad, which includes discouraged jobseekers. The third type (Type 3) is a diverse set of indicators that represent different aspects of a dimension. For example, material deprivation can be measured by ownership of a range of household goods, such as a refrigerator or television.

Basic Services: Energy Access, Water Access, Sanitation, and Housing

Household access to electricity, piped water, adequate sanitation, and formal housing are all national priorities in South Africa. The GHS records seven levels of access to piped water (based on distance from the dwelling) and eight levels of sanitation. The official water target is "25*l* of potable water per person per day without interruption for more than 7 d within 200m of the dwelling," known as the Reconstruction and Development Programme (RDP) standard (87), and the official sanitation indicator is "access to at least a ventilated pit latrine on site." In 2011/2012, 23.5% of households were deprived of electricity access, 4.5% were deprived of piped water access (RDP standard), 16.6% were deprived of adequate sanitation, and 22.3% were deprived of formal housing.

Public Goods: Education, Health Care, and Voice

There are numerous indicators to choose from when measuring education and health care. We did not use Raworth's (30) MDG indicators because South Africa has achieved the MDG target of universal access to primary school, and there is no data for "access to essential medicines." We chose the SAIMD education indicator "adults with no secondary schooling," the adult illiteracy rate in Development Indicators, which was 19.3% in 2011. The only health care (rather than health) indicator in Development Indicators is "infant immunization coverage" (90.8% in 2011), which we used. Raworth did not define an indicator for voice and experts recommended that voice should measure public participation in decision-making, which does not appear in Development Indicators. We chose to keep the dimension without a national indicator, with further research required.

Livelihoods: Jobs and Income

Poverty, unemployment, and inequality make up South Africa's "triple challenge" (90) and little progress has been seen since 1994. We chose the broad unemployment rate (36.3% in 2012) as our jobs indicator, with the potential for incorporating Raworth's (30) indicator for sex equality, "the employment gap in waged work (excluding agriculture)," if the data becomes available. The official national poverty lines used in South Africa are a food poverty line of R305 per person per month (pppm), a lower-bound poverty line of R416 pppm, and an upper-bound poverty line of R577 pppm in 2011 Rands (87). We used the latter as our income indicator, with a deprivation status of 52.3% in 2011.

Living Standards: Food Security, Household Goods, and Safety

Food security, household goods, and safety are important measures of living standards in South Africa. The only regularly reported national measure of hunger and food access is provided in the GHS, and we used the "households without adequate food" as our food security indicator, with a deprivation status of 23.1% in 2013. The SAIMD uses the indicators "ownership of a refrigerator" and "ownership of a radio and/or landline telephone" to measure material deprivation. We selected the former as our household goods indicator (28.1% in 2013) because radio and landlines are being replaced by cell phones (88). Safety is a complex dimension to measure, as crime statistics do not compare well across jurisdictions, except murder. Our choice of indicator was limited because most indicators measure rates and not proportions of the population; hence, we chose "households that feel unsafe walking alone at night in their area," which was 63.5% in 2011.

Summary of National Barometer Results

The results of our case study are presented as two radar charts, environmental stress in Fig. 2*A* and social deprivation in Fig. 2*B*, which together form a barometer for inclusive sustainable development in South Africa. Four dimensions—climate change, freshwater use, marine harvesting, and biodiversity loss—have exceeded their boundaries by 2%, 34%, 45%, and 37%, respectively; whereas arable land use, phosphorous loading, and air pollution are within 10% of exceeding their boundaries. Depri-

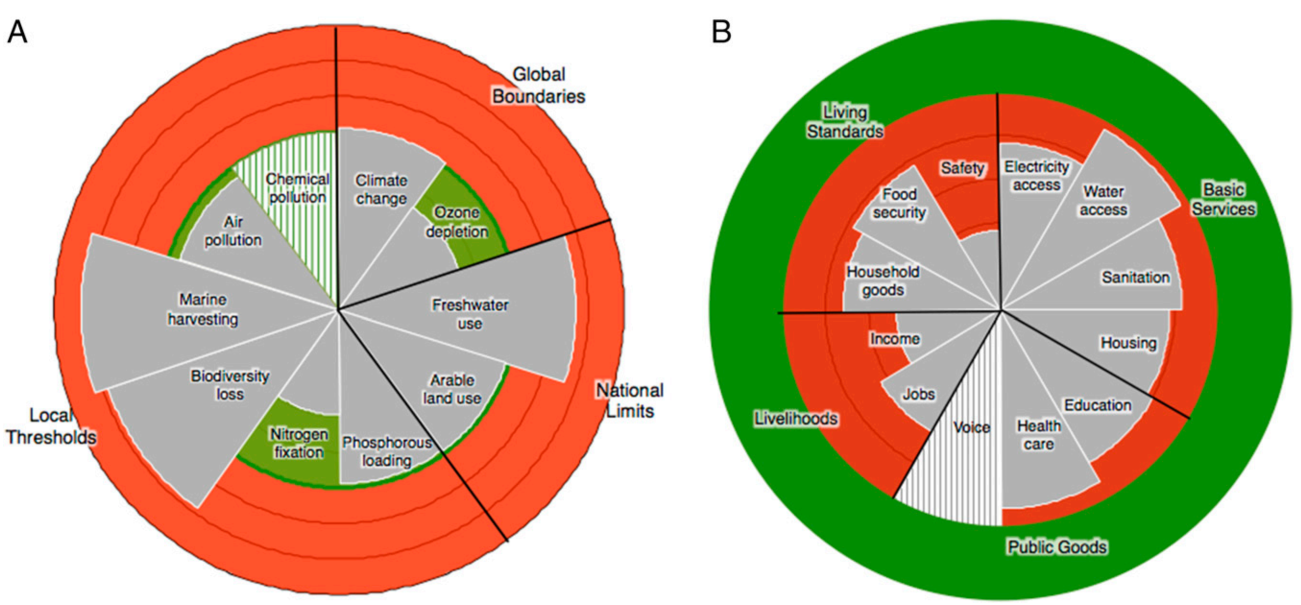

Fig. 2. A national barometer for inclusive sustainable development in South Africa. The green areas represent the safe and just space, beyond which is excessive environmental stress (*A*) and social deprivation (*B*), shown in red. The gray wedges measure the national status for each dimension compared to its boundary as a percentage (0% at the centre, 100% at the boundary), striped wedges show indicators still to be determined, the black dividing lines delineate the three types of environmental boundaries (*A*) or the four social domains (*B*).

vation was most widespread regarding safety (63.5%), income (52.5%), and jobs (36.3%) and least prevalent in basic services, such as electricity and water access. Tables 1 and 2 summarize the details of the dimensions and Fig. 3 shows trends in the indicators since 1990. Trends in environmental stress are difficult to analyze for five dimensions because of multiyear gaps between data points (land, water, biodiversity, nitrogen), a change in methodology (biodiversity), or a recent start to current data reporting (marine harvesting). Climate change and freshwater use have been moving toward or beyond the safe boundary, and recent progress away from the boundary can been seen for ozone depletion and air pollution. Social deprivation has decreased in all dimensions (ranging from 33.8% in water access to 0.8% in food security) except safety and income, where deprivation has increased by 19.5% and 2.0%, respectively. When the barometer's environmental dimensions are framed in terms of national policy applications (Table 3), it is clear that exceeding the environmental boundaries has implications for energy security, food security, water security, job security, and human health; these in turn have the potential to affect the national economy and bilateral trade agreements, highlighting that decisions on socio-economic development need to take environmental boundaries into account.

Discussion

Utility of the Barometer. The main aim of this case study was to evaluate the applicability of the SJS framework at the national level. The findings show that it is possible to maintain the original design and concept of the framework while making it meaningful in the national context. In interviews we conducted, there was consensus among experts that a "national barometer for inclusive sustainable development" could be a very useful tool in South Africa, and this view is supported by the National Development Plan, which recognizes the need to measure and monitor progress on important social and environmental indicators (58). If the barometer were adopted nationally, the indicators would need to be further developed iteratively over time in a dialogue between scientists, civil society, and government (as indicated in the flowchart shown in Fig. 1).

SDIs are not new and are regularly used in "state of environment" or "environment outlook" reports (e.g., ref. 91) and made more visually appealing in maps, such as the Dashboard of Sustainability (92), and quantified metaphors, such as footprints (11). The novelty of the barometer is twofold. First, it presents a visual snapshot of the state of a broad but manageable set of environmental and social indicators in relation to national priorities and realities that goes beyond color-coding or single figures. Our trend charts provide additional information about progress (or lack thereof) over time that aid decision-making, and the combination of environmental and social dimensions highlights the dual nature of the sustainability challenge. Second, it goes beyond being merely a measure of the current status and highlights the country's proximity to its environmental boundaries and its acceptable level of social well-being. It is aimed at a national audience first and an international audience second, to encourage national action, and is science-based. Specific uses identified by the experts interviewed were that it removes intersectoral barriers, communicates a complex set of indicators in a relatively simple way, identifies gaps in the underlying knowledge base, and raises new questions in the discourse on social deprivation and environmental sustainability. Inclusion of

Table 1. Dimensions and indicators of environmental stress for South Africa (using the most recent data available)

		State				Boundary			
Dimension	Indicator	Value	Year	Data source	Level of confidence	Value	Source	Proximity to Boundary (%)	Type* of Boundary
Climate change	Annual direct CO_2 emissions	460.1 $MtCO_2$	2010	UN 2013 (66)	High	451 $MtCO_2$	Scenario Building Team 2007 (65)	102	Type A2
Ozone depletion	Annual HCFC consumption	262.0 ODPt	2013	UN 2014 (63)	High	369.7 OPDt	NEDLAC 2012 (64)	71	Type A1
Freshwater use	Consumption of available freshwater resources	18,895 Mm^3/yr	2013	DWA 2014 (67)	Low	14,196 Mm^3/yr	DWA 2004 (68), 2013 (69)	134	Type B2
Arable land use	Rain-fed arable land converted to cropland	11.9%	2005	Schoeman et al., 2013 (72)	Medium	12.1%	Collett 2013 (73)	98	Type B1
Nutrient cycle	Total phosphorous concentration in dams	0.098 mg/L	2012	DWA 2013 (75)	Medium	0.10 mg/L	Oberholster and Ashton 2008 (76)	98	Type C1
	Nitrogen application rate for maize production	85 kg N/ha	2012	FSSA 2013 (78)	Low	144 kg N/ha	Brentrup and Palliere 2010 (79)	59	Type C1
Biodiversity loss	Endangered and critically endangered ecosystems	37%	2011	Driver et al., 2012 (56)	Medium	0%	Expert judgment	137	Type C2
Marine harvesting	Depleted marine fisheries stocks	45%	2011	DAFF 2012 (82)	Medium	0%	Expert judgment	145	Type C2
Air pollution	Annual average PM10 concentration	46.9 $\mu g/m^3$	2012	DEA 2013 (83)	High	50.0 $\mu g/m^3$	DEA 2013 (83)	94	Type C1
Chemical pollution	To be determined								

*Type A1: global boundary with internationally agreed target; Type A2: global boundary with national target; Type B1: national resource limit without human intervention; Type B2: national resource limit with human intervention; Type C1: single local biophysical threshold; Type C2: aggregate local biophysical threshold.

Table 2. Dimensions and indicators of social deprivation in South Africa

Dimension of well-being	Indicator of deprivation	Current status of deprivation (%)	Year	Change since 1994*	Source	Type of Indicator Set†	Domain
Energy	Households without access to electricity	23.5	2012	−25.6% (1995)	DPME 2013 (87)	Type 1	Basic services
Water	Households without access to piped water within 200m (≥ RDP standard)	4.5	2012	−33.8%	DPME 2013 (87)	Type 1	
Sanitation	Households without a toilet or ventilated pit latrines	16.6	2012	−32.5%	DPME 2013 (87)	Type 1	
Housing	Households without formal dwellings	22.3	2011	−13.7% (1996)	DPME 2013 (87)	Type 1	
Education	Adults (≥20 y old) without more than 7 y of schooling (adult illiteracy)	19.3	2011	−11.1% (1995)	DPME 2013 (87)	Type 3	Public goods
Health care	Infant (<1 y) immunization coverage	9.2	2011	−27.8% (1998)	DPME 2013 (87)	Type 3	
Voice	To be determined						
Jobs	Broad unofficial unemployment rate (adults aged 15–64 available to work)	36.3	2012	−1.4% (2001)	DPME 2013 (87)	Type 2	Livelihoods
Income	Population living below the national poverty line (R577/mo in 2011 Rands)	52.5	2011	+2.0%	DPME 2013 (87)	Type 2	
Household goods	Household does not own a refrigerator	28.1	2012	−20.9% (2001)	StatsSA 2014 (88)	Type 3	Living standards
Food security	Households without adequate food	23.1	2013	−0.8% (2010)	StatsSA 2014 (88)	Type 3	
Safety	Households feel unsafe walking alone in their area at night	63.5	2011	+19.5% (1998)	DPME 2013 (87)	Type 3	

*Or since start of measurements, year given in brackets. Negative value represents reduction in deprivation; positive value represents increase in deprivation.
†Type 1: range of levels of deprivation; Type 2: range of definitions of the same indicator; Type 3: diverse set of indicators that represent different aspects of a dimension.

the barometer in national reports, such as the State of Environment Report, was suggested as being highly beneficial.

It is recognized, however, that indicators are limited and can oversimplify complexities, making them better suited to conveying broad messages and encouraging discourse (93). Indeed, a criticism of the barometer from some experts was that it hides the complexity of the local scale (i.e., the geography of social deprivation and environmental stress), which was also a critique of the planetary boundaries. Biophysical thresholds vary spatially (e.g., from dry to wet regions), therefore the issue of scale is an important consideration in acting on national barometer results at subnational scales. Specific subnational analysis is needed to investigate if and how national thresholds could be determined that incorporate and do not mask this heterogeneity. Analysis at the subnational level would also reveal inequalities in access to and use of resources, where both the ecological and political-economic borders are important. Nevertheless, broad sustainability indicators can provide substantial momentum to a more detailed debate, as the evidence from the MDGs shows, and can serve as first-order proxies for inclusive development.

National-Regional-Global Links. As a nation's political borders seldom match borders of biophysical systems, the national state of environmental stress has local, regional, and global components. Similarly, perceived social and economic benefits lead to regional migration into South Africa, which affects overall national social well-being. The fact that South Africa has exceeded or is close to exceeding almost all of its environmental boundaries highlights its own vulnerability, as well as that of its neighbors, and raises the importance of international and regional cooperation. The proximity to Type A "global boundaries" is likely to result in international pressure for South Africa to act, as seen in climate negotiations. The proximity to Type B "national limits" indicates that neighboring countries may be called on to provide water and arable land for regional food production, already evidenced by the DWA assessment of crop production potential in the region (94). The proximity to Type C "local biophysical thresholds" will probably result in pressure from local civil society.

International pressure will highlight the respective national contributions to the pressure on the planetary boundaries. South Africa has roughly 0.7% of the world's people (3) and 0.9% of its land area (95). It contributed 1.4% of global CO_2 emissions in 2010 (96), 4.4% of HCFC consumption in 2013 (63), 0.5% of global freshwater use (based on ref. 13), and 0.4% of global nitrogen fertilizer consumption in 2010 (97). South Africa is therefore not a big contributor to the global pressure on the planetary boundaries. It is, however, the main contributor on the African continent, and as a member of the BRICS group, is closely associated with countries that do have a significant global impact; this provides impetus to act, but also raises the issue of how national environmental boundaries are determined.

Table 3. Links between environmental stress and national policy applications in South Africa

Environmental dimension	Energy security	Water security	Food security	Job security	Human health
Climate change	✓	✓	✓	✓	✓
Ozone depletion					✓
Freshwater use		✓	✓		
Land use change			✓	✓	
Nutrient loading		✓	✓		✓
Biodiversity loss		✓	✓		✓
Marine harvesting			✓	✓	
Air pollution					✓

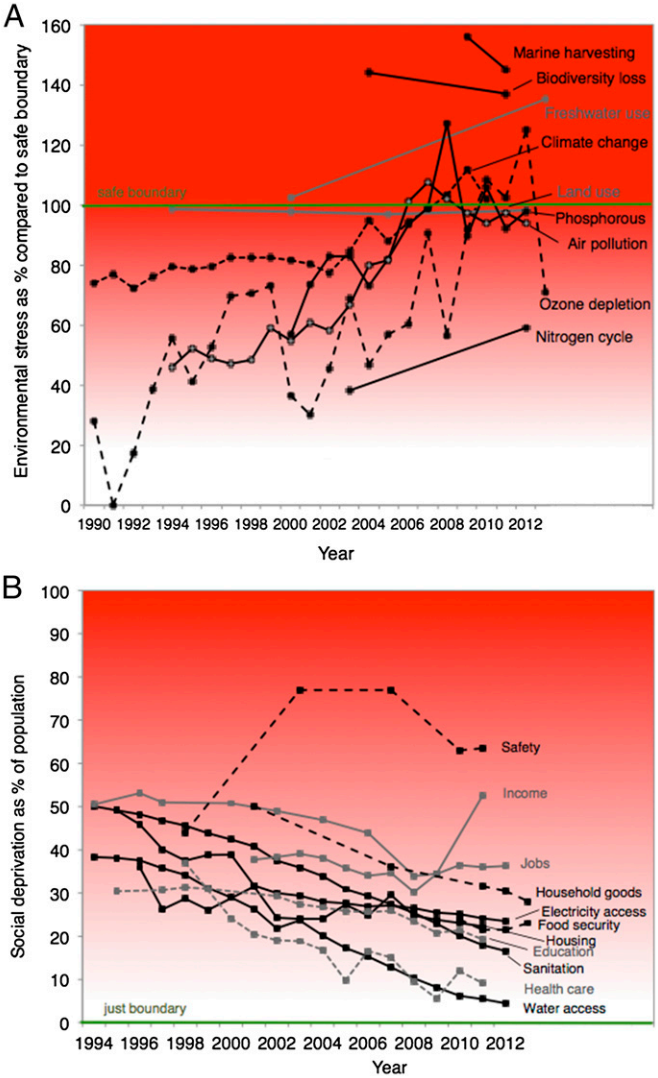

Fig. 3. (*A*) Change in environmental stress indicators in South Africa from 1990 to 2013 (Data sources in Table 1). Darker red shading indicates direction of increasing environmental stress. Black dotted lines are Type A boundaries (climate change, ozone depletion), gray solid lines are Type B boundaries (freshwater use, land use), black solid lines are Type C boundaries (phosphorous, nitrogen, biodiversity loss, marine harvesting, air pollution). (*B*) Change in social deprivation in South Africa from 1994 to 2013 (Data sources in Table 2). Darker red shading indicates increasing social deprivation. Black solid lines are basic services (electricity, water, sanitation, housing) gray dotted lines are public goods (education, health care), gray solid lines are livelihoods (income, employment), black dotted lines are living standards (food security, household goods, safety).

Different boundaries could lead to different levels of international pressure and different national policy decisions. For example, Nykvist et al.'s (36) equal per capita share approach results in South Africa exceeding a global boundary for climate change by 335%, whereas our study (which uses nationally defined boundaries) puts the figure at 2%. The very large difference is because of the latter incorporating the UNFCCC principle of common but differentiated responsibilities and respective capabilities, which is arguably more realistic as no climate deal is likely to be agreed without it. Globally defined boundaries also fall short for other dimensions, where national resource limits and local thresholds are arguably more appropriate. For example, Rockström et al.'s (12) 15% cropland boundary is inappropriate in South Africa, as only 12% of the land is capable of supporting rain-fed crop production. Caution is also needed with comparing social deprivation across countries if different social boundaries, which need to be appropriate to the country's current level of development and able to adapt to changing circumstances, are used. For example, according to the MDG indicator for water access, 8.8% of South Africans are deprived; however, according to the more stringent SAIMD indicator (piped water inside the dwelling or yard), 26.6% of South Africans are deprived. South Africa's latest MDG Country Report (98) includes 69 "domesticated indicators" that were developed by "adjusting the MDGS to reflect the local situation while ensuring that the globally designed targets and indicators are in line with local reality" through a stakeholder consultation process. Indicators that are inappropriate in the national context were identified and new targets and indicators required to fully reflect the local context were created. Although the government supports the MDGs, viewing them as an integral part of the development agenda (98), the global indicators are used for international comparison and the domestic equivalents are used for monitoring national development. South Africa is likely to take the same approach to the SDGs. This adoption of multiple indicators for different purposes could be taken if we were to upscale a set of national barometers to the global scale. Each dimension could have a national and global indicator to meet the needs of both audiences.

The downscaling of the global SJS framework is not only complex for setting boundaries but also in calculating the current status. The social dimensions are relatively straightforward to calculate at different scales, as they are all aggregations of individual people or households, although care must be taken to ensure consistency when using either household or individual data and adjusting for changes to political boundaries over time. The status of each environmental dimension is more difficult to calculate because they occur naturally at different scales. Despite the unavoidable complexity, each is based on local data sources and can therefore be scaled up to the national level, and possibly to the global level to recalculate Rockström et al.'s original planetary boundaries (12, 13). The methodology for this would be similar to the one we have used for turning local data into national values for South Africa. Some dimensions would be simpler than others; for example, CO_2 emissions and ODP substances are already aggregated to regional and global levels in UN databases. Although land and water use are also aggregated in global databases, the figures do not take into account national boundaries and need to be adjusted accordingly. The ecosystem level dimensions, such as biodiversity loss and phosphorous loading, could in principle be up-scaled through simple aggregation. One significant challenge is obtaining data for the same indicators across many countries, and additional indicators could be developed for each dimension to ensure there is some overlap. For example, marine harvesting could be changed to aquatic harvesting to incorporate a second indicator on freshwater fisheries to accommodate landlocked countries.

Gaps in the Data and Science. Our report has provided a methodology for other countries to use to develop their own national barometers. We chose South Africa for this case study partly because it has a wealth of good data and research. Other developing countries may struggle to find the appropriate data to populate their own national barometer, as the levels of research and monitoring are often much lower than that of South Africa. This is likely to also be the case with the implementation of the SDGs. Perhaps instead of this being seen as a barrier, it should be used as an opportunity for data-poor countries to begin an efficient targeted collection of specific data needed to address these global and national challenges. This has been one of the positive outcomes of the MDGs: that new longitudinal data have been collected in developing countries, aiding national governments in making more informed policy decisions (99). For now, the second-best solution (100)—where existing constraints prevent the first-best solution from being obtained—is to use existing data and proxies and to refine the barometer over time as more data are gathered. We note that the approach we have taken is supported by UN Environment Programme recommendations in limiting the number of indicators, using existing data and proxies, being sensitive to scale, and engaging stakeholders early on (101).

According to the Rio+20 outcome document, the SDGs must be "action-oriented, concise and easy to communicate, limited in number, aspirational, global in nature and universally applicable to all countries, while taking into account different national realities, capacities and levels of development and respecting national policies and priorities" (102). Our barometer meets the first four of these five criteria and attempts to address the last and toughest criteria of global applicability and national relevance, which is a challenge given the significant socio-economic differences between the 193 countries in the UN. As we have shown, some of the MDG indicators do not suit the South African context and there is disagreement over the sharing of responsibilities for addressing environmental stress, especially climate change.

Based on the Zero Draft (103) from the Open Working Group on SDGs (established by the UN General Assembly in January 2013), all of the dimensions in the barometer are likely to appear in the SDGs. The proposal has 17 goals (*Supporting Information*, section D), which together have 148 targets. No indicators have been developed as yet, but there are likely to be more than 200 and therefore intrinsically difficult to communicate with ease. Our barometer seeks a balance between simplicity and complexity, and although countries will have to measure and report on all of the SDGs in time, it makes sense to highlight some of the more important indicators and ensure that the necessary data are gathered early on in the process. It is likely that social indicators will be more readily available than environmental indicators, and multiyear research projects will be required to fill in the data gaps.

Apart from the data challenges, there are also gaps in the science on defining environmental boundaries, at both global and subglobal scales. Considerable effort is currently being put into investigating both the causes of tipping points in Earth systems and uncovering indicators of the proximity to critical thresholds (104). Schellnhuber (105) argues that the tipping elements issue "probably poses one of the toughest challenges for contemporary science" and highlights "social tipping elements" as an important research area. Similarly, Galaz (106) believes that "social connectors," which can lead to tipping points that would not otherwise occur, need to be researched. Although different scientific perspectives can lead to different national boundaries and indicators, so indeed could different political interests. Both scientific input and a robust process that involves all stakeholders are needed.

Conclusion

We have described a worked case study for applying Raworth's "safe and just space" (30) framework at the national scale, using South Africa as our test case. We developed a decision-based methodology for identifying and quantifying indicators and boundaries for both environmental and social dimensions, creating what is, to our knowledge, the first national barometer for inclusive sustainable development in South Africa. The barometer highlights environmental risks and unacceptable social deprivation intended to prompt public debate; indeed, similar barometers could be developed for other countries. Four dimensions—climate change, freshwater use, marine harvesting, and biodiversity loss—have exceeded their safe boundaries by 2%, 34%, 45%, and 37%, respectively, and arable land use, phosphorous loading, and air pollution are within 10% of exceeding their boundaries. Social deprivation was most widespread regarding safety (63.5%), income (52.5%), and jobs (36.3%) and least prevalent for basic services, such as water access. Trends show that environmental stress is still increasing for two dimensions (climate change and freshwater use), and social deprivation has reduced in all areas except safety and income. This case study provides insights into the challenges and complexities of developing relevant indicators and boundaries at national scales, and highlights areas where additional research is needed to refine and further develop the framework.

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Supporting Information

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Section A. Environmental Parameters

This section explains the choice of the indicator and determination of the boundary for the nine environmental dimensions in South Africa. Table S1 compares the original Rockström et al. (1) indicators to the relevant indicators in South Africa's annual Environmental Sustainability Indicators (ESI) Technical Report 2011 published by the Department of Environmental Affairs (DEA) (2) and the actual indicators used in our barometer. Each environmental dimension is described below, and is grouped by boundary type (i.e., Type A Global Boundaries, Type B National Limits and Type C Local Thresholds).

Type A: Global Boundaries.

Climate change. Climate change is inherently global, and Rockström et al. (1) use the global atmospheric concentration of CO_2 (in ppm) as their indicator and the Intergovernmental Panel on Climate Change (IPCC)'s estimated biophysical threshold of 350 ppm CO_2 as their safe global boundary. The global concentration of CO_2 cannot be disaggregated to the national scale; however, direct CO_2 emissions (production-based) are reported in national inventories and are aggregated to the global scale to inform international negotiations. Work on consumption-based accounting of CO_2 emissions is growing (e.g., ref. 3) but the data are limited. There are other significant greenhouse gases (GHG), such as methane (CH_4) and nitrous oxide (N_2O); however, CO_2 is most commonly used as an indicator and has the least uncertainty in the data (4). Land use change and forestry is also included in calculations of GHG emissions; however, because of the lack of data they are often not reported or used.

In South Africa, CO_2 contributes 85% of GHG emissions (measured in $MtCO_2e$) whereas CH_4 contributes 10% and N_2O only 3% (5). Although there are a number of possible indicators, the ESI reports annual per capita and total direct CO_2 emissions (excluding land use change and forestry) as they are Millennium Development Goal (MDG) indicators. We chose "Total annual CO_2 emissions" as our indicator as it is a direct measure, is of national importance and is reported annually by the national Department of Environmental Affairs (DEA). The current status of 460.1 $MtCO_2$ was sourced from the UN MDG indicators database (6), which uses data from the Carbon Dioxide Information Analysis Center (7), as this is used by DEA. It is an aggregation of multiple sources of CO_2 emissions in the country, including domestic energy, industry, and agriculture so subnational analysis can also be done.

South Africa has ratified the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, and has an influential role in international climate negotiations as a member of the BASIC group (Brazil, South Africa, India, China). As a developing country, South Africa has been exempt from taking mandatory action to reduce GHG emissions, however this is likely to change in 2020 when legally binding targets under the Durban Platform come into force. Although nations have agreed to limit global warming to 2 °C, there are no internationally agreed boundaries for CO_2 emissions. In the Copenhagen Accord in 2009, South Africa pledged to reduce emissions to 34% below business as usual (BAU) by 2020 and 42% below BAU by 2030. These pledges were based on the long-term mitigation scenarios and mitigation actions (8).

BAU in the long-term mitigation scenarios is a scenario called "Growth without constraints" and its emissions trajectory reaches 720 $MtCO_2$ in 2020, 1,000 $MtCO_2$ in 2030, and 1,640 $MtCO_2$ in 2050. The alternative is the "Required by Science" scenario, which uses the IPCC biophysical threshold of 350 ppm CO_2 based on a 2 °C maximum global warming target and the stated need to reduce GHG concentrations by 60–80% from 1990 levels by 2100. In the Required by Science scenario, "climate security" is guaranteed through joint international action as developed countries reduce emissions by 80% from 1990 levels by 2050, and a developing country like South Africa reduces its emissions by 30–40% from 2003 levels (446 $MtCO_2$). This trajectory peaks in 2020 at 473 $MtCO_2$ and declines to 440 $MtCO_2$ in 2030 and 290 $MtCO_2$ (65% of baseline) in 2050. The 2010 Required by Science target is 451 $MtCO_2$ and we used this as our national safe boundary. This is a Type A2 environmental boundary, which South Africa has exceeded by 2%.

Because this boundary has a large political component, alternative boundaries could be determined. For example, to compare countries Nykvist et al. (9) chose a boundary of 2 tCO_2 per capita per year based on the contraction and convergence approach, which translates to 106 $MtCO_2$ in 2010 for South Africa [using the 2013 midyear population estimate (10) of 52.98 million]. This amount is less than a quarter of the country's self-determined boundary of 451 $MtCO_2$ (and the current status of 460 $MtCO_2$ is 335% over this boundary), as it does not take equity and the principle of common but differentiated responsibilities and respective capabilities into account. This is a controversial area of debate, which is still being negotiated under the UNFCCC.

Ozone depletion. Ozone depletion (ODP) is a global phenomenon, which Rockström et al. (1) measured using the stratospheric ozone (O_3) concentration. This cannot be disaggregated to a national scale, hence a more appropriate indicator is the national production or consumption of ozone depleting substances. These measurements are reported annually by the United Nations Environment Program (UNEP) Ozone Secretariat (11) and also appear in MDG reports under Goal 7. Internationally agreed boundaries for ODP exist in the Montreal Protocol, which sets out phasing out schedules (different for developed and developing countries) for the production and consumption of 96 ODP substances. Many of the phase-out periods have passed and the focus now is on the consumption of methyl bromide (MBr) and hydrochlorofluorocarbons (HCFCs). The developing country target is to phase out the use of MBr by 2015 and HCFCs by 2040.

Since signing the Montreal Protocol in 1990, South Africa has phased out all ODP substances except HCFCs, which are used for refrigeration and air-conditioning services and manufacturing of polystyrene and polyurethane (12). HCFCs have been declared national priority air pollutants in terms of Section 29(1) of the Air Quality Act (13) and are reported in ESI 2012 (14). HCFC consumption was therefore used for the ODP indicator. The current status of 262 t for the year 2013 was taken from the UNEP database as it has the most recent data. In accordance with the Montreal Protocol commitments, the government aims to freeze HCFC consumption and limit it to a baseline of 369.7 ODPt (the officially reported average consumption of 2009 and 2010) by 2013, reduce it by 10% by 2015, 35% by 2020, 67.5% by 2025, 97.5% by 2030, and phase it out by 2040 (12). The safe boundary for 2013 is therefore 370 ODPt and the current status is 29% below the boundary, which represents a global international agreement, and therefore a Type A1 environmental boundary.

Type B: National Limits.

Freshwater use. Rockström et al. argue that freshwater is a finite planetary resource and human pressure is driving change in the function and distribution of the global freshwater system (15).

Their control variable, or indicator, is the consumption of freshwater by humans, a global aggregation of local use. The global consumptive use is 65% of global withdrawals of runoff water, and is the cause of environmental degradation and water shortages. Rockström et al. propose a danger zone of consumptive freshwater use and set the safe boundary at the lower limit, which equates to 32% of available river runoff or 27% of total renewable water resources. This danger zone is based on research suggesting that withdrawals of runoff water in excess of 40% of available freshwater resources can lead to severe regional water scarcity, and DeFraiture et al.'s 2001 estimate that water withdrawals exceeding 60% of the utilizable resource is a threshold for physical water scarcity. Rockström et al. highlight that crossing a global threshold could have both environmental (e.g., collapse of ecosystems) and social impacts (e.g., famine) at multiple scales.

South Africa's mean annual runoff (MAR; the average natural run-of-river flow per year over a long-term time period) is 49,210 $Mm^3 \cdot yr^{-1}$ and its estimated utilizable groundwater exploitation potential (maximum allowable water level drawdown) is 7,500 $Mm^3 \cdot yr^{-1}$ (16). Its total freshwater resources are therefore 56,710 $Mm^3 \cdot yr^{-1}$ and Rockström et al.'s (15) boundary would equate to 15,747 $Mm^3 \cdot yr^{-1}$ (32% of MAR) or 15,312 $Mm^3 \cdot yr^{-1}$ (27% of total). However, South Africa is the 30th driest country in the world with low and highly variable rainfall (both inter- and intra-annually), erratic runoff, high evaporation, and shallow dam basins (17). More than 60% of its river flow arises from only 20% of the land area requiring large-scale interbasin transfers (18). The South African economy primarily depends on its stored surface water resources, having 31,620 $Mm^3 \cdot yr^{-1}$ of surface storage capacity (19), and imported water from Lesotho. A boundary based on a global rule of thumb is therefore unlikely to represent the local context.

The Department of Water Affairs' (DWA) first National Water Resource Strategy (NWRS), published in 2004, describes South Africa's water resources and requirements in the year 2000 (20), which are summarized in Tables S2 and S3. The minimum amount of water needed for ecological functioning in rivers, the "ecological reserve," was estimated at 9,545 $Mm^3 \cdot yr^{-1}$ or 19% of MAR at the national level. This is an aggregation of the reserve calculated in each of the 19 Water Management Areas (WMA), which varied from 11% of MAR to 28% of MAR. These estimates do not take estuaries into account, which usually require a greater proportion of MAR. Hughes and Munster's (21) hydrological variability index based on desktop reserve estimates shows that for rivers, which are strongly baseflow driven, the reserve can vary from 17% to 80% of MAR for different ecological management classes, but that this range and %MAR reduces as variability increases.

The second edition of the NWRS, published in 2013 (17), states that 25% of MAR is needed for the ecological reserve and that although the ecological reserve is mandated in the National Water Act of 2008, it is not met in at least four of the nine new WMAs. The DWA is in the process of classifying all significant water resources to determine the ecological reserve for each catchment. The national Water Resource Classification System incorporates socio-economic considerations and aims to facilitate a balance between resource protection and resource development and utilization at different scales, recognizing that there must be trade-offs (22). Three management classes that reflect the future desired condition of an aquatic ecosystem have been defined and will be used to guide the quantity and quality of water to be reserved for that ecosystem (23), and therefore the amount available for human use. To date only the Olifants-Doorn catchment (the old WMA 17, located in the Western Cape and Northern Cape Provinces) has been completed, but six other catchment assessments are underway (24). This process is likely to result in an updated national figure for the ecological reserve, but until it is complete we must rely on the NWRS2 estimate of 25% of MAR.

Using this estimate of the ecological reserve, we could calculate that 36,908 $Mm^3 \cdot yr^{-1}$ of surface water remains for human consumption, although 3,000 $Mm^3 \cdot yr^{-1}$ of this is lost as evaporation from dams (25), leaving 33,908 $Mm^3 \cdot yr^{-1}$. This result is not completely accurate though, as the impact of water use on the reserve varies depending on the season; for example, in the north and east of South Africa, the agricultural growing season is the rainy season and, hence, there is minimal impact on the reserve, whereas in the southwest the growing season is generally the dry season and it has a big impact on the reserve. Another flaw with this approach is that it does not take the availability of freshwater resources throughout the year into account, a prerequisite for domestic and industrial use.

The DWA calculates an annual total available surface water yield, which is "the amount of water that can be supplied in a catchment using a set of human-built water supply schemes (such as dams and interbasin transfers) as well as taking into account a specified reliability of supply, termed the 'assurance of supply'" (26). A 98% assurance of supply is used, which means that water will be available in 98 of 100 y. The DWA uses a hydrological systems model to simulate flows based on MAR, dam storage potential, water transfers, and abstraction, and it incorporates the effects of land-use change, including irrigation, afforestation, alien vegetation, mining, and urbanization (25). The model calculates yields for large water supply systems and therefore excludes available water that is not being captured in storage dams, although there is very limited potential for new dams in South Africa (17). People living in rural areas continue to source water from rivers and streams where MAR is high, but water services are limited. According to the 2011 Census (27), the main source of water for 17.5% of households in the Eastern Cape and 8.5% of households in KwaZulu Natal is a river or stream. Nationally, 651,244 million households, or roughly 2.6 million people, use rivers or streams as their main source of water. Using the DWA recommendations for low-income housing of 60 L per person per day, we can estimate this water demand to be 57 $Mm^3 \cdot yr^{-1}$. This demand should partly be addressed by the building of two multipurpose dams in the Eastern Cape, which will provide hydropower and store 490 Mm^3 for domestic and agricultural use from 2018 (28), which should then increase DWA's total available yield.

The DWA estimated that the available surface water yield was 10,240 $Mm^3 \cdot yr^{-1}$ in 2000, whereas the total available yield for human consumption was 13,227 $Mm^3 \cdot yr^{-1}$, which included groundwater yield of 1,088 $Mm^3 \cdot yr^{-1}$ and usable return flows of 1,899 $Mm^3 \cdot yr^{-1}$. The NWRS 2013 estimate of groundwater yield was 2,000 $Mm^3 \cdot yr^{-1}$, which would take the current total yield to 14,139 $Mm^3 \cdot yr^{-1}$. If we add an estimated rural use direct from rivers, the total is 14,196 $Mm^3 \cdot yr^{-1}$.

Given the complexities in the data and modeling, it is difficult to determine a safe boundary for freshwater resources in South Africa. We decided that the best option was to use our updated total available yield of 14,196 $Mm^3 \cdot yr^{-1}$, as the indicator being measured is consumptive freshwater use by humans; that is, water that is not supplied or allocated by the DWA cannot be used, except in rural areas where there is little or no water service provision. This is a Type B2 boundary because it is a national resource limit that has both an ecological component (the ecological reserve) and a physical component (infrastructure and imports), and crossing the boundary has both environmental and social impacts. The total available yield could increase in the future if additional water is imported from neighboring countries, additional groundwater is accessed, return flows increase, and physical water losses in municipalities are reduced.

South Africa's total freshwater requirements for human use in 2000 were 12,871 $Mm^3 \cdot yr^{-1}$, thus water supply and demand were roughly in balance. However, these statistics are now 14 y old, a significant length of time in a rapidly changing policy environment and where population has increased by 18% (8.22 million people) since 2000 (10). Domestic consumption is likely to have increased by at least 18% as water access has increased and incomes have grown. Power generation increased by 3,616 GWh or 23% (29) and the economy has grown by an average of 3.5% each year (30) despite mine production falling by 12% (31). According to the DWA's Water Authorisation and Registration Management System (WARMS) database (as at 15 April 2014) (32), irrigation is currently allocated 11,005 $Mm^3 \cdot yr^{-1}$, mining and bulk industrial are allocated 907 $Mm^3 \cdot yr^{-1}$, urban use is allocated 3,325 $Mm^3 \cdot yr^{-1}$, and trade and services are allocated 2,278 $Mm^3 \cdot yr^{-1}$. Although these figures may not reflect actual water use, they are the best available estimate of current consumptive use. Taking all these changes into account, we estimate that overall water consumption in 2013 was 18,985 $Mm^3 \cdot yr^{-1}$ (Table S3), 34% more than the total available yield of 14,196 $Mm^3 \cdot yr^{-1}$. This finding implies that either water is overallocated by the DWA or allocations are being exceeded.

Land use. Land-use change occurs at the local level and is largely driven by demand for food and fiber. Rockström et al. (1) highlight the negative consequences on biodiversity, as well as climate and hydrological cycles, and use the indicator "ice-free land converted to cropland" with a boundary of 15%. Because biodiversity loss, climate change, and freshwater use are already addressed in other dimensions, and because South Africa's land cover has remained relatively stable since 1961 (33), we have chosen to focus on arable land use.

It is important to differentiate between land capability, land suitability, and land use. South Africa is largely a semiarid country with very limited land capable of supporting sustainable crop production. In 2002, the national Department for Agriculture published a National Land Capability Classification (34) and accompanying 1:250,000 map, which adapted the international concept of land capability to the South African context using a national dataset developed over 30 y. The classification incorporates environmental risks and limits based on terrain (slope), soil quality, and climate to classify land into eight main classes of agricultural potential, as shown in Table S4. The crop production limitations include the choice of crop and the timing of planting, growing, and harvesting, but exclude low nutrient status because this can be rectified by liming or fertilization (34). Classes I to IV constitute arable land (i.e., land that can be used for crop production), and classes V to VIII constitute nonarable land. Classes I to III represent rain-fed arable land of acceptable quality for crop production, and class IV represents marginal land for rain-fed crop production.

Since 2002, provincial studies of land capability have been undertaken for Gauteng and Limpopo and in 2012, the Department of Agriculture, Forestry and Fisheries (DAFF) updated the land capability information as part of the development of a new national policy on the "Preservation and Development of Agricultural Land" (35). The analysis excluded water bodies, protected areas, and areas under forest plantations that are not available for agricultural production, which reduced the amount of agricultural land from the original 2002 definition. In addition, the analysis indicated that 3,139,290 ha of agricultural land were permanently converted for urban and mining developments, 63% of which was arable land (Table S4). Thus, in 2012, only 25% of land in South Africa is arable and only 12.1% of land is termed "acceptable arable land." Arable land can also be degraded and South Africa is particularly susceptible to land degradation because of its semiarid climate and unique land tenure situation of former homelands of the Apartheid regime (36). Land degradation within different land-cover types would be a useful indicator but these data are difficult to find.

Although land capability is based on ecological sustainability, land suitability depends on economic and social factors in addition to environmental factors. Hence, an area of land can be capable of crop production but deemed suitable for urban development or mining, resulting in the reduction in the total area of arable land available as indicated above. Land use in South Africa has been recorded in the 1:250,000 National Land Cover datasets of 1994/1995 (37) and 2000 (38), which categorized land use as cultivated land, degraded land, forest plantations, urban built-up land, mines and quarries, and natural land. According to the DEA, the accuracy of the land-cover database ranges from 51% to 93%, depending on the geographic area (2). In 2009 South African National Biodiversity Institute (SANBI) (39) updated the national land-cover map based on provincial studies (generated from satellite imagery); however, actual values for the different categories at a national scale were not published. Most of South Africa's agricultural expansion took place before the 1960s, although the threat of sanctions during the Apartheid era led the government to provide agricultural subsidies to promote food security, which in turn led to cultivation of marginal land (40). Schoeman et al. (38) developed a national land-cover change map for the period 1994 and 2005, which showed a 1.2% change in land use. Urban, forestry, and mining all increased their land cover; however, cultivated land decreased by 0.5%. Niedertscheider et al.'s (33) socio-ecological analysis in 2012 shows that land cover in South Africa was stable from 1961 to 2006, with cropland expansion and decline and the spread of settlements and forest plantations only causing minor changes in area extent for the whole period. Land degradation is difficult to measure, however, and is likely to be underestimated.

Based on the South African situation, we decided to measure how much of the limited national resource of arable land has been converted to cropland to provide a measure of land use and food production constraints, which contributes to food security. Because there is no available direct comparison of arable land and cultivated land, we had to combine the indicator "land used for crop production" (11.9% in 2005) and the boundary "acceptable arable land for crop production (class I–III)" (12.1% in 2012). Using this measure, South Africa is close to exceeding its boundary for cropland. The land-use figures are 8 y old and must be updated as soon as the data becomes available. The boundary for land is a Type B1 boundary because it represents a natural resource limit that has not been expanded by human intervention. This would change to a Type B2 boundary if class IV marginal cropland, which requires irrigation in dry seasons, were included in the boundary. Based on Geographic Information Systems maps of land cover and land capability, it is clear that cultivation is occurring on marginal land; hence, we considered incorporating marginal land in the boundary. However, we felt that excluding it represented a more ecologically sustainable approach, particularly considering the water resource constraints already identified, and as Biggs and Scholes (40) point out, marginal land is more prone to crop failures.

Type C: Local Thresholds.

Biodiversity loss. Biodiversity loss occurs at the local scale and is aggregated by Rockström et al. (1) to the global scale, using rate of extinction as the indicator. The more common way to measure biodiversity loss, however, is threat of extinction. The International Union for Conservation of Nature (IUCN)'s Red List Index documents species threat status and is used by the UN Convention on Biological Diversity as an indicator for the "2010 Biodiversity Target." It is also an MDG 7 indicator (41). Threat of extinction, or threat status, is categorised as critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), and least concern (LC) by the IUCN (42).

South Africa has undertaken biodiversity assessments since 1980 and has made a significant contribution to global conservation efforts (43). The *Red Data Book of Mammals of South Africa* (44), published in 2004, assessed 295 terrestrial and marine mammals. The online "Red List of South African Plants" was published in 2010, making South Africa the first megadiverse country to fully assessed the status of its entire flora, some 20,456 plant taxa, 13,265 of which are endemic (43).

The SANBI, established in 2004 through the National Environmental Management: Biodiversity Act, has shifted from a species approach to an ecosystem approach to biodiversity assessments, and ecosystem threat status was assessed for the first time in 2004 (45). National assessments are done every 7 y and the 2011 National Biodiversity Assessment (46) reported the ecosystem threat status of 1,763 ecosystem types across six categories: terrestrial, rivers, wetlands, estuaries, coastal and inshore, and offshore, as shown in Fig. S1. This assessment uses a threat status classification very similar to the IUCN Red List; ecosystems with less than 20% of their original extent in good ecological condition (as oppose to fair or poor condition) are classified as CR, ecosystems with less than 35% of their original extent in good condition are EN, and ecosystems with less than 60% of their original extent in good condition are VU. The classification therefore incorporates biophysical thresholds, and CR represents the so-called biodiversity target, the minimum proportion of an ecosystem required to maintain a representative sample of that ecosystem type and its species.

To calculate a single national indicator and safe boundary for biodiversity loss, all six ecosystem categories have to be combined. Experts recommended combining the CR and EN classes to measure the total number or percentage of endangered ecosystems, rather than including VU to measure total threatened ecosystems. The current status can be calculated in two ways; either by using the absolute numbers of ecosystem types (Fig. S1*A*), which gives a total of 42% of ecosystems endangered or critically endangered, or by using the percentages for each category (Fig. S1*B*), which gives a total of 37% of ecosystems endangered or critically endangered. The former approach biases the total toward wetlands and terrestrial ecosystems because they have significantly more ecosystem types than the other categories; therefore we used the latter approach. The national safe boundary is zero ecosystems endangered (CR and EN) and was based on expert opinion. South Africa has therefore exceeded its safe boundary for biodiversity loss by 37%.

Because CR is called the "biodiversity target," it could be used for the indicator and boundary; however, only 20% of the original extent of the ecosystems in good condition was not considered safe.

Ocean acidification and marine harvesting. Ocean acidification is a climate change-associated phenomenon, which will impact on the natural marine resources of South Africa within the 21st century (47). South Africa is at a very early stage in understanding ocean acidification and in March 2013 the Council for Scientific and Industrial Research held a workshop to start a national research response. The council found that there is currently no long-term time series of in situ data available to evaluate the current status and trends of the oceanic pH for the continental shelf ecosystems of South Africa, and therefore cannot confirm or reject the global biogeochemical climate model projections (47). The current national priority for oceans is rather the sustainability of marine resources. This priority is dependent on human drivers, which include acidification from CO_2 emissions, but also includes fishing and other pressures. To better reflect this reality, the "ocean" dimension was changed from ocean acidification to marine resources.

Commercial, subsistence, and recreational fisheries in South Africa catch more than 630 marine species. The *Status of South African Marine Fishery Resources*, published by the DAFF in 2012 (48), provides information on 17 fishery sectors in 2011. These fisheries can contain a single species or multiple species. Two indicators are used: stock status, which is a result of a large variety of factors, and fishing pressure, the factor that can be managed most directly. Stock status is reported as unknown, abundant ($B > B_{MSY}$), optimal ($B = B_{MSY}$), depleted ($B < B_{MSY}$), and heavily depleted ($B << B_{MSY}$), where B is the present biomass level (or population size) and B_{MSY} is that biomass level at which maximum sustainable yield (MSY)—the target for optimal utilization—is obtained. For example, deep-water hakes (currently the most economically valuable fishery) have been depleted to 21% of the prefished biomass of 1,358,000 tons (B) and have a B_{MSY} of 24% of prefished biomass (325,920 tons), and are therefore classified as "depleted." For some but not all multiple-species fisheries, the status is given per species. In some cases, the stock status or fishing pressure for a species may vary around South Africa's coastline, in which case species are subdivided into two or more categories (e.g., Atlantic and Indian swordfish).

The 2012 stock status is reported for 45 species (or subspecies or multiple species), as shown in Fig. S2 (species that are estimated between two status categories (e.g., abalone is depleted/heavily depleted) are counted as 0.5 in each category). Of these species, 5 are unknown, 5 are abundant, 17 are optimal, 12.5 are depleted, and 5.5 are heavily depleted. The indicator for this case study was based on expert judgment and is the percentage of marine stocks that are depleted or heavily depleted. This result could be either the percentage of all 45 species or of only the 40 whose status is known, and we chose the latter (i.e., 45%). The safe boundary was set at 0% (i.e., no marine fisheries are overexploited), therefore South Africa has exceeded its safe boundary for marine harvesting by 45%.

Further research could be done on weighting the fisheries by volume, economic value, or employment.

Nutrient cycles: Phosphorous loading. Phosphorous (P) is one of the building blocks of life and is essential for food production. Unlike other major elements, such as nitrogen and carbon, it has no gaseous phase and therefore the phosphorous cycle is more local and regional than global. Natural resources are concentrated in a few countries (Morocco has 85% of current known reserves) and the "peak phosphorous" debate estimates that finite phosphate rock resources may be depleted in 30–300 y, posing a global food security concern (49). Phosphorous enters freshwater systems and oceans through natural weathering, through phosphate mining and its use in fertilizers, and through wastewater. Rockström et al.'s (1) indicator for the phosphorous cycle is the annual inflow of phosphorus to the ocean, which could cause eutrophication at a regional scale.

Eutrophication of freshwater resources is widespread in South Africa and is a national concern (50). In 1980 the Department of Water Affairs and Forestry (DWAF) set an effluent discharge standard of 1 mg/L P and started its first monitoring program in 1985. In 1988 the Phosphorous Management Objective of mean total phosphorous concentration in reservoirs was set at 130 μg/L P. In 2002, the National Eutrophication Monitoring Program (NEMP) was implemented to measure mean annual levels of chlorophyll and phosphorous. NEMP currently has over 1,200 monitoring points in 16 drainage basins in its database, some of which date back to 1978. Single national values are reported in ESI 2011 for the period 2000–2011 (2).

We therefore chose "mean annual total P in dams" as our indicator of P loading, and obtained data for 11 drainage basins from the DWA for 2012. We calculated a weighted average based on the gross volume of freshwater in each drainage basin to create a single national value of 0.098 mg/L. This result obviously does not take the seasonal variations into account and hides the variation in the drainage basins where individual values range from 0.02 to 0.26 mg/L, an order-of-magnitude difference.

The NEMP categorizes the potential for algal and plant productivity based on mean annual total phosphorous as negligible ($P \leq 0.015$), moderate ($0.015 < P \leq 0.047$), significant ($0.047 < P \leq 0.13$), and serious ($P > 0.13$). Oberholster and Ashton (51), however, specify 0.10 mg/L as the critical threshold for P in freshwater and this value is currently used as the effluent discharge limit for wastewater treatment plants in South Africa, the biggest point source of phosphorous in freshwater. We therefore chose this biophysical threshold as the safe boundary, and South Africa is therefore 2% below its boundary for phosphorous loading.

Nutrient cycles: Nitrogen fixation. Nitrogen (N), like phosphorous, is essential for food production; however, it is taken from the atmosphere in the form N_2 rather than from rock and is therefore a shared global resource. Nitrogen fixation has a range of local negative effects, described by De Vries et al. (52) as: (*i*) eutrophication of terrestrial and marine ecosystems, (*ii*) acidification of soils and fresh waters, (*iii*) formation of the greenhouse gas N_2O, (*iv*) air pollution resulting from ozone formation, (*v*) groundwater contamination by nitrate, and (*vi*) stratospheric ozone depletion. Rockström et al.'s (1) global indicator for the nitrogen cycle is the pressure "nitrogen fixation during fertilizer production expressed in tons of N," rather than the impact. Their global nitrogen boundary is estimated as 25% of current nitrogen fixation which equates to 35 Tg N (or Mt N) per annum, which according to Schlesinger "seems arbitrary and might just as easily have been set at 10% or 50%" (53). De Vries et al. (52) estimate that future global demand for nitrogen in fertilizers will range from 50 to 80 Tg N/yr^{-1} (depending on use efficiency) and will therefore exceed this boundary. The authors calculate global nitrogen fixation boundaries for different N compounds (in air or surface water runoff) that vary from 20 to 120 Tg N/yr^{-1}, highlighting that the local impacts resulting from nitrogen fixation are critical for determining its boundary.

There are a number of approaches and indicators that could be taken to determine a national nitrogen indicator and boundary, focusing on the local impacts of nitrogen or on the use of nitrogen in fertilizer production. We reviewed various possible approaches and summarize them below.

Local impacts. De Vries et al. (52) suggest four possible indicators for national nitrogen boundaries based on local impacts: (*i*) atmospheric NH_3 concentrations that negatively affect biodiversity, (*ii*) radiative forcing from greenhouse gas NO_2, (*iii*) nitrate (NO_3) concentrations in groundwater that negatively affect human health, and (*iv*) dissolved organic N concentrations in surface water that cause eutrophication. Three of these four indicators overlap with other planetary boundaries—biodiversity loss, climate change, and surface water quality (through phosphorous loading, although nitrate is not necessarily correlated with phosphorous)—however, groundwater quality has not been assessed in any other dimension. Nitrate occurs extensively in groundwater in southern Africa as a natural feature of the semiarid to arid landscape and the nitrate concentration can vary greatly depending on the aquifer and its recharge characteristics (54). The main anthropogenic source of nitrate in groundwater is on-site sanitation (unlike high income countries where agriculture is the main source of nitrate), whereas other sources are livestock feedlots, fertilizer application, land clearing, and tilling of the soil (54). South Africa has official DWA specifications for potable water and stock watering similar to the World Health Organization's guidelines. Potability classes measured with nitrate concentration are: ideal (<6 NO_3–N mg/L), acceptable (6–10 NO_3–N mg/L), marginal (10–20 NO_3–N mg/L), poor (20–40 NO_3–N mg/L), and unacceptable (>40 NO_3–N mg/L). For livestock watering the acceptable level is <100 NO_3–N mg/L (55). In 2009 Maherry et al. (56) created a national map of nitrate levels in groundwater that concludes that the Western Cape has seen elevated nitrate concentrations over the last decade; the Limpopo and Kalahari region have been and still are strongly affected by elevated nitrate concentration, and there is a scarcity of datapoints in certain urban centers and the central part of South Africa. Although nitrates pose a human health risk in communities dependent on groundwater, it is not a national priority.

Similarly, nitrate concentrations (NO_3 as N in mg/L) in surface water are measured on a weekly or monthly basis under NEMP, but are not considered national indicators by the government. A rapid analysis of the latest data obtained from the DWA shows the median value of all 3,112 datapoints in 2012 was 0.125 mg/L, well below DWA's ideal potable water threshold of 6 mg/L. Nitrogen compounds [ammonia (NH_4) as nitrogen (N) and nitrate (NO_3)/nitrite (NO_2) as N] are also reported in the DWA's Green Drop regulation program, which measures and compares the performance of 153 municipalities and 831 wastewater treatment systems to create a National Green Drop Performance Barometer (57). National data were not available and the local thresholds vary based on license type and discharge locations, making a single national boundary impossible.

Fertilizer use. Nykvist et al. (9) calculated an equal share per capita nitrogen boundary of 5 kg N fertilizer consumption per year, based on Rockström et al.'s (1) global boundary and used it to compare 60 nations. Using this method, South Africa would exceed the global boundary by 54% at 7.1 kg N per capita; however, this absolute value does not take into account national conditions, such as soil quality, rainfall, and arable land area, and assumes that N fertilizer use has negative consequences, which may not be the case especially in developing countries. A better global comparison would be N fertilizer use per hectare of arable and permanent cropland, or per unit food produced, although the global boundary would ignore other national conditions. According to the Food and Agriculture Organization (FAOStat) (58), in 2010 South Africa used 31 kg N/ha compared with 53 kg N/ha for the Americas, 11 kg N/ha for Africa as a whole, 121 kg N/ha for Asia, and 46 kg N/ha for Europe, and ranked 81 of 159 countries.

The Fertilizer Society of South Africa (FSSA) publishes annual national data on fertilizer consumption and planted areas for different crops or crop types each year. In 2012, 6.873 Mha were planted with crops and 368,720 tons of N were applied at an average application rate of 53.6 kg N/ha, although rates varied from 12.9 kg N/ha for fiber crops to 170 kg N/ha for roots and tubers (59). Maize consumed almost two-thirds of N (62.2% or 229,420 t N) on 39% of total cropland, and sugar crops consumed 8.9%, fruits consumed 7.4%, vegetables consumed 4.4%, and wheat consumed 4.2% of total N. Crop production in South Africa contributes to food security, employment (on-farm and agro-processing), exports, and gross domestic product (60); therefore, sustainable levels of N in the soil need to be maintained. A possible indicator is therefore "Sustainable N-application for crop production"; however, determining a national boundary is more difficult.

Recommended fertilizer application rates are based on yield potential and soil status of N, P, and K, as well as climate, soil depth, and soil type, and therefore vary geographically as well as by crop and are affected by previous farming practices and irrigation. For example, the *FSSA Fertilizer Handbook* (61) recommends N-application rates for maize ranging from 20 kg/ha for a yield potential of 2 t/ha to 270 kg/ha for a yield potential of 12 t/ha, and provides adjusted N-application rates for soils with clay content above 5%. In 2013, Adriaanse (62) reviewed 13 y of N-calibration studies for dry-land maize by the Agricultural Research Council, Grain Crops Institute in South Africa to establish a single threshold value for inorganic N (in the top 600-mm soil) of 100 kg N/ha (i.e., above this application rate the improvement in yield is less than 10%). Adriaanse also established that inorganic N application rates should be between 70 and 133 kg N/ha (the range reflects different soil types and different levels of organic N) for biological and economic reasons, with a maximum of 174 kg N/ha for maximum yield. Beyond this maximum, N application can have a negative impact on yield.

Brentrup and Palliere (63) describe two policy-relevant indicators for sustainable fertilizer use. The "N balance," an established Organization for Economic Cooperation and Development (OECD) indicator, is the difference between N inputs (fertilizer, manure, and so forth) and N outputs (arable, permanent, and fodder crops) and is measured in kg N/ha. The nitrogen use efficiency (NUE) has a number of definitions and methodologies; however, the one most suited to a policy context is the ratio between the amount of fertilizer N removed from the field by the crop and the amount of fertilizer N applied (i.e., N removed divided by N applied) (63). The NUE considers productivity more than the balance and requires interpretation. Theoretically, a NUE of 100% would be ideal; however, in practice N losses, such as leaching, are partly unavoidable (63). A range of 80–90% is considered well balanced, whereas more than 90% poses a risk of soil mining (partly because the N requirements for roots and straw are not met by N input) and less than 70% poses a risk of high losses of N into the soil. The global average NUE was 55% in 2006. To explore these alternative measures, we have used maize, the biggest user of N and the staple crop in South Africa, as an example but this would need to be done for all major crops types.

On average, maize removes 27 kg N from the soil per ton of marketable product (61). In 2011/2012, South Africa produced 11.83 Mt of maize on 3.141 Mha (60), a yield of 3.8 t/ha; therefore, 101.7 kg N/ha were removed from the soil. This amount is practically the same as Adriaanse's (62) yield threshold of 100 kg N/ha. As mentioned, this number was replaced by an estimated 229,420 t N on 2.699 Mha in 2012 or 85 kg N/ha. The N balance is therefore negative (−16 kg/ha) and the N removed is not being replaced. The NUE is 119% and would be classified as soil mining. Although in the long-term this could cause soil degradation, it may not be a concern in the short-term. The result is also almost 50% higher than the threshold for N losses into the soil from overapplication of N, which affect water quality, so this is clearly not a concern.

This is a difficult safe boundary to define, as too much or too little fertilizer is problematic, although Rockström et al. (1) identified the overapplication of N as the main global concern. We therefore used the NUE threshold of 70%, which would translate to an N application rate of 144 kg N/ha for maize in South Africa. At 85 kg N/ha, South Africa would be 41% below this N-application boundary.

In summary, there are eight possible indicators and boundaries for the nitrogen cycle in South Africa. The four measures that have both the indicator and boundary give very different results, ranging from 16% to 154%. As the 5-kg per capita boundary does not take national circumstances into account, and surface water quality is already addressed, a sustainable crop application-rates indicator is the most appropriate. We selected the N-application rate as it the easiest to understand and measure against the boundary. Because of lack of available data, we used maize production figures, but all crops should be assessed in future. This analysis could contribute to the identification of the most suitable crops for South Africa.

Aerosol loading and air pollution. Aerosol loading is a driver of regional climate change. Rockström et al.'s (1) indicator for aerosol loading is overall particulate concentration in the atmosphere on a regional basis. Because aerosol loading is not a major concern in South Africa, we decided to change this dimension to address the important national issue of air pollution that affects human health.

South Africans have a Constitutional right to clean and healthy air and Government Outcome 10 Output 2 Suboutput 2.2 is "Atmospheric pollutants reduced" (64). The South African Air Quality Information System stores data from 90 ambient air quality monitoring stations across the country on CO_2, CH_4, carbon monoxide, nitrogen oxides (NO_x), sulfur dioxide (SO_2), ground-level ozone, benzene, toluene, p-xylene, and particulate matter (fine particles found in the atmosphere, including soil dust, dirt, soot, smoke, pollen, ash, aerosols, and liquid droplets) less than 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$) (65). South Africa has three national priority air-quality hotspots—the Vaal Triangle, the Highveld, and the Waterberg—linked to coal and gold mining areas.

The government (66) has identified PM_{10} and SO_2 as problem pollutants at a national scale, and the DEA uses the annual average concentration of each (from all monitoring stations) to calculate a National Air Quality Indicator. Every year, the DEA presents the "State of Air" in the country and the latest results for 2012 (66) show that PM_{10} is now the "greatest national cause for concern in terms of air quality." We therefore chose an annual average PM_{10} concentration as our indicator for air pollution. The DEA has determined a safe boundary for PM_{10} of 50 $\mu g/m^3$ and a policy target of "100% national compliance with National Ambient Air Quality Standards by 2020" (66). In 2012, the current status was 46.9 $\mu g/m^3$, down from a peak concentration of 53.7 $\mu g/m^3$ in 2009, showing that the policy intervention has had a positive effect.

Although this single national value is useful for showing overall progress on improving air quality, it is an aggregation of multiple point sources across seven hotspots: the Vaal Triangle, the Highveld, Eskom, Johannesburg, Tshwane, eThekwini, and Cape Town. In 2011, the PM_{10} values at the monitoring stations varied from 10–225 $\mu g/m^3$ and 16 of 42 stations (38%) crossed the safe boundary (67). The National Air Quality Indicator has replaced the indicator "Number of metropolitan and district municipalities with air quality that does not conform to ambient air quality standards," defined in the 2007 National Framework. In 2009, 50 municipalities were considered to be noncompliant, although only 26 were known (>90% confidence) to be noncompliant (64). Together these municipalities are home to 36 million, 70% of the national population in 2011. Therefore, although South Africa has not crossed the national safe boundary based on average PM_{10}, a large proportion of the population is living with poor air quality.

Chemical pollution. Chemical pollution, such as radioactive compounds, heavy metals, and organic compounds, occurs at the local scale but has global impacts on human and ecological functioning, and affects other planetary boundaries (1). The international Basel Convention on trade in hazardous waste and the International Convention for Prevention of Pollution at Sea both seek to address it through global governance. Rockström et al. did not identify an indicator for this dimension because of the huge number of chemicals and the lack of aggregate global-level analysis. The authors did suggest indicators based on emissions, concentrations, or effects on ecosystem and Earth System functioning of persistent organic pollutants, plastics, endocrine disruptors, heavy metals, and nuclear wastes. Rockström et al. identified two approaches: to focus on persistent pollutants with global distribution (such as mercury) or to focus on their negative large-scale effects.

South Africa is a signatory to the international Basel Convention and has progressive national legislation in the National Environmental Waste Management Act 2008; however, in practice there is a large gap between policy and practice (68). The National Waste Management Strategy sets targets for waste management and the National Waste Information Baseline Report (69), published by the DEA in November 2012, provides an estimated current status. Over 1.3 Mt of hazardous waste were generated in 2011 and were reported in 20 hazardous waste categories. Five categories dominated: 25% were "miscellaneous," 22% were "inorganic waste," 19% were "tarry and bituminous waste," and 15% were "other organic waste without halogen or sulfur," all of which were landfilled. In addition, 49 Mt of unclassified waste were reported. The baseline is, however, limited by voluntary reporting; companies that generate hazardous waste are reluctant to report it. In addition, as many large industries manage waste on-site, it does not enter the formal waste stream and is not measured. The South African Waste Information System will provide updated information of enforced waste reporting in the future.

Because of the lack of detailed and accurate information on chemical pollution and its thresholds, we did not define an indicator or boundary for this dimension.

Section B. Social Deprivation Parameters

This section explains our choice of social indicators, and hence boundaries for social deprivation, and contrasts them with those used by Raworth (70) at the global scale. Table S5 compares Raworth's social indicators with the South African Index of Multiple Deprivation (SAIMD) indicators and the indicators used in this barometer. As explained in the main text, there are three different types of indicator sets to choose from: Type 1, a set of indicators that represent a range of levels of deprivation (which are commonly found in household surveys); Type 2, a range of definitions of the same indicator; or Type 3, a diverse set of indicators that represent different aspects of wellbeing. We grouped the indicators into four domains—basic services, public goods, livelihoods, and living standards—to make the results easier to analyze.

We chose social indicators based on the SAIMD as it is being used by the Department of Social Development to identify the most deprived areas to target their social grants and initiatives. SAIMD has five deprivation domains—income and material, employment, health (2000 version only), education, living environment—and the selection for these domains was based on the following criteria (71): (*i*) it must be domain-specific and appropriate for the purpose (as direct as possible measures of that form of deprivation); (*ii*) it must measure major features of that deprivation (not conditions just experienced by a very small number of people or areas); and (*iii*) it must be statistically robust.

The SAIMD reports national values for domains only, not for the individual indicators, and it would require significant statistical work to determine the national current status. Instead, the most similar indicators and their current status were taken from the 2012 Development Indicators Report (72) published by the Department for Performance Monitoring and Evaluation in the Presidency and the statistical report by StatsSA on the 2012 General Household Survey (GHS), which surveyed a representative national sample of 31,144 Dwelling Units (73).

Domain 1: Basic Services.

Energy access. Raworth used two indicators for energy access, "Population lacking access to electricity" and "Population lacking access to clean cooking facilities," neither of which appear in the MDGs. The SAIMD indicator is "Number of people living in a household with electricity access" and the Development Indicators reports "Number of households with electricity access" (76.5% in 2011/2012). GHS 2012 reports the percentage of households that were connected to the mains electricity supply (85% in 2012) and the Census 2011 (27) reports the household electricity use (for cooking, lighting and heating) rather than access. Alternative forms of energy (gas, paraffin, wood, coal, candles, animal dung, solar, other) are recorded in Census 2011 and GHS 2012; however, universal electricity access is the clear national priority. We chose the simplest deprivation indicator, "Number of households without electricity access," and in 2012, 23.5% of households were deprived of electricity access, down from 49.1% in 1995 (72).

Water access. Raworth's (70) indicator for water access was "Population without access to an improved drinking water source," which is MDG 7.8. The global MDG target is "20*l* per person per day within 1km of household"; however, the South African MDG target is higher at "25*l* of potable water per person per day without interruption for more than 7 d within 200m of the household," known as the Reconstruction and Development Programme (RDP) standard (74), and both are reported in Development Indicators 2012. Census 2011 and GHS 2012 record both access to piped water and the source of water. There are seven levels of access to piped water based on distance from the dwelling, ranging from "tap water in dwelling" to "no access to tap water," shown in Table S6. The SAIMD indicator is "Number of people living in a household without piped water in their dwelling or yard," which combines the best two levels. Census 2011 reports household access at this level as 73.4%. Therefore, 26.6% of households were deprived of this level of water access, down from 39.3% in 1996. Table S7 also shows the possible range in the current status based on the level of access that is chosen as the indicator (i.e., the boundary of unacceptable deprivation). The difference between level 1 and level 2 is 29.1% and the difference between level 2 and level 3 is 11.7%. We used the RDP standard quoted in Development Indicators 2012, where 4.5% of households were deprived of this level of water access, down from 38.3% in 1994, as it is used as the official government indicator. This value of 4.5% is quite different to the Census 2011 value of 14.9% and should be reviewed in subsequent versions.

Sanitation. Raworth's (70) indicator for sanitation was the MDG 7.9 indicator "Proportion of population using an improved sanitation facility." The South Africa MDG report 2010 (74) further specifies it as "All households to have access to at least a ventilated pit latrine on site," which is reported in Development Indicators 2012. Similar to water access, Census 2011 and GHS 2012 define eight levels of sanitation for households that range from a "flush toilet connected to a sewerage system" to "chemical toilet" to "bucket toilet" to "none." The indicator used for the SAIMD indicator is "Number of people living in a household without a ventilated pit latrine or a flush toilet," which combines the first four levels and is reported in Development Indicators. We therefore used this indicator. In 2012, 16.6% of households were deprived of this level of sanitation, down from 49.1% in 1994.

In the South African Social Attitudes Survey (SASAS) 2005, 84% of respondents said that having a flush toilet in the house was essential (80). This finding could be used as the indicator (combining level 1 and 2) in the future, which would change the current status of deprivation from 16.6% to 60.1%.

Housing. Housing was added as a new dimension, as it is included in SAIMD and is a Constitutional right in South Africa. Large informal settlements emerged during Apartheid and now hinder the provision of basic services. Over 3.38 million houses have been built since 1994 by the government to correct this historical imbalance and to support poverty alleviation (72). The SAIMD indicators are "Number of people living in a shack (informal dwelling)" and "Number of people living in a household that is crowded." Development Indicators 2012 reports the number of "households in formal dwelling" and we used this indicator as it reports national data. In 2011, 22.5% of households were deprived of formal housing, down from 40.0% in 1996.

Other indicators that can be taken from Census 2011 are average household size (3.4 in 2011, down from 4.5 in 1996) and tenure status (41.3% owned and fully paid off, 11.8% owned but not paid off, 25% rented, 18.6% occupied rent-free, and 3.4% other).

Domain 2: Public Goods.

Education. Raworth (70) used two MDG indicators for education: "Children not enrolled in primary school" (MDG 2.1) and "Illiteracy among 15–24-y-olds" (MDG 2.3). South Africa has achieved universal access to primary school and therefore no longer reports this indicator. The SAIMD uses "Number of adults (18–65 y) with no secondary schooling," which is a higher level of achievement and more suited to a middle-income country. Development Indicators reports an adult literacy rate, which is the percentage of adults 20 y and older who have achieved 7 y of education (i.e., passed grade 7, based on the GHS). We chose the deprivation indicator "Adults without (≥20 y old) without more than 7 y of schooling (adult illiteracy)." We used the current status given in Development Indicators 2012, which differs slightly from the GHS 2013 figures (73), as it has more historical data. In 2011, 19.3% of adults were deprived of this level of education, down from 30.4% in 1995. The GHS has historically measured adult literacy rates based on an individual's functional literacy (i.e., whether they have completed grade 7). Because this may not correlate to an individual's ability to read and write, in GHS 2009, a separate question was introduced on the level of difficulty an individual has in reading and writing (73).

A number of other indicators are reported in Development Indicators 2012, including early childhood development, learner-educator ratios, national senior certificate pass rates, and the sex parity index (GPI) for basic and higher education. These provide an indicator of the quality of education and sex equality in education. A sex component could therefore be added to education by including the GPI, which is the ratio of GER (Gross Enrolment Rate) of female learners to the GER of male learners regardless of age, in public and independent ordinary schools for a given year. In 2011, the GPI was 0.98 for primary schools, 1.071 for secondary schools, and 1.39 for higher education (72), showing a decrease in sex equality as children progress through the education system.

Health care. Raworth's (70) indicator for health care was "lack of regular access to essential medicines" (MDG 8.13), but there is no data available in national MDG reports. A number of health-related indicators are reported under MDG 4, MDG 5, and MDG 6, and many, such as child mortality, HIV and tuberculosis prevalence, malaria fatality rates, and immunization coverage, are reported in Development Indicators 2012.

The SAIMD identifies health deprivation as years of potential life lost, where the level of unexpected mortality is weighted by the age of the individual who has died (76). This is a sex- and age-standardized measure of premature death and no national values exist. The closest indicator in Development Indicators 2012 is life expectancy (58.7 y in 2012), however this gives an average for the population; hence, it cannot measure what percentage of the population is deprived. The Department of Health's Health Data Advisory and Coordinating Committee established a set of high-level indicators for Government Outcome 2 and identified the Rapid Mortality Surveillance maintained by the South African Medical Research Council as an important source of data (77). In addition to life expectancy and mortality rates, the Rapid Mortality Surveillance reports an "adult mortality index ($_{45}q_{15}$)," the probability of a 15-y-old person dying prematurely before the age of 60 y. In 2011, the adult mortality index in South Africa was 40%, down from 46% in 2009 (78). Again, this indicator does not suit the barometer, as it does not measure what percentage of the population is deprived. The most suitable indicator for the barometer is immunization coverage, because it measures a proportion of the population (9.2% of infants were immunised in 2011) rather than a rate or absolute number. A sex component could be added to health by including "maternal mortality ratio."

Additional health-related data can be found in Census 2011, which reports on disabilities and assistive devices and medication. The four levels of disability reported are subjective (i.e., dependent on how the respondent rated themselves) (27). Very few people are totally disabled, up to 1.5% have a lot of difficulty with one or more disabilities, 1–10% of people have some difficulty, and generally over 90% of the population has no difficulty. Results also showed that 12.3% of the population was on chronic medication, 14.0% used eye glasses, 2.8% used a hearing aid, 3.2% used a walking stick or frame, and 2.3% used a wheelchair. Disability is not a measure of deprivation; rather, the lack of access to assistive devices represents deprivation. As these data are not readily available, it could not be used.

Voice. There is no agreed definition of "voice" and Raworth (70) did not define an indicator for voice, although her sex-empowerment indicator "sex gap in parliament" could be provide a sex component to this dimension. Development Indicators 2012 has a number of indicators under the heading "Social cohesion: Voice and Accountability." Social cohesion has become a common term in South African development debates, where it refers to the ideal of a harmonious society, very different to the racially divided Apartheid society (79). Research by Struwig et al. (79) at the University of the Western Cape is on-going to develop a social cohesion barometer for South Africa. The Development Indicators that could measure voice are membership of voluntary organizations, voter turnout, female representation in parliament, and the corruption perceptions index. None of these indicators were used, based on expert judgment or because the indicator is not a deprivation measure or is sex-specific.

Instead, experts recommended that voice should measure public participation in decision-making. South Africa has progressive legislation on local government where communities are consulted on their Integrated Development Plans (IDPs). In the 2005 SASAS, however, only 8% of respondents indicated that they participated in the IDP process, although this is thought to be overreported (80). The majority (91%) of those who participated in the IDP process felt they had "some" to "much" influence on local government decision-making, whereas only 28% of those who did not participate felt the same. The results from Round 5 of the Afrobarometer (citizen surveys of democracy and governance in Africa) in South Africa (81) show that 16% of respondents do not feel free to say what they think, 37% think that local councillors never take time to listen to people like them, 51% think local councillors are involved in corruption, 58% would never attend a protest march, 51% do not trust the police, 21% fear becoming a victim of political intimidation during election campaigns, and 3% think that South Africa is not a democracy.

Because of the lack of wide support for any specific indicator, and the large range in values for different indicators, we decided to keep the dimension without a national indicator at this stage, with further research required.

Connectivity. Connectivity was considered as a new dimension in the Public Goods domain. Two aspects were reviewed: Internet access and access to public transport. However, neither met all of the criteria for indicator selection and, hence, we did not include it. The analysis does show potential for including connectivity in future versions of the barometer.

Internet access is reported under "global competitiveness" in Development Indicators 2012 as the percentage of the population who were Internet subscribers (10.7%) and broadband subscribers (3.6%) in 2009. According to GHS 2012, 40.6% of South African households have at least one member with access to the Internet at home, work, place of study, or Internet cafés. This is a 5% increase from 2011 when the Census reported that 16% of households access the Internet via cell phones, 8.6% accessed it from home, and 4.7% access it from work and 5.6% access it from elsewhere. This result provides a measure of deprivation that could fit into the barometer; however, it is not seen as a national priority at present.

Access to public transport is more complicated than Internet access. It could be measured using GHS 2012 data on modes of transport for getting to school and work. Only 3.4% of scholars and only 9.2% of the workforce use the bus or train. This finding is partly because of affordability and proximity (69% of scholars walk to school) and partly because of private car ownership (36% of people use a private car to get to work), and does not directly measure deprivation as individual choice is involved.

Domain 3: Livelihoods.

Jobs. Raworth (70) did not define an indicator for jobs but suggested "Labor force not used in decent work." SAIMD calculates employment deprivation by adding the number of people who are unemployed (using the official definition) and the number of people who are not working because of illness or disability, which totalled 37.8% in 2007. Using data from StatsSA's labor force surveys, Development Indicators 2012 reported a broad unofficial unemployment rate (adults aged 15–64 without work and available to work) of 36.3% and a narrow official unemployment rate (adults aged 15–64 without work and available to work and have taken steps to look for work or start a business) of 25.1% in 2012. Because the broad definition is closest to SAIMD, it was chosen for this case study.

The narrow unemployment rate is further disaggregated by province, age, and sex, and into long-term unemployed (68% of total) and short-term unemployed (32% of total). Youth unemployment (age 15–24) is 50.9% and female unemployment (27.9%) is 5.5% higher than male unemployment. Raworth's indicator for sex equality, "the employment gap in waged work (excluding agriculture)," could be incorporated into this dimension, but as the broad official unemployment figures are not disaggregated we could not include it here.

Income. Raworth's (70) indicator for income was the MDG indicator "Population living on less than USD 1.25 (PPP) per person per day," although USD 2.5 (PPP) is also an MDG indicator. This amount can be measured by income or expenditure and for South Africa it equates to R191 or R382 per person per month in 2011 constant Rands (72). The SAIMD in 2007 used "household income below 40% of the mean equivalent household income" (~R1,003 per person per month in 2007) in the absence of an official national poverty line. A number of different poverty lines have been used in South Africa since 1994; however, Development Indicators 2012 reports a food poverty line (amount of money an individual will need to consume the minimum required energy intake) of R305 per person per month (in 2011 Rands), and an upper-bound and lower-bound poverty line (food poverty line plus average amount derived from nonfood items of households whose total food expenditure is equal to the food poverty line) of R577 and R416, respectively. These numbers are based on the Living Conditions Survey 2007/2008 (82), which reported that 26% of the population lived below the food poverty line, 39% lived below the lower-bound poverty line, and 52% lived below the upper-bound poverty line.

There are, therefore, a range of different indicators that can be used for income deprivation, which give a very different picture of poverty in the country. We used the national upper-bound poverty line because it is an official level and is the closest to the SAIMD value, although it is still only roughly half of the SAIMD value.

Domain 4: Living Standards.

Food security. Food security has three components: access, availability, and utilization (83). South Africa has been food-secure at a national scale for a number of decades and has produced enough maize for 47 of the past 50 y, with drought causing the insufficiency in 3 y. Raworth's (70) indicator was "Population malnourished," which is based on MDG 1.9 "Proportion of population below minimum level of dietary energy consumption," but there is no recent national data for this in South Africa. The 2005 National Food Consumption Survey indicated that the proportion of underweight children under 5 y of age was about 10% while stunting in this age group was about 21% (72). The national MDG Report and Development Indicators have data for "Severe malnutrition in children under five years old" (MDG 1.8) but there are concerns over the accuracy of the data, which is sourced from the District Health Information System. Food is not part of SAIMD, as income was seen as a good proxy for food, and food was not recorded in the 2001 Census or 2007 Community Survey. The GHS 2013 did include questions about food access and it reports what percentage of households are vulnerable to hunger and percentage of households with either adequate, inadequate, or severely inadequate food (84). We used the indicator "households without adequate food," which was 23.1% in 2013.

An alternative approach could be to use the food poverty line mentioned in the section on income. In 2008/2009, 26.3% of the population lived under the food poverty line (i.e., on less than R305 per person per month).

Household goods. We added "Household goods" as a new dimension, as it is included in SAIMD as part of material deprivation. The SAIMD has two indicators: "ownership of a refrigerator" and "ownership of a radio and/or landline telephone." We chose the former indicator because radios and landlines are being replaced by cell phones (radio ownership fell from 72% in 2001–67.5% in 2011 and landline ownership fell from 23.9% in 2001–14.5% in 2011) (27). These data are collected in some household surveys and is reported in Census 2011 and GHS 2013, although it is not mentioned in the MDGs or the Development Indicators reports. In 2013, 28.1% of households did not own a refrigerator (84).

Other indicators for household goods reported in Census 2011 are household ownership of a cell phone (88.9%), television (74.5%), computer (21.4%), stove (77%), car (29.5%), satellite television (25.8%), DVD player (59.3%), or washing machine (31.5%), which have all increased since 2001 (i.e., deprivation has decreased).

In the SASAS 2005 (80), the household items that more than half of all respondents felt were essential were a refrigerator (89% said this was essential), a radio (77%), an electric cooker (74%), a television (72%), a landline phone (64%), a cell phone (63%), and a sofa/lounge suite (52%).

Safety. Safety was added as a new dimension because it is an important issue in South Africa and it was intended to be included in SAIMD but was left out because of lack of small area data. Safety is a complex dimension to measure; crime statistics do not compare well across jurisdictions (except for murder), perceptions of safety do not necessarily reflect potential for victimisation, and high risk does not necessarily equate to high crime rates. StatsSA has conducted four Victims of Crime Surveys (1998, 2001, 2010, 2011), which measure household perceptions and experiences of crime. Development Indicators 2012 reports a range of indicators including perceptions of safety, serious crime rates, detection rates, and prison inmates. Most of these indicators cannot be used as they measure rates and not proportions of the population. We chose the indicator "households that feel unsafe walking alone at night," which was 63.5% in 2012, an increase of nearly 20% from in 44% in 1998. As one of the few social indicators that are trending toward larger deprivation levels, this highlights a serious concern.

Raworth's Dimensions That Were Removed.

Resilience. Raworth did not define an indicator for resilience. Most South African experts thought that it did not fit in the barometer because it is a cumulative effect and is dependent on the other dimensions, and therefore an indirect measure. For example, having a good health and education makes an individual more resilient to unemployment. Because it does not meet the criteria, it was removed as a dimension for this case study.

Of interest is the National Income Dynamics Survey, which includes questions on household shocks (85), and therefore provides a qualitative measure of resilience. This survey measures the types of shocks (health, economic, and so forth), the severity of the shocks, and households' coping mechanisms. Results show that most people respond to shocks by reducing spending and substituting with inferior goods (e.g., using firewood instead of electricity). One of the biggest shocks is unforeseen shocks, such as food price spikes.

Social equity. Raworth's (70) indicator for social equity is "Population living on less than the median income in countries with a Gini coefficient exceeding 0.35" (i.e., it measures income inequality). The Gini coefficient is a popular measure of income inequality; however, it is slow to change. The Palma index (ratio of top 10% income to bottom 40% income) for South Africa increased from 5.69 in 1993–7.05 in 2008 (86), and the Theil index for racial inequality dropped from 0.549 in 1993 to 0.240 in 2009 (87). Inequality is not confined to income but exists across the multiple dimensions of deprivation. In fact, the other dimensions of the barometer already discussed provide a set of inequality measures for South Africa, and we therefore removed it as a dimension. We would like to see future versions of the barometer incorporate inequality across race, sex, and geographical location.

Sex equality. Raworth (70) had two indicators for sex equality: "Employment gap between women and men in waged work (excluding agriculture)" and "Representation gap between women and men in national parliaments." These have both been discussed in the earlier sections on jobs and voice. As with social inequality, sex equality is a cross-cutting issue that cannot be simplified into a single indicator. The UN's Sex Inequality Index (GII) combines five indicators: maternal mortality, adolescent fertility, education, representation, and labor force participation (88). As already mentioned, these could be addressed under the dimensions of health, education, voice, and jobs. Ideally, sex equality should be measured for all of the dimensions of the barometer. This was not done in this case study because of lack of available data, but data analysis of household survey results could provide the necessary information for future iterations.

Section C. Experts Interviewed in South Africa

Semistructured interviews were held with 43 experts from government, national research institutes, universities, and international nongovernmental organizations in Johannesburg, Pretoria, Cape Town, Stellenbosch, Durban, and Pietermaritzburg (Table S7). A draft version of the barometer for inclusive sustainable development for South Africa was shown to the experts. Questions covered five aspects: perceptions of the barometer, environmental stress dimensions, social deprivation dimensions, the utility of the barometer, and suggested experts to contact. The interview questions were tailored to the expert's sector/specialism so that experts were asked to recommend the most suitable indicator, boundary, and data source for each dimension of the barometer. Experts were also asked about data quality and availability and relevant current and future research.

Section D. Proposed Sustainable Development Goals

The Open Working Group (OWG), established in January 2013 by the UN General Assembly, was tasked with preparing a proposal for the Sustainable Development Goals. The OWG has developed 17 proposed goals to be attained by 2030, listed below, which together have 148 targets, defined as "global targets, with each government setting its own national targets guided by the global level of ambition but taking into account national circumstances" (89). No indicators have been developed as yet, but there are likely to be at least double the number of goals. Equity and sex equality are mentioned in most of the proposed goals and climate change is mentioned in nearly half of them. Table S8 compares the indicators used in our barometer with the most relevant goals in the OWG's Zero Draft (89). All of the indicators in the barometer are covered, except "household goods," although this could be incorporated into proposed goal 1.

i) End poverty everywhere (7 targets).
ii) End hunger, improve nutrition and promote sustainable agriculture (9 targets).
iii) Attain healthy lives for all (10 targets).
iv) Provide quality education and life-long learning opportunities for all (9 targets).
v) Attain sex equality, empower women and girls everywhere (9 targets).
vi) Ensure availability and sustainable use of water and sanitation for all (7 targets).
vii) Ensure sustainable energy for all (6 targets).
viii) Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (7 targets).
ix) Promote sustainable infrastructure and industrialisation and foster innovation (8 targets).
x) Reduce inequality within and between countries (10 targets).
xi) Make cities and human settlements inclusive, safe, and sustainable (8 targets).
xii) Promote sustainable consumption and production patterns (10 targets).
xiii) Tackle climate change and its impacts (4 targets).
xiv) Conserve and promote sustainable use of oceans and seas and marine resources (8 targets).
xv) Protect and promote sustainable use of terrestrial ecosystems, halt desertification and biodiversity loss (9 targets).
xvi) Achieve peaceful and inclusive societies, access to justice for all, and effective and capable institutions (10 targets).
xvii) Strengthen the means of implementation and the global partnership for sustainable development (17 targets).

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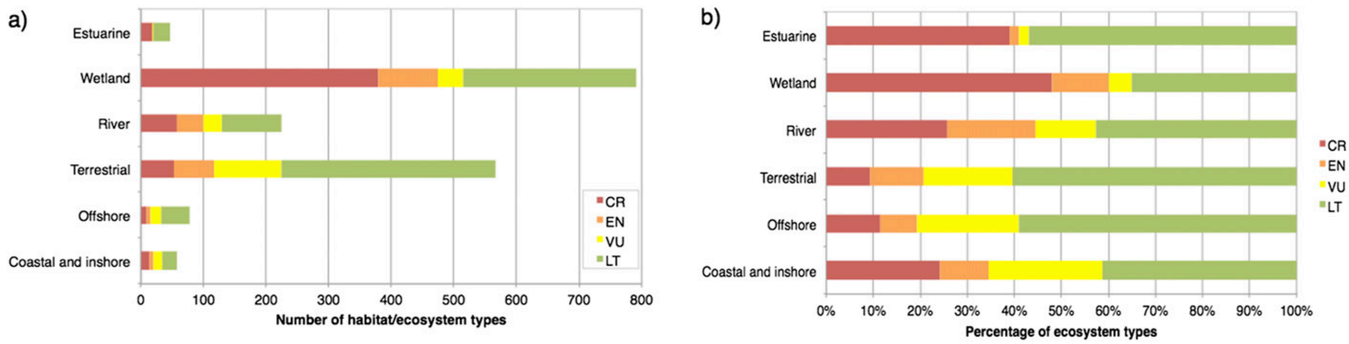

Fig. S1. Threat status of ecosystem types by (*A*) number and (*B*) percentage [Data source: NBA 2011 (46)].

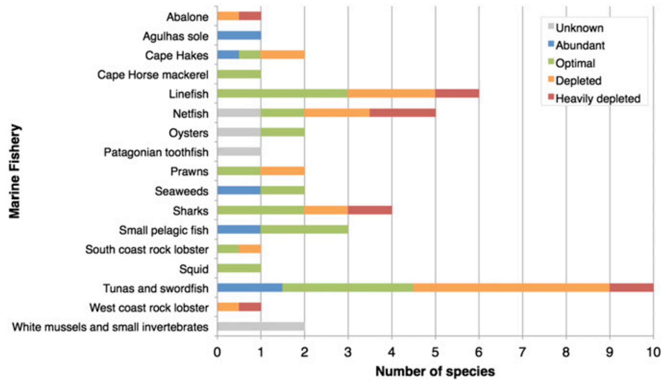

Fig. S2. Status of South African Marine Fishery Resources 2012 [Data source: DAFF 2013 (48)].

Table S1. Comparison of the indicators for the planetary boundaries (1), the ESI 2011 (2), and our environmental barometer

Dimension	Planetary boundary indicator	DEA's environmental sustainability Indicators 2011	Actual indicator used
Climate change	CO_2 concentration (ppmv) Change in radiative forcing (Wm^2)	Annual CO_2 direct emissions (total and per capita)	Annual total CO_2 direct emissions
Ozone depletion	Ozone concentration (Dobson units)	Annual production of CFCs, MBr and HCFCs Annual consumption of CFCs, MBr and HCFCs	Annual consumption of HCFCs
Biodiversity loss	Extinction rate (number of species per million species per year)	Threatened bird, mammal, amphibian and reptile species (%) Threat and protection status of vegetation types per biome (%)	Endangered and critically endangered ecosystems
Nitrogen and Phosphorous cycles	Amount N_2 removed from atmosphere for human use (Mt/yr)	Fertilizer sales (kg)	Nitrogen application rate for maize production
	Phosphorous flowing into oceans (P Mt/yr)	Freshwater quality – Total phosphate concentration in dams (P mg/L) Freshwater quality – Orthophosphate concentration in dams (PO4 mg/L)	Total mean annual P concentration in dams in mg/L
Ocean acidification/marine harvesting	Global mean saturation state of aragonite in surface sea water	West coast rock lobster landings (t) Catches of selected marine species (kg/nominal mass) Marine protected areas (status)	Depleted marine fisheries stocks (percent of known species)
Freshwater use	Consumption of freshwater by humans (km^3/yr)	Available water per capita (m^3) Capacity and levels of dams (m^3) Groundwater quantity (distance below ground level) Water stress per WMA in 2025 (yield v requirements)	Consumption of freshwater by humans in Mm^3/yr
Land use change/land use	Percent global land cover converted to cropland	Degraded and transformed land (%) Grazing capacity (ha/livestock) Protected land area (%)	Rain-fed arable land converted to cropland
Aerosol loading/Air pollution	Overall particulate concentration in the atmosphere	Domestic fuel burning (Households by energy source for cooking & heating & lighting) Coal consumption (TJ) Vehicle use (vehicles/area) Death rate from respiratory diseases and tuberculosis	Annual mean PM_{10} concentration in $\mu g/m^3$
Chemical pollution	Not defined	Not mentioned	Not defined

Table S2. Water resources in South Africa

	Water resources	Annual volume ($Mm^3 \cdot yr^{-1}$)	Percentage of MAR (%)	Source
A1	Mean annual runoff (MAR)	49,210		Enhanced WR2005 (16)
A2	Ecological Reserve (in-stream flow requirements)	12,302	25	NWRS 2013 (17)
A3	Surface water storage capacity	31,620	64	DWA 2014 (19)
A4	Evaporation from dams	3,000	6	Pitman 2011 (25)
A5	Available surface water yield (assurance of supply)	10,240	21	NWRS 2004 (20)
A6	Surface water used in rural areas (direct from source)	57	0	Census 2011 (27)
B1	Utilizable groundwater exploitation potential	7,500		Enhanced WR2005 (16)
B2	Available groundwater yield	2,000		NWRS 2013 (17)
C1	Usable return flows/effluent yield	1,899		NWRS 2004 (20)
	Total available yield (assurance of supply)	14,196		

Table S3. Water use in South Africa based on the NWRS 2004 (20), NWRS 2013 (17), and the WARMS database in 2014 (32)

	Requirements in 2000		Allocation in 2013	
Water use	$Mm^3 \cdot yr^{-1}$	% of total	$Mm^3 \cdot yr^{-1}$	% of total
Irrigation	7,920	62	11,005	58
Forestry	428	3	428	2
Power generation	297	2	365	2
Mining and bulk industrial (nonurban)	755	3	907	5
Urban (industry and other)	2,897	23	3,325	17
Rural	574	4	677	4
Trade and Services*			2,278	12
Total	12,871	100	18,895	100

*The WARMS category Water Supply Services includes construction, trade, services, tourism, transport, and communication.

Table S4. South Africa's 2002 land capability classification and agricultural land in 2012 [Data source: Collett 2013 (35)]

				Agricultural land in 2012			
Land capability class			Land capability area in 2002 (ha)*	Area (ha)	Percentage of total land (%)		
Arable	I	Very intensive crop production	2,733	2,634	0.0	12.1	25
	II	Intensive crop production	1,878,597	1,720,506	1.4		
	III	Moderate crop production	14,003,339	12,971,417	10.7		
	IV	Limited crop production (marginal cropland)	16,447,446	15,658,941	12.9	12.9	
Nonarable	V	Pastures	13,609,335	13,354,526	11.0	61.4	71.4
	VI	Veld reinforcement	18,114,793	17,576,101	14.4		
	VII	Veld and Forestry	45,343,216	45,061,442	37.0		
	VIII	Wildlife	12,279,370	12,193,972	10.0	10.0	
		Water bodies	246,052	—	—	—	
Total			121,924,881	118,539,538	97.4	97.4	

*The 2002 land capability study covered all land in South Africa.

Table S5. Comparison of social indicators in Raworth's SJS (70), SAIMD (71, 76), and our social barometer

Dimension	Raworth's SJS Indicator	SAIMD Indicators	Indicator used in barometer
Energy	Population lacking access to electricity Population lacking access to clean cooking facilities	Number of people living in a household without use of electricity for lighting	Households without access to electricity
Water	Population without access to an improved drinking water source	Number of people living in a household without piped water inside their dwelling or yard	Households without access to water infrastructure ≥ RDP standard (25l potable water per person per day within 200m of household)*
Sanitation	Population without access to improved sanitation	Number of people living in a household without a pit latrine with ventilation or flush toilet	Households without access to sanitation (ventilated improved pit latrines)*
Housing	—	Number of people living in a shack, or in a household that is crowded	Households not in formal dwellings
Education	Children not enrolled in primary school Children enrolled in tertiary education Illiteracy among 15- to 24-y-olds	Number of adults (18–65 y) with no secondary schooling	Adults without more than 7 y of schooling (adult illiteracy rate)*
Health care	Population estimated to be without regular access to essential medicines	Years of Potential Life Lost† (standardized mortality ratio)	Infant (<1 y) immunization coverage
Jobs	For example: Labor force not used in decent work	Number of people who are unemployed (using official definition) plus number of people who are not working because of illness or disability	Broad unofficial unemployment rate (adults aged 15–64 available to work)
Income	Population living below US$1.25 (PPP) per day	Number of people living in a household that has a household income (need-adjusted using the modified OECD equivalence scale) that is below 40% of the mean equivalent household income (~ R1,003/mo in February 2007 Rands)‡	Population living below the upper national poverty line (R577 a month in 2011 constant Rands)
Social equity	Population living on less than the median income in countries with a Gini coefficient exceeding 0.35	—	—
Sex inequality	Employment gap between women and men in waged work (excluding agriculture) Representation gap between women and men in national parliaments	—	—
Food	Population undernourished	—	Households without adequate food
Voice	Not defined	Not mentioned	Not defined
Household goods	—	Number of people living in a household without a refrigerator Number of people living in a household with neither a television nor a radio	Households without a refrigerator
Safety	—	—§	Households who feel unsafe walking alone in their area during the night

*These indicators also appear in ESI 2011 (2).
†In SAIMD 2001 (76), which was based on the 2001 Census but not in SAIMD 2007 (71), which was based on the 2007 Community Survey.
‡This was used in the SAIMD because a national poverty line had not yet been defined.
§The intention was to include crime in the SAIMD but it was excluded because of lack of data in 2001 and 2007.

Table S6. Levels of water access in South Africa in October 2011 [Data source: Census 2011 (27)]

Level of household water access	Indicator	Percentage access (%)	Access deprivation (%)
1 - Tap water in dwelling		46.3	53.7
2 - Tap water in dwelling or yard	SAIMD	73.4	26.6
3 - Tap water within 200 m of dwelling	RDP standard	85.1	14.9
4 - Tap water within 500 m of dwelling		88.7	
5 - Tap water within 1 km of dwelling	MDG 7.8	90.4	
6 - Tap water >1 km from dwelling		91.2	
7 - No tap water access			8.8

Table S7. Organization, location and number of experts interviewed

Organization	City	No. of experts
Government		
National Government, Department of Environmental Affairs (DEA)	Pretoria	9
National Government, Department of Agriculture, Forestry and Fisheries (DAFF)	Pretoria	2
National Government, Department of Water Affairs (DWA)	Pretoria	1
National Government, Department of Social Development (DSD)	Pretoria	1
Western Cape Government, Department of Environmental Affairs and Development Planning	Cape Town	1
Ethekweni Municipal Government, Department of Climate and Environment Protection	Durban	1
	Subtotal	15
National research institutes		
Council for Scientific and Industrial Research (CSIR)	Stellenbosch, Durban	8
Human Sciences Research Council (HSRC)	Cape Town, Durban	2
South African National Biodiversity Institute (SANBI)	Cape Town	2
	Subtotal	12
Universities		
University of Stellenbosch (US)	Stellenbosch	1
University of Cape Town (UCT)	Cape Town	4
University of KwaZulu Natal (U.K.ZN)	Pietermaritzburg	1
	Subtotal	6
International nongovernmental organizationss		
World Wildlife Fund – South Africa (WWF-SA)	Cape Town	8
Oxfam GB	Johannesburg	2
	Subtotal	10
	Total	43

Table S8. Comparison of the barometer and the proposed Sustainable Development Goals from the OWG (89)

Dimension	Indicator used in barometer	Most relevant proposed SDG target	SDG proposed goal
Climate change	Annual direct CO_2 emissions	Integrate climate change adaptation and mitigation into national strategies and plans (UNFCCC targets may be included)	13
Freshwater use	Consumption of freshwater ($Mm^3 \cdot yr^{-1}$)	By 2030 bring freshwater extraction in line with sustainable supply, protect and restore ecosystems	6
Land use change	Use of arable land for cropland (ha)	By 2030, implement sustainable and resilient agricultural practices	2
Phosphorous cycle	Annual mean phosphorous concentration in reservoirs (mg/L)	By 2030 significantly improve water quality	6
Nitrogen cycle	Nitrogen application rate for maize production (kg/ha)	By 2030, implement sustainable and resilient agricultural practices	2
Biodiversity loss	Endangered ecosystems (%)	By 2020 take urgent and significant action to halt the loss of biodiversity, and protect and prevent the extinction of known threatened species	15
Marine harvesting	Depleted fish stocks (%)	By 2020 effectively regulate harvesting, end overfishing, illegal, unreported and unregulated (IUU) fishing and destructive fishing practices to restore by 2030 fish stocks at least to levels that can produce maximum sustainable yield	14
Air pollution	Average PM10 concentration (μg)	By 2030, substantially reduce the number of deaths and illnesses from air (indoor and outdoor) pollution	3
Chemical pollution	To be determined	Promote the sound management of chemicals and hazardous wastes in accordance with agreed international frameworks and by 2030 significantly reduce their release to air, water and soil	12
Energy	Households without access to electricity	By 2030 ensure universal access to affordable, sustainable and reliable energy services	7
Water	Households without access to water infrastructure ≥ RDP standard	By 2030 achieve universal access to safe and affordable drinking water for all	6
Sanitation	Households without access to at least ventilated improved pit latrines	By 2030 achieve adequate sanitation and hygiene for all, paying special attention to the needs of women and girls	6
Housing	Households not in formal dwellings	By 2030 ensure universal access to adequate and affordable housing	10
Education	Adults without more than 7 y of schooling (adult illiteracy rate)	By 2030 ensure all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	4
		By 2030 increase adult literacy and basic numeracy by at least x%	4
Health care	Infant (<1 y) immunization coverage	Achieve universal health coverage	3
Jobs	Broad unofficial unemployment rate (adults aged 15–64 available to work)	By 2030 achieve full and productive employment and decent work for all women and men, including young people and persons with disabilities, and equal pay for work of equal value	8
Income	Population living below the upper national poverty line (R577 a month in 2011 constant Rands)	By 2030, eradicate extreme poverty (less than $1.25/d)	1
		By 2030, reduce by half the proportion of people living below national poverty lines	1
Food	Households without adequate food	By 2030, end hunger and ensure that all people have access to adequate, safe and nutritious food all year round	2
Voice	Not defined	By 2030 increase inclusive, participatory and representative decision-making at all levels	16
Household goods	Households without a refrigerator		
Safety	Households who feel unsafe walking alone in their area during the night	By 2030 reduce levels of violence and halve related death rates everywhere	16