Planetary Boundary: ‘Atmospheric aerosol loading’

The boundary of atmospheric aerosol loading as well as its threshold behavior is yet to be determined. Certain instead is though that the overall particulate concentration of aerosols in the atmosphere interacts with the boundaries of climate change and global freshwater use as well (Rockström et al. 2009). The following introduction is a combination of paper excerpts, derived from Andrae (1995), Steffen et al. (2015) and Rockström et al. (2009).

Sources of aerosols

“...Aerosol particles can be produced by two distinct mechanisms: the direct injection of particles into the atmosphere (e.g. dust, sea spray) resulting in so-called “primary” aerosols, or the production of “secondary” aerosols by the conversion of gaseous precursors into liquid or solid particles. Primary aerosols dominate the “coarse” fraction of the aerosol (the particles with diameter greater than 1μm), while secondary particles constitute most of the “fine” aerosols (particle sizes typically below 1μm). Table 1 summarizes the various sources of aerosol particles and presents estimates of their magnitude.”

Climatic effects of aerosols

"Aerosols interact with the Earth’s radiation budget both directly by scattering and absorbing radiation, and indirectly by modifying the extent and radiative properties of clouds. Unfortunately, neither effect is related in a straightforward, linear fashion to a single variable, such as the total mass burden of atmospheric aerosols. Instead, the effects are dependent on the size spectrum of the aerosol particles, on their chemical composition, on their spatial and temporal distribution etc. This makes an assessment of their climatic effect much more difficult than that of the long-lived and relatively evenly distributed greenhouse gases [...]. Aerosols not only scatter radiation, but also absorb certain amounts of short-wave and long-wave radiation. Both scattering and absorption of light result in a loss of radiation arriving at the earth’s surface, and therefore lead to negative forcing at the surface. But light absorbed by aerosols still enters the Earth’s radiation budget and produces a warming effect in the atmosphere. Siliceous materials, i.e. soil and desert dust, absorb strongly in the thermal infrared region, and dense dust clouds can therefore lead to a trapping of infrared radiation in the same way as the trace gas greenhouse effect.”

Table 1: Estimates of present-day global emission of major aerosol types (in Tg/year)

<table>
<thead>
<tr>
<th>Source</th>
<th>Present flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td></td>
</tr>
<tr>
<td>Soil dust (mineral aerosol)</td>
<td>1,000</td>
</tr>
<tr>
<td>Sea-salt</td>
<td>1,000</td>
</tr>
<tr>
<td>Volcanic dust</td>
<td>4</td>
</tr>
<tr>
<td>Biological debris</td>
<td>26</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
</tr>
<tr>
<td>Sulphates from biogenic gases</td>
<td>60</td>
</tr>
<tr>
<td>Sulphates from volcanic SO2</td>
<td>4</td>
</tr>
<tr>
<td>Organic matter from biogenic NMHC(^*)</td>
<td>40</td>
</tr>
<tr>
<td>Nitrates from NO(_x)</td>
<td>10</td>
</tr>
<tr>
<td><strong>Anthropogenic</strong></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td></td>
</tr>
<tr>
<td>Industrial dust etc.</td>
<td>40</td>
</tr>
<tr>
<td>Black carbon (soot and charcoal)</td>
<td>10</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
</tr>
<tr>
<td>Sulphates from SO2</td>
<td>120</td>
</tr>
<tr>
<td>Biomass burning (w/o black carbon)</td>
<td>50</td>
</tr>
<tr>
<td>Nitrates from NO(_x)</td>
<td>20</td>
</tr>
<tr>
<td>Organics from anthropogenic NMHC(^*)</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>2,390</td>
</tr>
</tbody>
</table>

\(^*\)NMHC, non-methane hydrocarbons.

Impact of aerosols on regional ocean-atmospheric circulation

“Aerosols have well-known, serious human health impacts, leading to about 7.2 million deaths per year (64). They also affect the functioning of the Earth System in many ways (65). Here we focus on the impact of aerosols on regional ocean-atmosphere circulation as the rationale for a separate aerosols boundary. We adopt aerosol optical depth (AOD) as the control variable and use the South Asian monsoon as a case study, based on the potential of widespread aerosol loading over the Indian subcontinent to switch the monsoon system to a drier state. The background AOD over South Asia is ~0.15 and can be as high as 0.4 during volcanic events (66). Emissions of black carbon and organic carbon from cooking and heating with biofuels and from diesel transportation, and emission of sulfates and nitrates from fossil fuel combustion, can increase seasonal mean AODs to as high as 0.4 (larger during volcanic periods), leading to decreases of 10% to 15% of incident solar radiation at the surface. A significant decrease in monsoon activity is likely around an AOD of 0.50, an increase of 0.35 above the background (67). Taking a precautionary approach towards uncertainties surrounding the position of the tipping point, we propose a boundary at an AOD of 0.25 (an increase due to human activities of 0.1), with a zone of uncertainty of 0.25 to 0.50. The annual mean AOD is currently about 0.3 (66), within the zone of uncertainty.”


The planetary boundary

“We consider atmospheric aerosol loading as an anthropogenic global change process with a potential planetary boundary for two main reasons: (i) the influence of aerosols on the climate system and (ii) their adverse effects on human health at a regional and global scale.

Human activities since the pre-industrial era have doubled the global concentration of most aerosols (Tsigaridis et al. 2006). Aerosols influence the Earth’s radiation balance directly by scattering incoming radiation back to space (Charlson et al. 1991, 1992) or indirectly by influencing cloud reflectivity and persistence (Twomey 1977, Albrecht 1989). Aerosols can also influence the hydrological cycle by altering the mechanisms that form precipitation in clouds (Ferek et al. 2000, Rosenfeld 2000). Aerosols may have a substantial influence on the Asian monsoon circulation (Ramanathan et al. 2005, Lau et al. 2008): absorbing aerosols over the Indo-Gangetic plain near the foothills of the Himalayas act as an extra heat source aloft, enhancing the incipient monsoon circulation (Lau and Kim 2006). The same aerosols lead to a surface cooling over central India, shifting rainfall to the Himalayan region. This “elevated heat pump” causes the monsoon rain to begin earlier in May–June in northern India and the southern Tibetan plateau, increases monsoon rainfall over all of India in July–August, and reduces rainfall over the Indian Ocean. Although the influences of aerosols on the Asian monsoon are widely accepted, there is still a great deal of uncertainty surrounding the physical processes underlying the effects and the interactions between them.

From the perspective of human-health effects, fine particulate air pollution (PM2.5) is responsible for about 3% of adult cardiopulmonary disease mortality, about 5% of tracheal, bronchial, and lung cancer mortality, and about 1% mortality from acute respiratory infection in children in urban areas worldwide (Cohen et al. 2005). These effects convert to about 800 000 premature deaths and an annual loss of 6.4 million life years, predominantly in developing Asian countries. Mortality due to exposure to indoor smoke from solid fuels is about double that of urban air pollution (roughly 1.6 million deaths), and exposure to occupational airborne particulates accounts for roughly 300 000 deaths per year, mainly in developing countries.
The same aerosol components (e.g., particulates, tropospheric ozone, oxides of sulphur and N) lead to other deleterious effects. Crop damage from exposure to ozone, forest degradation and loss of freshwater fish due to acidic precipitation, changes in global precipitation patterns and in energy balance are further examples of indirect effects of air pollution on human well-being.

The complexity of aerosols, in terms of the large variety of particles involved, with different sources, impacts, and spatial and temporal dynamics, makes it difficult to define a planetary boundary above which effects may cause unacceptable change. Additionally, although aerosols have been clearly linked with changes in monsoon circulation and with adverse human-health effects, the processes and mechanisms behind these correlations remain to be fully explained. For these reasons, we conclude that it is not yet possible to identify a safe boundary value for aerosol loading.”


**Exercise:**

In order to introduce the planetary boundary of ‘atmospheric aerosol loading’ to the rest of the group, please summarize the main sources for and impacts of aerosols. Further describe the difficulty of defining a planetary boundary. If possible try to find an example to visualize your findings.
Planetary Boundary: ‘Chemical pollution’

Chemical pollution describes the process of chemicals being released into the environment polluting the ecosystems. There are many sources of chemical pollution. Our technological advances have made us a species largely reliant on chemicals and these chemicals are toxic to life and our environment. The following is an excerpt of a scientific article about the boundary of chemical pollution, derived from Rockström (2009).

“Primary types of chemical pollution include radioactive compounds, heavy metals, and a wide range of organic compounds of human origin. Chemical pollution adversely affects human and ecosystem health, which has most clearly been observed at local and regional scales but is now evident at the global scale. Our assessment on why chemical pollution qualifies as a planetary boundary rests on two ways in which it can influence Earth System functioning: (i) through a global, ubiquitous impact on the physiological development and demography of humans and other organisms with ultimate impacts on ecosystem functioning and structure and (ii) by acting as a slow variable that affects other planetary boundaries. For example, chemical pollution may influence the biodiversity boundary by reducing the abundance of species and potentially increasing organisms’ vulnerability to other stresses such as climate change (Jenssen 2006, Noyes et al. 2009). Chemical pollution also interacts with the climate-change boundary through the release and global spread of mercury from coal burning and from the fact that most industrial chemicals are currently produced from petroleum, releasing CO2 when they are degraded or incinerated as waste. There could be even more complex connections between chemical, biodiversity, and climate-change boundaries. For example, climate change will change the distributions of pests, which could lead to increased and more widespread use of pesticides. Setting a planetary boundary for chemical pollution requires knowledge of the critical impacts on organisms of exposure to myriad chemicals and the threshold concentrations at which these effects occur.

Deleterious consequences could be caused by direct exposure to chemicals in the abiotic environment—air, water, or soil—or through bioaccumulation or biomagnification up food chains, which could lead to effects in, for example, top predators. By current estimates, there are 80,000 to 100,000 chemicals on the global market (U.S. Environmental Protection Agency 1998, Commission of the European Communities 2001). It is impossible to measure all possible chemicals in the environment, which makes it very difficult to define a single planetary boundary derived from the aggregated effects of tens of thousands of chemicals. Some toxicity data exist for a few thousand of these chemicals, but there is virtually no knowledge of their combined effects. We can identify two complementary approaches for defining a planetary boundary for chemical pollution. One is to focus on persistent pollutants with global distributions, and the other to identify unacceptable, long-term, and large-scale effects on living organisms of chemical pollution.

The first approach highlights chemicals such as mercury that are capable of undergoing long-range transport via ocean or atmospheric dynamics. Specifically, it identifies pollutants that have significant effects on a range of organisms at the global scale and the threshold levels associated with these effects. Chronic, low-dose exposure may lead to subtle sub-lethal effects that hinder development, disrupt endocrine systems, impede reproduction, or cause mutagenesis. Often, younger organisms are most vulnerable to exposures to a particular pollutant (e.g., lead neurotoxicity in children). Thresholds can be identified for only a few single chemicals or chemical groups and for only a few biological species, such as some top predators (de Wit et al. 2004, Fisk et al. 2005). A well-known example is the DDT threshold concentration in the eggs of birds of prey that causes critical eggshell thinning and reproductive failure (Lincer 1975). Although most efforts to reduce chemical pollution have focused on local
and regional scales, the 2001 UN Stockholm Convention on Persistent Organic Pollutants (POPs) implicitly recognized that global concentrations of a few specific POPs (e.g., PCB, dioxins, DDT, and several other pesticides) have crossed an, as yet unquantified, planetary boundary. The bans imposed were based on known effects and observed high concentrations of these POPs in some top predators and human populations. Widening the approach from a few well-studied pollutants would require determination of critical effects for each chemical or chemical group, which is a gigantic task and would require identification of thresholds associated with mixtures of chemicals, an equally daunting challenge. A boundary focusing on effects of chemical pollution, on the other hand, could be based on reduced or failed reproduction, neurobehavioral deficits, or compromised immune systems, which are linked to the combined exposure to many chemicals. Such a planetary boundary would need to cover subtle effects on the most sensitive life stages in the most sensitive species and/or humans, with effects observable at the global scale. An example of this approach has been reviewed based on the suggested increase in neurodevelopmental disorders such as autism and attention deficit and hyperactivity disorder (ADHD) in children.

The widespread exposure to low concentrations of multiple chemicals with known or suspected neurotoxic effects may have created a silent pandemic of subtle neurodevelopmental disorders in children, possibly on a global scale (Grandjean and Landrigan 2006). Of the 80 000 chemicals in commerce, 1000 are known to be neurotoxic in experiments, 200 are known to be neurotoxic in humans, and five (methyl mercury, arsenic, lead, PCBs, toluene) are known to be toxic to human neurodevelopment. Ultimately, a chemical pollution boundary may require setting a range of sub-boundaries based on the effects of many individual chemicals combined with identifying specific effects on sensitive organisms. Furthermore, a chemical pollution boundary interacts with the planetary boundary for aerosols, because many persistent pollutants are transported long distances on aerosol particles. In summary, however, we conclude that it is not possible at this time to define these nor is it clear how to aggregate them into a comprehensive single planetary boundary."


Exercise:

In order to introduce the planetary boundary of ‘chemical pollution’ to the rest of the group, please summarize the main causes for and impacts of chemical pollution. If possible try to find an example to visualize your findings.
Planetary Boundary: ‘Climate change’

By now, climate change is accepted to be one of mankind’s greatest challenges. In order to stop global warming and prevent the climate to rise above the universal threshold of 2°C, measures striving towards a more sustainable development need to be taken. Hence climate change is established as one of the planetary boundaries introduced previously. The following is a set of scientific introductions to the matter of climate change, derived from two reports of the Intergovernmental Panel on Climate Change, IPCC (2007) and IPCC (2014).

What is Climate Change?

"Climate change refers to a change in the state of the climate that can be identified by changes in the average and/or the variability of its properties (e.g., temperature, precipitation), and that persists for an extended period, typically decades or longer. Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

The temperature of the Earth has risen by about 0.74 °C over the last century. While that may seem like a small increase, it has had profound effects on the planet’s physical and biological systems, which, in turn, have impacted society. A large majority of the climate science community has very high confidence that the net effect of human activities since 1750 has been one of warming. They also conclude that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations. Global GHG emissions will continue to grow over the next few decades due to increases in the human activities that generate GHG, notably the combustion of fossil fuels and certain land use practices. [...]

Higher temperatures would cause further widespread change, including: a decrease in snow cover and sea ice; an increase in frequency of hot extremes, heat waves and heavy precipitation; an increase in tropical cyclone intensity; precipitation increases in high latitudes and likely decreases in most subtropical land regions, among many other impacts; sea level rise, and accelerated species extinction, among many other impacts.

These phenomena would have far-reaching impacts on society. Altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems. Projected impacts include increased pest outbreaks in agriculture, increasing water scarcity and diminished water quality, increased risk of heat-related mortality, relocation of coastal populations and infrastructure, and declining air quality in cities. There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. Possible
positive impacts of climate change include increased yields in colder environments and reduced energy demand for heating. Some planned adaptation (of human activities) is occurring now; more extensive adaptation is required to reduce vulnerability to climate change. Unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt. Making development more sustainable by integrating climate change adaptation and mitigation measures into sustainable development strategy, can make a major contribution towards addressing climate change problems. Although the problems are complex, we know enough today to take the first effective steps on adaptation and mitigation.

Causes of change

The dominant factor in the radiative forcing of climate in the industrial era is the increasing concentration of various greenhouse gases in the atmosphere. Several of the major greenhouse gases occur naturally but increases in their atmospheric concentrations over the last 250 years are due largely to human activities. Other greenhouse gases are entirely the result of human activities. The contribution of each greenhouse gas to radiative forcing over a particular period of time is determined by the change in its concentration in the atmosphere over that period and the effectiveness of the gas in perturbing the radiative balance. Current concentrations of atmospheric CO$_2$ and CH$_4$ far exceed pre-industrial values found in polar ice core records of atmospheric composition dating back 650,000 years. Multiple lines of evidence confirm that the post-industrial rise in these gases does not stem from natural mechanisms.

The total radiative forcing of the Earth’s climate due to increases in the concentrations of the long-lived GHGs CO$_2$, CH$_4$ and N$_2$O, and very likely the rate of increase in the total forcing due to these gases over the period since 1750, are unprecedented in more than 10,000 years. It is very likely that the sustained rate of increase in the combined radiative forcing from these greenhouse gases over the past four decades is at least six times faster than at any time during the two millennia before the Industrial Era, the period for which ice core data have the required temporal resolution. The concentration of atmospheric CO$_2$ has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. [...] The annual CO$_2$ growth rate was larger during the last 10 years than it has been since continuous direct atmospheric measurements began.”


Future Climate Changes, Risks and Impacts

“Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks.

Future risks and impacts caused by a changing climate

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive and in some cases irreversible detrimental impacts. Some risks are particularly relevant for individual regions, while others are global. [...] The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds increases with rising temperature. For risk assessment, it is important to evaluate the widest
possible range of impacts, including low-probability outcomes with large consequences.

A large fraction of species faces increased extinction risk due to climate change during and beyond the 21st century, especially as climate change interacts with other stressors. Most plant species cannot naturally shift their geographical ranges sufficiently fast to keep up with current and high projected rates of climate change in most landscapes; most small mammals and freshwater molluscs will not be able to keep up at the rates projected [...]. Future risk is indicated to be high by the observation that natural global climate change at rates lower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years. Marine organisms will face progressively lower oxygen levels and high rates and magnitudes of ocean acidification, with associated risks exacerbated by rising ocean temperature extremes. Coral reefs and polar ecosystems are highly vulnerable. Coastal systems and low-lying areas are at risk from sea level rise, which will continue for centuries even if the global mean temperature is stabilized.

Climate change is projected to undermine food security. Due to projected climate change by the mid-21st century and beyond, global marine species redistribution and marine biodiversity reduction in sensitive regions will challenge the sustained provision of sheries productivity and other ecosystem services. For wheat, rice and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late 20th century levels, although individual locations may benefit. Global temperature increases of ~4°C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food security globally. Climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, intensifying competition for water among sectors.

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist. Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change. [...]

In urban areas climate change is projected to increase risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise and storm surges. These risks are amplified for those lacking essential infrastructure and services or living in exposed areas. Rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world. Aggregate economic losses accelerate with increasing temperature, but global economic impacts from climate change are currently difficult to estimate. From a poverty perspective, climate change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales.

Climate change is projected to increase displacement of people. Populations that lack the resources for planned migration experience higher exposure to extreme weather events, particularly in developing countries with low income. Climate change can indirectly increase risks of violent conflicts by amplifying well-documented drivers of these conflicts such as poverty and economic shocks."

**Exercise:**
In order to introduce the planetary boundary of ‘climate change’ to the rest of the group, please summarize the main causes for and impacts of climate change. If possible try to find an example to visualize your findings.

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**Figure 2.** Representative key risks for each region, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation. Each key risk is assessed as very low, low, medium, high or very high. Risk levels are presented for three time frames: present, near term (here, for 2030–2040) and long term (here, for 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially across different emission scenarios. For the long term, risk levels are presented for two possible futures (2°C and 4°C global mean temperature increase above pre-industrial levels). For each timeframe, risk levels are indicated for a continuation of current adaptation and assuming high levels of current or future adaptation. Risk levels are not necessarily comparable, especially across regions. (Figure 2.4)
**Planetary Boundary: ‘Global freshwater use’**

The boundary of global freshwater use is measured by the consumptive blue water use (km$^3$yr$^{-1}$). The scientific evidence of ecosystem response to the advanced use of freshwater resources is only limited so far. Rockström et al. 2009 therefore define the boundary of global freshwater use as a “slow process without known global scale” (Rockström et al. 2009). The following introduction is derived from two papers, Koehler (2008) and Rockström et al. (2009).

**Why do we need freshwater?**

“Freshwater is one of the planet’s most valuable resources being an essential life-sustaining element which cannot be substituted. Acting as the source of drinking water and the basis for hygiene and food supply, it is indispensable for humans, while at the same time ensuring biodiversity and pivotal ecosystem functions on which ultimately we all depend. We are witnessing a steadily worsening situation of rapidly decreasing freshwater resource availability which threatens 1.1 billion people around the globe lacking sufficient access to safe drinking water (UN 2006). Spreading water scarcity in many regions of the world endangers food production (about 70% of today’s global freshwater consumption feeds agriculture!), puts food security at risk, and burdens human health due to malnutrition (e.g., in Asia and Africa). The overexploitation of surface water bodies and (fossil) groundwater for the soaring agricultural production (e.g., in China, India, Western USA) may jeopardize the freshwater abundance of future generations. Irrigation and damming cause fragmentations of river basins drastically reduce the downstream freshwater availability and alarmingly threaten aquatic and terrestrial ecosystems. Inappropriate water resource management endangers ecological functions and biodiversity, provokes disturbed water cycling and desiccation of rivers, streams, and land.

If all that were not bad enough! On top, climate change promises to intensify the looming water crisis by changing rainfall patterns and inducing elevated evaporation and dramatic droughts in many regions of the world: Some 20% of the increase in water scarcity in the coming decades will be caused by climate change according to recent UN estimates (UN 2006). Being a fundamental building block for human civilization and economic development, freshwater also is a strategic resource, just like energy (Wall Street Journal 2008). Freshwater resources and their allocation increasingly play a central role in poverty alleviation and urban water supply, facing growing competition with other economic sectors particularly in low and middle-income countries. Rapidly rising urban populations put the pressure to shift water from agriculture to vastly expanding cities (e.g., in China). Global trade of manufactured goods and services, all of which require water at some point, fuel the demand for capturing the freshwater use-related environmental, economic, and social impacts.”


**The Global Boundary**

“The global freshwater cycle has entered the Anthropocene (Meybeck 2003) because humans are now the dominant driving force altering global-scale river flow (Shiklomanov and Rodda 2003) and the spatial patterns and seasonal timing of vapor flows (Gordon et al. 2005). An estimated 25% of the world’s river basins run dry before reaching the oceans due to use of freshwater resources in the basins (Molden et al. 2007).

Global manipulations of the freshwater cycle affect biodiversity, food, and health security and ecological functioning, such as provision of habitats for fish recruitment, carbon sequestration, and climate regulation, undermining the resilience of terrestrial and aquatic ecosystems. Threats to human livelihoods due to deterioration of global water resources are threefold: (i) the loss of soil moisture resources (green water) due to land
Planetary Boundary – Global freshwater use

degradation and deforestation, threatening terrestrial biomass production and sequestration of carbon, (ii) use and shifts in runoff (blue water) volumes and patterns threatening human water supply and aquatic water needs, and (iii) impacts on climate regulation due to decline in moisture feedback of vapor flows (green water flows) affecting local and regional precipitation patterns. Estimates indicate that 90% of global green water flows are required to sustain critical ecosystem services (Rockström et al. 1999), whereas 20%–50% of the mean annual blue water flows in river basins are required to sustain aquatic ecosystem functioning (Smakhtin 2008). Water-induced thresholds at the continental or planetary scale may be crossed as a result of aggregate sub-system impacts at local (e.g., river basin) or regional (e.g., monsoon system) scales caused both by changes in water resource use and climate change-induced shifts in the hydrological cycle.

Green water flows influence, at the regional scale, rainfall levels through moisture feedback and, thereby, the availability of blue water resources. Green water-induced thresholds include collapse of biological sub-systems as a result of regional drying processes. Examples include the abrupt change from a wet to a dry stable state in the Sahel region approximately 5000–6000 years BP (Scheffer et al. 2001, Foley et al. 2003) and the future risk of a rapid savannization of the Amazon rainforest due to abrupt decline in moisture feedback (Oyama and Nobre 2003). Blue water-induced thresholds include collapse of riverine habitats if minimum environmental water flow thresholds are crossed (Smakhtin 2008) and the collapse of regional lake systems (such as the Aral Sea).

A planetary boundary for freshwater resources must thus be set to safely sustain enough green water flows for moisture feedback (to regenerate precipitation), allow for the provisioning of terrestrial ecosystem functioning and services (e.g., carbon sequestration, biomass growth, food production, and biological diversity), and secure the availability of blue water resources for aquatic ecosystems. Thresholds related to moisture feedbacks occur “upstream” of and impact directly on runoff water flows. The close interactions between land and water, and between vapor flows and runoff, make it difficult to define an appropriate freshwater boundary that captures the complexity of rainfall partitioning across scales. However, as a first attempt, we propose runoff depletion in the form of consumptive runoff or blue water use as a proxy for capturing the full complexity of global freshwater thresholds.


Exercise:

In order to introduce the planetary boundary of ‘global freshwater use’ to the rest of the group, please summarize the main causes for and impacts of the scarcity of global freshwater resources. If possible try to find an example to visualize your findings.
Planetary Boundary: Land-system change

While changes in land use and land cover occur on a local scale, the impacts are perceptible on a global level and of serious consequences for the Earth System. Land cover changes result from increasing agricultural activities, expanding infrastructure and ongoing urbanization, affecting water flows and the biogeochemical circles of nitrogen, phosphorus and carbon and intensifying biodiversity loss. The following are excerpts of different scientific introductions about the planetary boundary of land-system change, derived from Foley et al. (2005) and Rockström et al. (2009).

“Land-use activities—whether converting natural landscapes for human use or changing management practices on human-dominated lands—have transformed a large proportion of the planet's land surface. By clearing tropical forests, practicing subsistence agriculture, intensifying farmland production, or expanding urban centers, human actions are changing the world's landscapes in pervasive ways (1, 2) (Fig. 1, fig. S1, and table S1). Although land-use practices vary greatly across the world, their ultimate outcome is generally the same: the acquisition of natural resources for immediate human needs, often at the expense of degrading environmental conditions. Several decades of research have revealed the environmental impacts of land use throughout the globe, ranging from changes in atmospheric composition to the extensive modification of Earth's ecosystems (3–6). For example, land-use practices have played a role in changing the global carbon cycle and, possibly, the global climate: Since 1850, roughly 35% of anthropogenic CO\textsubscript{2} emissions resulted directly from land use (7). Land-cover changes also affect regional climates through changes in surface energy and water balance (8, 9). Humans have also transformed the hydrologic cycle to provide freshwater for irrigation, industry, and domestic consumption (10, 11). Furthermore, anthropogenic nutrient inputs to the biosphere from fertilizers and atmospheric pollutants now exceed natural sources and have widespread effects on water quality and coastal and freshwater ecosystems (4, 12). Land use has also caused declines in biodiversity through the loss, modification, and fragmentation of habitats; degradation of soil and water; and overexploitation of native species (13) (SOM Text S1).

Ironically, just as our collective land-use practices are degrading ecological conditions across the globe, humanity has become dependent on an ever-increasing share of the biosphere's resources. Human activities now appropriate nearly one-third to one-half of global ecosystem production (14), and as development and population pressures continue to mount, so could the pressures on the biosphere. As a result, the scientific community is increasingly concerned about the condition of global ecosystems and “ecosystem services” [(15, 16) (SOM Text S2).

Land use thus presents us with a dilemma. On one hand, many land-use practices are absolutely essential for humanity, because they provide critical natural resources and ecosystem services, such as food, fiber, shelter, and freshwater. On the other hand, some forms of land use are degrading the ecosystems and services upon which we depend, so a natural question arises: Are land-use activities degrading the global environment in ways that may ultimately undermine ecosystem services, human welfare, and the long-term sustainability of human societies? [...]
Figure 1. Global human land-use and land-cover change. Global distribution of potential natural vegetation without human influence on land use and the extent of land cover and land use through agriculture during the 1990s. Derived from Foley et al. (2005).

Food Production

Together, croplands and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying ~40% of the land surface (17, 18)(Fig.2). Changing land-use practices have enabled world grain harvests to double in the past four decades, so they now exceed ~2 billion tons per year (19). Some of this increase can be attributed to a ~12% increase in world cropland area, but most of these production gains resulted from “Green Revolution” technologies, including high-yielding cultivars, chemical fertilizers and pesticides, and mechanization and irrigation (4, 20) (fig. S2A). During the past 40 years, there has been a ~700% increase in global fertilizer use (4, 5) and a ~70% increase in irrigated cropland area (21, 22). Although modern agriculture has been successful in increasing food production, it has also caused extensive environmental damage. For example, increasing fertilizer use has led to the degradation of water quality in many regions (4, 12, 13) (fig. S2B). In addition, some irrigated lands have become heavily salinized, causing the worldwide loss of ~1.5 million hectares of arable land per year, along with an estimated $11 billion in lost production (20). Up to ~40% of global croplands may also be experiencing some degree of soil erosion, reduced fertility, or overgrazing (20). The loss of native habitats also affects agricultural production by degrading the services of pollinators, especially bees (23, 24). In short, modern agricultural land-use practices may be trading short-term increases in food production for long-term losses in ecosystem services, including many that are important to agriculture.

Freshwater Resources

Land use can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared (25, 26). For instance, the Tocantins River basin in Brazil showed a ~25% increase in river discharge between 1960 and 1995, coincident with expanding agriculture but no major change in precipitation (26). Water demands associated with land-use practices, especially irrigation, directly affect freshwater supplies through water withdrawals and diversions. Global water withdrawals now total ~3900 km$^3$ yr$^{-1}$, or ~10% of the total global renewable resource, and the consumptive use of water (not returned to the watershed) is estimated to be ~1800 to 2300 km$^3$ yr$^{-1}$ (22, 27) (fig. S3A). Agriculture alone accounts for ~85% of global consumptive use (22). As a result, many large rivers,
especially in semiarid regions, have greatly reduced flows, and some routinely dry up (21, 28). In addition, the extraction of groundwater reserves is almost universally unsustainable and has resulted in declining water tables in many regions (21, 28) (fig. S2, B and C). Water quality is often degraded by land use. Intensive agriculture increases erosion and sediment load, and leaches nutrients and agricultural chemicals to groundwater, streams, and rivers. In fact, agriculture has become the largest source of excess nitrogen and phosphorus to waterways and coastal zones (12, 29). Urbanization also substantially degrades water quality, especially where wastewater treatment is absent. The resulting degradation of inland and coastal waters impairs water supplies, causes oxygen depletion and fish kills, increases blooms of cyanobacteria (including toxic varieties), and contributes to waterborne disease (12, 30).

**Forest Resources**

Land-use activities, primarily for agricultural expansion and timber extraction, have caused a net loss of ~7 to 11 million km² of forest in the past 300 years (17, 32, 33). Highly managed forests, such as timber plantations in North America and oil-palm plantations in Southeast Asia, have also replaced many natural forests and now cover 1.9 million km² worldwide (31). Many land-use practices (e.g., fuel-wood collection, forest grazing, and road expansion) can degrade forest ecosystem conditions—in terms of productivity, biomass, stand structure, and species composition—even without changing forest area. Land use can also degrade forest conditions indirectly by introducing pests and pathogens, changing fire-fuel loads, changing patterns and frequency of ignition sources, and changing local meteorological conditions (34). [...]  

**Regional Climate and Air Quality**

Land conversion can alter regional climates through its effects on net radiation, the division of energy into sensible and latent heat, and the partitioning of precipitation into soil water, evapotranspiration, and runoff. Modeling studies demonstrate that land-cover changes in the tropics affect climate largely through water-balance changes, but changes in temperate and boreal vegetation influence climate primarily through changes in the surface radiation balance (38). Large-scale clearing of tropical forests may create a warmer, drier climate (39), whereas clearing temperate and boreal forest is generally thought to cool the climate, primarily through increased albedo (40) (table S2, A and B). Urban “heat islands” are an extreme case of how land use modifies regional climate. The reduced vegetation cover, impervious surface area, and morphology of buildings in cityscapes combine to lower evaporative cooling, store heat, and warm the surface air (41). A recent analysis of climate records in the United States suggests that a major portion of the temperature increase during the last several decades resulted from urbanization and other land-use changes (9). Land-cover change has also been implicated in changing the regional climate in China; recent analyses suggest that the daily diurnal temperature range has decreased as a result of urbanization and other land-use changes (42). Land-use practices also change air quality by altering emissions and changing the atmospheric conditions that affect reaction rates, transport, and deposition. For example, tropospheric ozone (O₃) is particularly sensitive to changes in vegetation cover and biogenic emissions. Land-use practices often determine dust sources, biomass burning, vehicle emission patterns, and other air pollution sources. Furthermore, the effects of land use on local meteorological conditions, primarily in urban heat islands, also affect air quality: Higher urban temperatures generally cause O to increase (43). [...]  

**Confronting the Effects of Land Use**

Current trends in land use allow humans to appropriate an ever-larger fraction of the biosphere’s goods and services while simultaneously diminishing the capacity of global ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality,
Planetary Boundary – Land-system change

and mediate infectious diseases. This assertion is supported across a broad range of environmental conditions worldwide, although some (e.g., alpine and marine areas) were not considered here. Nevertheless, the conclusion is clear: Modern land-use practices, while increasing the short-term supplies of material goods, may undermine many ecosystem services in the long run, even on regional and global scales. Confronting the global environmental challenges of land use will require assessing and managing inherent trade-offs between meeting immediate human needs and maintaining the capacity of ecosystems to provide goods and services in the future (Fig. 3) (2, 16). Assessments of trade-offs must recognize that land use provides crucial social and economic benefits, even while leading to possible long-term declines in human welfare through altered ecosystem functioning (2). Sustainable land-use policies must also assess and enhance the resilience of different land-use practices. Managed ecosystems, and the services they provide, are often vulnerable to diseases, climatic extremes, invasive species, toxic releases, and the like (51–53). Increasing the resilience of managed landscapes requires practices that are more robust to disturbance and can recover from unanticipated “surprises.”

There is an increasing need for decision-making and policy actions across multiple geographic scales and multiple ecological dimensions. The very nature of the issue requires it: Land use occurs in local places, with real-world social and economic benefits, while potentially causing ecological degradation across local, regional, and global scales. Society faces the challenge of developing strategies that reduce the negative environmental impacts of land use across multiple services and scales while maintaining social and economic benefits.

What strategies can ameliorate the detrimental effects of land use? Examples of land-management strategies with environmental, social, and economic benefits include increasing agricultural production per unit land area, per unit fertilizer input, and per unit water consumed (19, 21, 54, 55); maintaining and increasing soil organic matter in croplands, which is a key to water-holding capacity, nutrient availability, and carbon sequestration (56–58); increasing green space in urban areas, thereby reducing runoff and “heat island” effects; employing agroforestry practices that provide food and fiber yet maintain habitats for threatened species; and maintaining local biodiversity and associated ecosystem services such as pollination and pest control. Many of these strategies involve management of landscape structure through the strategic placement of managed and natural ecosystems, so the services of natural ecosystems (e.g., pest control by natural predators, pollination by wild bees, reduced erosion with hedgerows, or filtration of runoff by buffer strips) are available across the landscape mosaic.

“For humanity to stay within this boundary, cropland should be allocated to the most productive areas, and processes that lead to the loss of productive land, such as land degradation, loss of irrigation water, and competition with land uses such as urban development or biofuel production, should be controlled. Demand-side processes may also need to be managed; these include diet, per capita food consumption, population

size, and wastage in the food distribution chain. Agricultural systems that better mimic natural processes (e.g., complex agroecosystems) could also allow an extension of this boundary (Ericksen et al. 2009). Although the effects of land-system change act as a slow variable that influences other boundaries, such as biodiversity, water, and climate, they can also trigger rapid changes at the continental scale when land-cover thresholds are crossed. For example, conversion of the Amazon rainforest into cultivated or grazing systems may reach a level where an additional small amount of conversion would tip the basin into an irreversible transformation to a semi-arid savanna (Oyama and Nobre 2003, Foley et al. 2007). At the global scale, if enough high-productivity land is lost to degradation, biofuel production, or urbanization, food production may spread into marginal lands with lower yields and a higher risk of degradation. This may constitute a threshold where a small increment of additional food production may trigger an accelerating increase in cultivated land. The land-system boundary should be implemented at multiple scales through a fine-grained global land architecture (Turner 2009) that (i) reserves the most productive land for agricultural use, (ii) maintains high conservation-value forests and other ecosystems in their current states, and (iii) maintains carbon-rich soils and ecosystems in their undisturbed or carefully managed condition.

About 12% of the global land surface is currently under crop cultivation (Foley et al. 2005, Ramankutty et al. 2008). The allowed 3% expansion (approximately 400 Mha) to the level we propose as a land-system boundary will most likely be reached over the coming decades and includes suitable land that is not either currently cultivated or is under forest cover—e.g., abandoned cropland in Europe, North America, and the former Soviet Union and some areas of Africa's savannas and South America's cerrado.”


**Exercise:**

In order to introduce the planetary boundary of “land use change” to the rest of the group, please summarize the main points of the problem of land-system change and its effects. Try to visualize your outcomes if possible.
Planetary Boundary: ‘Nitrogen and phosphorus cycle’

Industrial and agricultural processes are negatively affecting the biogeochemical cycles of nitrogen and phosphorus. Particularly the enormous production and increasing use of fertilizer interfere with the natural nitrogen and phosphorus cycles, leading to shifts in nitrogen and phosphorus households of marine and aquatic ecosystems. The following is a set of scientific articles about the interference with the global nitrogen and phosphorus cycles, derived from Rockström et al. (2009), Pidwirny (2011) and Hogan (2012).

“Local to regional-scale anthropogenic interference with the nitrogen cycle and phosphorus flows has induced abrupt shifts in lakes (Carpenter 2005) and marine ecosystems (e.g., anoxia in the Baltic Sea) (Zillén et al. 2008). Eutrophication due to human induced influxes of nitrogen (N) and phosphorus (P) can push aquatic and marine systems across thresholds, generating abrupt non-linear change from, for example, a clear-water oligotrophic state to a turbid-water eutrophic state (Carpenter et al. 1999). Shifts between such alternate stable states depend on complex interactions between N and P flows and on the prevailing biogeochemical setting. Human-induced degradation of ecosystem states (e.g., overfishing, land degradation) and increase in N and P flows at regional to global scales may cause undesired non-linear change in terrestrial, aquatic, and marine systems, while simultaneously functioning as a slow driver influencing anthropogenic climate change at the planetary level.

We cannot exclude the possibility that the N and P cycles should, in fact, be separate planetary boundaries in their own right. They both influence, in complex and non-linear ways, human life-support systems at regional scales, and both have significant aggregate planetary impacts, which makes them key processes of the Anthropocene. The reason to keep them as one boundary in this paper is primarily the close interactions between N and P as key biological nutrients in driving abrupt shifts in sub-systems of the Earth. Human modification of the N cycle is profound (Galloway and Cowling 2002, Gruber and Galloway 2008). Human activities now convert more N from the atmosphere into reactive forms than all of the Earth’s terrestrial processes combined. Human-driven conversion occurs primarily through four processes: industrial fixation of atmospheric N$_2$ to ammonia (~80 Mt N yr$^{-1}$); agricultural fixation of atmospheric N$_2$ via cultivation of leguminous crops (~40 Mt N yr$^{-1}$); fossil-fuel combustion (~20 Mt N yr$^{-1}$); and biomass burning (~10 Mt N yr$^{-1}$). Although the primary purpose of most of this new reactive N is to enhance food production via fertilization, much reactive N eventually ends up in the environment—polluting waterways and coastal zones, adding to the local and global pollution burden in the atmosphere, and accumulating in the biosphere. Efforts to limit N pollution have, to date, been undertaken at local and regional scales only—for example, by limiting the concentration of nitrate in groundwater or the emission of nitric oxides to urban airsheds.

At the global scale, the addition of various forms of reactive N to the environment acts primarily as a slow variable, eroding the resilience of important sub-systems of the Earth System. The exception is nitrous oxide, which is one of the most important greenhouse gases and thus acts as a systemic driver at the planetary scale. Nitrous oxide is included in the climate-change boundary by applying radiative forcing (maximum +1 W m$^{-2}$ of anthropogenic forcing) as the control variable.

For the other forms of reactive N, setting a planetary boundary is not straightforward. The simplest and most direct approach is to consider the human fixation of N$_2$ from the atmosphere as a giant valve that controls a massive flow of new reactive N into the Earth System. The boundary can then be set by using that valve to control the amount of additional reactive N flowing into the Earth System. We suggest that the boundary initially be set at approximately 25% of its current value, or to about 35 Mt N yr$^{-1}$. We emphasize that this is a first guess only. Much more research and synthesis
of information is required to enable a more informed boundary to be determined.

Even this initial boundary would greatly reduce the amount of reactive N pushed into land, ocean, and atmospheric systems. It would eliminate the current flux of N onto the land and could trigger much more efficient and less polluting ways of enhancing food production. It would almost surely also trigger the return of N in human effluent back onto productive landscapes, thus further reducing the leakage of reactive N into ecosystems.

Although N forms part of a biological global cycle, P is a finite fossil mineral mined for human use and added naturally into the Earth System through geological weathering processes. The crossing of a critical threshold of P inflow to the oceans has been suggested as the key driver behind global-scale ocean anoxic events (OAE), potentially explaining past mass extinctions of marine life (Handoh and Lenton 2003). The dynamics between bi-stable oxic and anoxic conditions is believed to be induced by positive feedbacks between anoxia, P recycling from sediments, and marine productivity.

Modeling suggests that a sustained increase of P inflow to the oceans exceeding 20% of the natural background weathering rate could have been enough to induce past OAEs (Handoh and Lenton 2003). Assuming a relatively low estimate of "pre-agricultural" P input to the oceans of 1.1 Mt yr\(^{-1}\) (3.5 E10 mol P yr\(^{-1}\)), this increased inflow corresponds to only ~225,000 tonnes P yr\(^{-1}\) (0.72 E10 mol P yr\(^{-1}\)). Of the global human extraction of ~20 Mt yr\(^{-1}\) of P, an estimated 10.5 Mt yr\(^{-1}\) is lost from the world’s cropland, the primary source of P inflow to the oceans. The increase of reactive P to the oceans from human activities has been estimated (year 2000) at ~9 Mt yr\(^{-1}\) (8.5–9.5 Mt yr\(^{-1}\) depending on how detergent and sewage effluent fluxes are handled) (Mackenzie et al. 2002). Despite a substantial increase in anthropogenic P inflow to oceans (up to 8–9 times higher than the natural background rate), it remains highly uncertain whether and, if so, when anthropogenic P inflow could reach a point where a human-induced OAE would be triggered. For the global deep ocean to shift to an anoxic state requires strong recycling of P from sediments as bottom waters become more anoxic, thus fuelling increased productivity and amplifying the initial change in a positive feedback loop. In existing models, the resulting dynamics have a 10 000-year timescale due to the long residence time of deep ocean P (Lenton et al. 2008). Furthermore, even though humans have greatly accelerated the inflow of P to the oceans, it would still take in the order of 10 000 years to double P in the oceans. This suggests that for humans to trigger an OAE should still be over 1000 years away, thus shifting it down the list in our current sphere. Our tentative modeling analyses, using the model by Handoh and Lenton (2003), show that a 10-fold increase of P inflow to the oceans (i.e., slightly higher than the current level), if sustained for 1000 years, would raise the anoxic fraction of the ocean from 0.14 to 0.22. Current estimates of available phosphate rock reserves (up to 20 Gt of P) suggest that such an input could not be sustained for more than 1000 years. Even if P inflows were then returned to pre-industrial levels, the anoxic fraction would continue to rise for another 1000 years. However, a complete OAE (anoxic fraction of 1) would be avoided. It is uncertain what qualitative changes and regional state changes such a sustained inflow would trigger, however, current evidence suggests that it would induce major state changes at local and regional levels, including widespread anoxia in some coastal and shelf seas.

There are very large uncertainties in these analyses, due to the complex interactions between oxic-anoxic states, different forms of P in marine systems, and interactions between abiotic and biotic conditions in the oceans (not least driven by the other planetary boundaries of ocean acidification, N inflow, marine biodiversity, and climate change). Hence it is difficult to precisely quantify a planetary boundary of P inflow to the oceans that places humanity at a safe distance from triggering
deleterious, widespread ocean anoxia. The problem is partly one of defining what is deleterious, given (current) observations of abrupt P-induced regional anoxic events. We suggest that, at the very least, a boundary level should be set that (with current knowledge) allows humanity to safely steer away from the risk of triggering an OAE even over longer time horizons (>1000 years). This in turn may require that anthropogenic P inflow to the ocean is not allowed to exceed a human-induced level of ~10 times the natural background rate of ~1 Mt P yr⁻¹. This is higher than the proposed trigger rate of past OAEs, but a level that is believed to create a safe long-term (over centuries) global operating space. The proposed planetary boundary for anthropogenic P inflow to the oceans is thus tentatively placed at <10 times (<10×) the natural background weathering flux of P, with an equally tentative uncertainty range (<10×–<100×).”


The nitrogen cycle

“The nitrogen cycle represents one of the most important nutrient cycles found in ecosystems. (Figure 1). Nitrogen is a required nutrient for all living organisms to produce a number of complex organic molecules like amino acids, the building blocks of proteins, and nucleic acids, including DNA and RNA. The ultimate store of nitrogen is in the atmosphere, where it exists as nitrogen gas (N₂). This store is about one million times larger than the total nitrogen contained in living organisms. Other major stores of nitrogen include organic matter in soil and the oceans. Despite its abundance in the atmosphere, nitrogen is often the most limiting nutrient for plant growth. […]

In most ecosystems nitrogen is primarily stored in living and dead organic matter. This organic nitrogen is converted into inorganic forms when it re-enters the biogeochemical cycle via decomposition. Decomposers chemically modify the nitrogen found in organic matter to ammonium ion (NH₄⁺). This process is known as mineralization and it is carried out by a variety of bacteria and fungi. […]

Almost all of the nitrogen found in any ecosystem originally came from the atmosphere. Significant amounts enter the soil in rainfall or through the effects of lightning. The majority, however, is biochemically fixed in ecosystems by specialized micro-organisms, […]

Humans now fix approximately as much nitrogen industrially as does natural nitrogen fixation, thus dramatically altering the nitrogen cycle. Some of the major processes involved in this alteration include:
The application of nitrogen fertilizers to crops has caused increased rates of denitrification and leaching of nitrate into groundwater. The additional nitrogen entering the groundwater system eventually flows into streams, rivers, lakes, and estuaries. In these systems, the added nitrogen can lead to eutrophication and associated hypoxia.

Increased deposition of nitrogen from atmospheric sources because of fossil fuel combustion and forest burning. Both of these processes release a variety of solid forms of nitrogen through combustion and contribute to acid rain.

Livestock ranching. Livestock release a large amounts of ammonia into the environment from their wastes. This nitrogen enters the soil system and then the hydrologic system through leaching, groundwater flow, and runoff.

Sewage waste and septic tank leaching."


The phosphorus cycle

"The phosphorus cycle is the biogeochemical cycle which characterizes the transport and chemical transformation of phosphorus through the geosphere, hydrosphere and biosphere. Unlike many other biogeochemical cycles, the atmosphere does not play a significant role in the movement of phosphorus, since phosphorus and phosphorus-based compounds are typically solids at the normal ranges of temperature and pressure found on Earth. Therefore most of the phosphorus remains within rock, sediments, sand, and the ocean floor, with a fraction in living biomass. Phosphorus moves among trophic levels in an ecosystem by plant growth, herbivory and carnivory. [...]"

Role in biota

Plant species dissolve ionized forms of phosphate and take the mineral into their system. Herbivores obtain phosphorus by consuming plant biomass, and carnivores by consuming herbivores. Herbivores and carnivores excrete phosphorus as a waste product in urine and feces. Phosphorus is then released back into the soil when plants or animal matter decomposes and the cycle repeats. Phosphorus is an essential nutrient for plants and animals in the form of ions, including phosphate, $\text{PO}_4^{3-}$ and hydrogen phosphate, $\text{HPO}_4^{2-}$.

Phosphates are effective fertilizers, but they also cause pollution problems in lakes streams. Because phosphorus is often the nutrient in limited supply, even a small increase in availability can cause a significant effect. Over-enrichment of phosphate can lead to algae blooms. [...]"

Anthropogenic influence

Human influences in the phosphorus cycle arise chiefly from the introduction of synthetic fertilizers. Use of fertilizers mainly has significantly altered both the phosphorus and nitrogen cycles. Vegetation may not be able to utilize all of the phosphate fertilizer applied; as a consequence, much of the phosphate applied as fertilizer is lost from the land through water surface runoff. The dissolved phosphate in surface runoff is eventually precipitated as sediment at the bottom of the water body. In certain lakes and ponds, this phosphate may be redissolved and
recycled, often as an excessive nutrient. Animal wastes or manure are also be applied to land as fertilizer, particularly in developing countries. If misapplied on frozen ground during the winter, much of the fertilizer may be lost when ice melts and forms runoff. In certain areas very large or intense feed lots of animals, may result in excessive surface runoff of phosphate and nitrate into streams. Other human sources of phosphate are in the out flows from municipal sewage treatment plants. Without an expensive tertiary treatment, the phosphate in sewage is not removed during various treatment operations. Again an extra amount of phosphate enters the water."


**Exercise:**

In order to introduce the planetary boundary of “the nitrogen and phosphorus cycles” to the rest of the group, please summarize the main points of the problems with anthropogenic influences in the nitrogen and phosphorus cycles. Try to visualize the two cycles if possible.
Planetary Boundary: 'Ocean acidification'

The following is a set of excerpts of scientific articles about ocean acidification, derived from Dooney et al. (2009), Feely et al. (2009) and Rockström et al. (2009).

“When we burn gasoline in our cars, use electricity from burning natural gas or coal at power plants, or chop down and burn tropical forests for new agricultural land, we release carbon dioxide (CO$_2$) gas into the air. The quantity of carbon released by human activities is enormous. For 2008, the most recent year for which we have published data, total human CO$_2$ emissions were about 10 billion tons of carbon annually (equivalent to one million tons per hour or, on a per capita basis, ~0.2 kg person$^{-1}$ h$^{-1}$; note that 1 billion tons equals 1 Pg or 1 x 10$^{15}$ g). Of this amount, 8.7 ± 0.5 billion tons originates from fossil fuel combustion and cement production and another 1.2 ± 0.7 billion tons from deforestation (Le Quéré et al., 2009). The cumulative human CO$_2$ emissions over the industrial era now amount to close to 560 billion tons. A little less than half of this anthropogenic CO$_2$ remains in the atmosphere—certainly enough to be of grave concern as a greenhouse gas leading to climate change. The remainder is, at present, removed in roughly equal parts into the ocean and by land vegetation. Revelle and Suess (1957) wrote a prophetic view of our perturbations to the global carbon cycle: Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future—a sentiment that may be especially true for ocean acidification. The build-up of excess CO$_2$ in the atmosphere is clearly evident in time series such as the one established in 1958 by Charles David Keeling from the top of Mauna Loa volcano in Hawaii, the longest atmospheric CO$_2$ instrumental record. When Keeling started making measurements, atmospheric CO$_2$ was about 315 parts per million (ppm) (Keeling, 1960); present values (387 ppm) are already more than 37% greater than pre-industrial levels (~280 ppm) (Feely et al., 2009; Tans, 2009). If fossil fuel consumption continues unabated, it could double or triple before the end of this century (Tans, 2009). The current rapid rise in atmospheric CO$_2$ is as much as 30 times faster than natural rates in the geological past, and present levels are higher than at anytime in at least the last 850,000 years and likely several million years (Kump et al., 2009).”


“Since the beginning of the industrial revolution in the mid-eighteenth century, the release of carbon dioxide (CO$_2$) from humankind's combined industrial and agricultural activities has resulted in an increase in atmospheric CO$_2$ concentrations from approximately 280 to 387 parts per million (ppm), with as much as 50% of the increase occurring in the last three decades. Earth's atmospheric concentration of CO$_2$ is now higher than it has been for more than 800,000 years (Lüthi et al., 2008), and it is expected to continue to rise at an accelerating rate, leading to significant temperature increases in the atmosphere and the surface ocean in the coming decades. Over the industrial era, the ocean has absorbed about one-quarter of anthropogenic carbon emissions (Sabine and Feely, 2007; Canadell et al., 2007). This absorption has benefited humankind by significantly curtailing the growth of CO$_2$ levels in the atmosphere, thereby reducing the global warming realized to date. However, when the anthropogenic CO$_2$ is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion ($CO_3^{2-}$) concentration, and saturation states of the biologically important CaCO$_3$ minerals calcite ($\Omega_{ca}$) and aragonite ($\Omega_{ar}$) in a process commonly referred to as "ocean acidification" (Broecker and Clarke, 2001; Caldeira and Wickett, 2003, 2005; Orr et al., 2005; Doney et al., 2009; Figure 1). The pH of ocean surface waters has already decreased by about 0.1 since the industrial era began (Caldeira and Wickett, 2003, 2005; Orr et al., 2005), with a decrease of ~0.0018 yr$^{-1}$ observed over the last quarter century at several
open-ocean time-series sites (Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007; Dore et al., 2009). By the middle of this century, atmospheric CO2 levels could reach more than 500 ppm, and exceed 800 ppm by the end of the century (Friedlingstein et al., 2006). These CO2 levels would result in an additional decrease in surface water pH of 0.3 units from current conditions, 0.4 from pre-industrial, by 2100, which represents an increase in the ocean's hydrogen ion (H+) concentration by 2.5 times relative to the beginning of the industrial era. Results from large-scale ocean CO2 surveys and time-series studies over the past two decades show that ocean acidification is a predictable consequence of rising atmospheric CO2 (Feely et al., 2004; Bates and Peters, 2007; Santana-Casiano et al., 2007; Dore et al., 2009; Takahashi et al., 2009) that is independent of the uncertainties and outcomes of climate change.”


“Ocean acidification poses a challenge to marine biodiversity and the ability of oceans to continue to function as a sink of CO2 (currently removing roughly 25% of human emissions). The atmospheric removal process includes both dissolution of CO2 into seawater, and the uptake of carbon by marine organisms. The ocean absorption of anthropogenic CO2 is not evenly distributed spatially (Sabine et al. 2004) or temporally (Canadell et al. 2007). Addition of CO2 to the oceans increases the acidity (lowers pH) of the surface seawater. Many marine organisms are very sensitive to changes in ocean CO2 chemistry—especially those biota that use carbonate ions dissolved in the seawater to form protective calcium carbonate shells or skeletal structures. Surface ocean pH has decreased by about 0.1 pH units (corresponding to a 30% increase in hydrogen ion concentration and a 16% decline in carbonate concentrations) since pre-industrial times (Guinotte et al. 2003, Feely et al. 2004, Orr et al. 2005, Guinotte and Fabry 2008, Doney et al. 2009). This rate of acidification is at least 100 times faster than at any other time in the last 20 million years. Marine organisms secrete calcium carbonate primarily in the forms of aragonite (which is produced by corals, many mollusks, and other marine life) and calcite (which is produced by different single-celled plankton and other groups). Aragonite is about 50% more soluble in seawater than calcite (Mucci 1983). Thus, with rising ocean acidity, aragonite shells are expected to dissolve before those made of calcite unless the organism has evolved some mechanism to prevent shell dissolution. A third type of biogenic calcium carbonate, high magnesium calcite, is secreted by some marine life such as coralline red algae and sea urchins. Depending on its magnesium concentration, high magnesium calcite can be more soluble in seawater than aragonite. For all three of these types of calcium carbonate, the carbonate ion concentration strongly affects the saturation state of the mineral in seawater. If the pH of the oceans decreases sufficiently, the concomitant reduction in carbonate ion concentration results in a decrease in the seawater saturation state with respect to either aragonite or calcite. If the calcium carbonate saturation state is less than one, then calcium carbonate produced by marine organisms to make their solid shells becomes soluble unless the organism has some way of preventing dissolution (Feely et al. 2004, Fabry et al. 2008). Globally, the surface ocean aragonite saturation state (Ωarag) is declining with rising ocean acidity. It has fallen from a pre-industrial value of Ωarag = 3.44 to a current value of 2.9. A Ωarag value of 2.29 is projected for a doubling of CO2 (Guinotte and Fabry 2008). Even though globally averaged Ωarag values in surface waters remain above unity for a doubling of atmospheric CO2, large parts of the Southern Ocean and the Arctic Ocean are projected to become undersaturated with respect to aragonite as early as 2030–2060 (Orr et al. 2005, McNeil and Matear 2008, Steinacher et al. 2009). Aragonite undersaturation means that these waters will become corrosive to the aragonite and high magnesium calcite shells secreted by a wide variety of marine organisms. The projected rate of change in ocean CO2 chemistry
leaves little time for organisms to evolve adaptations. Although some species may be CO$_2$ insensitive or able to adapt (e.g., Miller et al. 2009), the energetic costs of achieving net shell growth and preventing dissolution in conditions of aragonite undersaturation will likely have other impacts on overall growth rates, predation, metabolism, or reproduction, as observed in organisms from other regions (e.g., Iglesias-Rodriguez et al. 2008, Fabry et al. 2008, Wood et al. 2008, Tunnicliffe et al. 2009). The large-scale depletion of aragonite-forming organisms would be a major disturbance in marine ecosystems, the consequences and impacts of which are highly uncertain. Deleterious effects on many marine organisms start well above the geochemical threshold of $\Omega_{\text{arag}} = 1$, with calcification rates for some organisms being reduced by 10%–60% for a doubling of atmospheric CO$_2$ (Guinotte and Fabry 2008, Fabry et al. 2008). Even small sensitivities of biota to increased CO$_2$ will become amplified over successive generations and may drive the restructuring of diverse marine ecosystems, the consequences of which are very difficult to predict (Fabry 2008). Furthermore, by the year 2200, under a business-as-usual scenario for fossil-fuel consumption, the reduction in seawater pH and phytoplankton could induce a large reduction in the export of marine organic matter from coastal waters leading to considerable expansion of hypoxic zones (Hofmann and Schellnhuber 2009). Ocean acidification may have serious impacts on coral reefs and associated ecosystems. Coral reefs are in danger of being exposed to marginal conditions ($\Omega_{\text{arag}}$ values between 3–3.5) or extremely marginal conditions ($\Omega_{\text{arag}}$ values below 3) almost everywhere by as early as 2050 (Kleypas et al. 1999, Guinotte et al. 2003, Langdon and Atkinson 2005, Hoegh-Guldberg et al. 2007), causing substantial changes in species composition and in the dynamics of coral and other reef communities (Kuffner et al. 2008, Guinotte and Fabry 2008, Doney et al. 2009). Similarly, marine plankton are also vulnerable (Riebesell et al. 2000), presumably with ripple effects up the food chain. Ocean acidification and warming combine and interact to decrease the productivity in coral reefs (Anthony et al. 2008), reinforcing the notion that multiple stressors on coral reefs often combine to have negative effects that are well beyond those expected from any single stressor (Bellwood et al. 2004). Although the threshold for aragonite saturation is easy to define and quantify, significant questions remain as to how far from this threshold the boundary value should be set. Combining estimates of the point at which calcification rates begin to be affected substantially, the values of aragonite saturation state at which conditions for corals go from adequate to marginal, and the point at which surface waters at high latitudes begin to approach aragonite undersaturation suggests a placement of the ocean acidification boundary well away from the aragonite saturation state at dissolution ($\Omega_{\text{arag}} = 1$). As a first estimate, we propose a planetary boundary where oceanic aragonite saturation state is maintained at 80% or higher of the average global pre-industrial surface seawater $\Omega_{\text{arag}}$ of 3.44. Recognizing that carbonate chemistry can be variable over diel and seasonal timescales (Tyrrell et al. 2008, Feely et al. 2008, Miller et al. 2009), we suggest that the typical diel and seasonal range of values of aragonite saturation state be incorporated into this boundary (i.e., $>80\%$ of the average surface ocean, pre-industrial aragonite saturation state $\pm$ diel and seasonal variability). The major rationale behind this subjective value is twofold: to keep high latitude surface waters above aragonite undersaturation and to ensure adequate conditions for most coral systems."


**Exercise:**

In order to introduce the planetary boundary of ‘ocean acidification’ to the rest of the group, please summarize the main causes for and impacts of ocean acidification. If possible try to find an example to visualize your findings.
Planetary Boundary: ‘Rate of biodiversity loss’

The following is a set of excerpts of scientific articles about the problem of biodiversity loss, derived from Dirzo/ Raven (2003), Armsworth et al. (2003) and Rockström et al. (2009).

“Somewhere between 3 and 100 million species inhabit the Earth (Heywood, 1995). As a shorthand description of this great variety of life, the term “biodiversity” is a contraction of “biological diversity”, and was first coined by Walter Rosen for the 1986 National Forum on BioDiversity(Wilson,1988). However, biodiversity refers to more than just an accumulation of species. If that were all that it was, then we might hope to conserve biodiversity in zoos. Instead, biodiversity also refers to organisms’ existence in situ, and incorporates the ecological and evolutionary interactions among them. For example, the UN Convention on Biological Diversity defines biodiversity as “...the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” (United Nations Environment Programme, 1992, p. 4)”

"Biodiversity - the sum total of all of the plants, animals, fungi, and microorganisms on Earth; their genetic and phenotypic variation; and the communities and ecosystems of which they are a part - is more rich and varied now than ever before (1), but it is threatened with a major pulse of extinction to which some authors have referred as the sixth major extinction of the Phanerozoic Era (2). Even though there is no consensus as to the magnitude of biodiversity on Earth, it has clearly reached unprecedented diversity as a result of more than 3.5 billion years of organic evolution. At the same time, human domination of the planet is so extensive (3) that Crutzen (4) has gone so far as to refer to the present as “the Anthropocene Era” (4). It is obvious to most scientists that extinction is rampant at present, but a few skeptics have demurred, claiming that this is “a doomsday myth” (5) or that the estimates of extinction are “strident, inconsistent and data-free” (6).”

“Historically, ecologists have tended to focus on the species level of biodiversity, and have quantified it in two ways:
• Richness: the number of species in a given area.
• Evenness: how evenly balanced are the abundances of each species, where the abundance of a species is the number of individuals present.”

"Local and regional biodiversity changes can have pervasive effects on Earth System functioning and interact with several other planetary boundaries. For example, loss of biodiversity can increase the vulnerability of terrestrial and aquatic ecosystems to changes in climate and ocean acidity, thus reducing the safe boundary levels for these processes. The current and projected rates of biodiversity loss constitute the sixth major extinction event in the history of life on Earth—the first to be driven specifically by the impacts of human activities on the planet (Chapin et al. 2000). Previous extinction events, such as the Tertiary extinction of the dinosaurs and the rise of mammals, caused massive permanent changes in the biotic composition and functioning of Earth’s ecosystems. This suggests non-linear and largely irreversible consequences of large-scale biodiversity loss. Accelerated biodiversity
loss during the Anthropocene (Mace et al. 2005) is particularly serious, given growing evidence of the importance of biodiversity for sustaining ecosystem functioning and services and for preventing ecosystems from tipping into undesired states (Folke et al. 2004). A diversity of functional response mechanisms to environmental variation among species in an ecosystem maintains resilience to disturbances. Consequently, ecosystems (both managed and unmanaged) with low levels of response diversity within functional groups are particularly vulnerable to disturbances (such as disease) and have a greater risk of undergoing catastrophic regime shifts (Scheffer and Carpenter 2003). Species play different roles in ecosystems, in the sense of having different effects on ecosystem processes and/or different responses to shifts in the physical or biotic environment (i.e., they occupy different niches). Species loss, therefore, affects both the functioning of ecosystems and their potential to respond and adapt to changes in physical and biotic conditions (Elmqvist et al. 2003, Suding et al. 2008). Currently, the global extinction rate far exceeds the rate of speciation, and consequently, loss of species is the primary driver of changes in global biodiversity. The average extinction rate for marine organisms in the fossil record is 0.1 to 1 extinctions per million species-years (E/MSY), and extinction rates of mammals in the fossil record also fall within this range (Pimm et al. 1995, Mace et al. 2005). Accelerated species loss is increasingly likely to compromise the biotic capacity of ecosystems to sustain their current functioning under novel environmental and biotic circumstances (Walker et al. 1999). Since the advent of the Anthropocene, humans have increased the rate of species extinction by 100–1000 times the background rates that were typical over Earth’s history (Mace et al. 2005), resulting in a current global average extinction rate of ≥100 E/MSY. The average global extinction rate is projected to increase another 10-fold, to 100010 000 E/MSY during the current century (Mace et al. 2005). Currently about 25% of species in wellstudied taxonomic groups are threatened with extinction (ranging from 12% for birds to 52% for cycads). Until recently, most extinctions (since 1500) occurred on oceanic islands. In the last 20 years, however, about half of the recorded extinctions have occurred on continents, primarily due to land-use change, species introductions, and increasingly climate change, indicating that biodiversity is now broadly at risk throughout the planet. The lower and upper bounds of extinction rates in the fossil record (0.1–1.0 E/MSY with a median rate for mammals estimated at 0.3 E/MSY) provide the best long-term estimates of the background extinction rates that have historically conserved global biodiversity. A background extinction rate of 1 E/MSY across many taxa has been proposed as a benchmark against which to assess the impacts of human actions (Pimm et al. 2006). There is ample evidence that the current and projected extinction rates are unsustainable (MEA 2005b). Nonetheless, it remains very difficult to define a boundary level for the rate of biodiversity loss that, if transgressed for long periods of time, could result in undesired, non-linear Earth System change at regional to global scales. Our primary reason for including biological diversity as a planetary boundary is its role in providing ecological functions that support biophysical subsystems of the Earth, and thus provide the underlying resilience of other planetary boundaries. However, our assessment is that science is, as yet, unable to provide a boundary measure that captures, at an aggregate level, the regulating role of biodiversity. Instead we suggest, as an interim indicator, using extinction rate as a substitute. In doing so, we conclude that humanity has already entered deep into a danger zone where undesired system change cannot be excluded, if the current greatly elevated extinction rate (compared with the natural background extinction) is sustained over long periods of time. We suggest an uncertainty range for this undesired change of 10–100 E/MSY, indicating
that a safe planetary boundary (here placed at 10 E/MSY) is an extinction rate within an order of magnitude of the background rate. This relatively safe boundary of biodiversity loss is clearly being exceeded by at least one to two orders of magnitude, indicating an urgent need to radically reduce biodiversity loss rates (Díaz et al. 2005). A major caveat in setting a safe extinction rate is the common observation that species are not equally important for ecosystem function. In particular, the loss of top predators and structurally important species, such as corals and kelp, results in disproportionately large impacts on ecosystem dynamics."


**Exercise:**

In order to introduce the planetary boundary of ‘Rate of biodiversity loss’ to the rest of the group, please summarize the main causes for and impacts of biodiversity loss. If possible try to find an example to visualize your findings.
Planetary Boundary: ‘Stratospheric ozone depletion’

The following is a set of extracts of scientific articles about the global stratospheric ozone depletion, derived from Hegglin et al. (2015), Rockström et al. (2009) and Steffen et al. (2015).

“Located in the atmospheric layer known as the stratosphere is a region of concentration of the ozone (O₃) molecule. This “ozone layer” is found at an altitude of about 10 to 50 kilometers (6 to 31 miles), with a maximum concentration in the stratosphere at an altitude of approximately 25 kilometers (16 miles). Starting in the late 1970s, scientists began measuring a seasonal depletion of ozone in the ozone layer mainly at the South Pole. The ozone layer naturally shields Earth’s life from the harmful effects of the Sun’s ultraviolet (UV) radiation. The nation’s of the world have responded to this global environmental problem by proposing a plan known as the Montreal Protocol, to reduce and eliminate the use of chlorofluorocarbons (CFCs) the human-made chemical primarily responsible for ozone loss.”


The stratospheric ozone depletion

“The stratospheric ozone depletion process begins with the emission of halogen source gases by human activities and natural processes. Those emitted by human activities are also called ozone-depleting substances (ODSs). Subsequent steps are accumulation, transport, conversion, chemical reaction, and removal. Ozone depletion by halogen source gases occurs globally. Large seasonal ozone losses occur in polar regions as a result of reactions involving polar stratospheric clouds (PSCs). Ozone depletion ends when reactive halogen gases are removed by rain and snow in the troposphere and deposited on Earth’s surface.”

“Depletion of the global ozone layer increased gradually in the 1980s and reached a maximum of
about 5% in the early 1990s. The depletion has lessened since then and now is about 3% averaged over the globe. The average depletion exceeds the natural year-to-year variations of global total ozone. The ozone loss is very small near the equator and increases with latitude toward the poles. The larger polar depletion is attributed to the late winter/early spring ozone destruction that occurs there each year. Global total ozone has decreased beginning in the 1980s (see Figure Q13-1). The decreases have occurred in the stratospheric ozone layer where most ozone resides (see Figure Q1-2). In the early 1990s, the depletion of global total ozone reached a maximum of about 5% below the 1964–1980 average. The depletion has lessened since then and during the early 2010s has averaged to about 3% below the 1964–1980 average. The observations shown in Figure Q13-1 have been smoothed to remove regular ozone changes that are due to natural seasonal and solar effects (see Q14). The depleted amounts are larger than the remaining natural variations in global total ozone amounts. The observed global ozone depletion in the last three decades is attributable to increases in reactive halogen gases in the stratosphere. The lowest global total ozone values since 1980 have occurred in the years following the eruption of Mt. Pinatubo in 1991, which temporarily increased the number of sulfuric acid-containing particles throughout the stratosphere. These particles significantly increased the effectiveness of reactive halogen gases in destroying ozone (see Q14) and, thereby, increased global ozone depletion by 1–2% for several years following the eruption. […]"


**Global total ozone changes and its ‘Boundary’**

“Stratospheric ozone filters ultraviolet radiation from the sun. The appearance of the Antarctic ozone hole was a textbook example of a threshold in the Earth system being crossed—completely unexpectedly. A combination of increased concentrations of anthropogenic ozone-depleting substances (like chlorofluorocarbons) and polar stratospheric clouds moved the Antarctic stratosphere into a new regime: one in which ozone effectively disappeared in the lower stratosphere in the region during the Austral spring. This thinning of the Austral polar stratospheric ozone layer has negative impacts on marine organisms (Smith et al. 1992) and poses risks to human health. Although it does not appear that there is a similar threshold for global ozone, there is the possibility that global warming (which leads to a cooler stratosphere) could cause an increase in the formation of polar stratospheric clouds. Were this to happen in the Arctic region, it could trigger ozone holes over the northern hemisphere continents, with potential impacts on populations there.

Although the ozone hole phenomenon is a classic example of a threshold, we have chosen to frame the planetary boundary around extra-polar stratospheric ozone. There are two main reasons for this framing. First, the ozone hole “tipping point” depends on anthropogenic ozone-depleting substances, but also on sufficiently cold temperatures and a sufficient amount of water vapor and, in some cases, nitric acid. Humans contribute directly to the first (and to some extent the last) of these, and indirectly to the others. Second, although polar ozone holes have local impacts, a thinning of the extra-polar ozone layer would have a much larger impact on humans and ecosystems.

In the case of global, extra-polar stratospheric ozone, there is no clear threshold around which to construct a boundary. As such, the placement of our boundary in this case is of necessity more uncertain than, for example, in the case of ocean acidification. We consider the planetary boundary for ozone levels to be a <5% decrease in column ozone levels for any particular latitude with respect to 1964–1980 values (Chipperfield et al. 2006).

Fortunately, because of the actions taken as a result of the Montreal Protocol (and its subsequent amendments), we appear to be on a path that
avoids transgression of this boundary. In 2005, the tropospheric concentrations of ozone-depleting gases had decreased by 8%-9% from their peak values in 1992–1994 (Clerbaux et al. 2006). Although there is a considerable lag time between concentration decreases in the troposphere and stratospheric ozone recovery, at least the major anthropogenic driver of ozone depletion is being reduced. The decline in stratospheric ozone concentrations between 60°S and 60°N seen since the 1990s has been halted (Chipperfield et al. 2006). However, the Antarctic ozone hole is expected to exist for some decades, and Arctic ozone losses may continue for the next decade or two. On balance, the case of stratospheric ozone is a good example where concerted human effort and wise decision making seem to have enabled us to stay within a planetary boundary.

"We retain the original control variable (O3 concentration in DU (Dobson Units) and boundary (275 DU). This boundary is only transgressed over Antarctica in the austral spring, when O3 concentration drops to about 200 DU (44). However, the minimum O3 concentration has been steady for about 15 years and is expected to rise over the coming decades as the ozone hole is repaired after the phasing out of ozone depleting substances. This is an example where, after a boundary has been transgressed regionally, humanity has taken effective action to return the process back to within the boundary."

Exercise:
In order to introduce the planetary boundary of “stratospheric ozone depletion” to the rest of the group, please summarize the main points of the problem of ozone depletion and the principle steps in stratospheric ozone depletion.