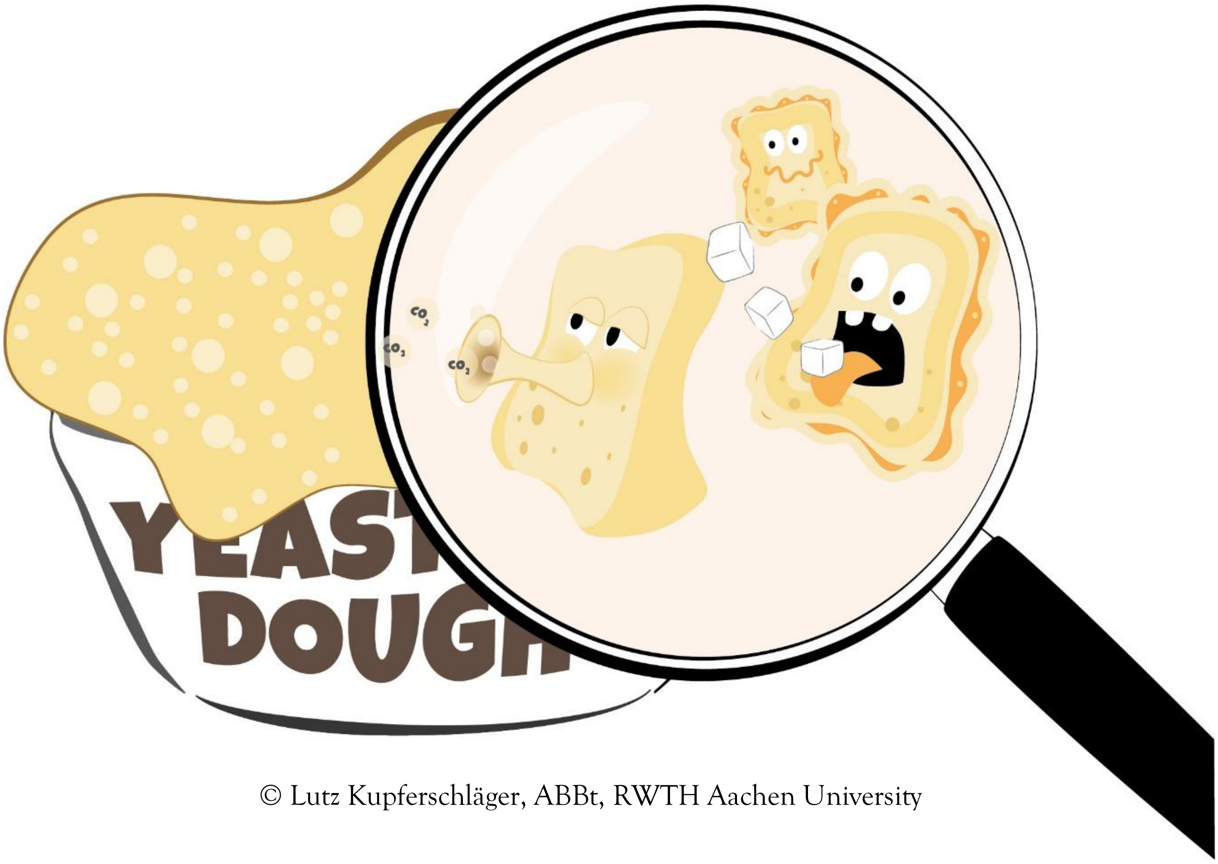
Planetary Boundaries

Dad, why does the pizza dough stop growing after some time?



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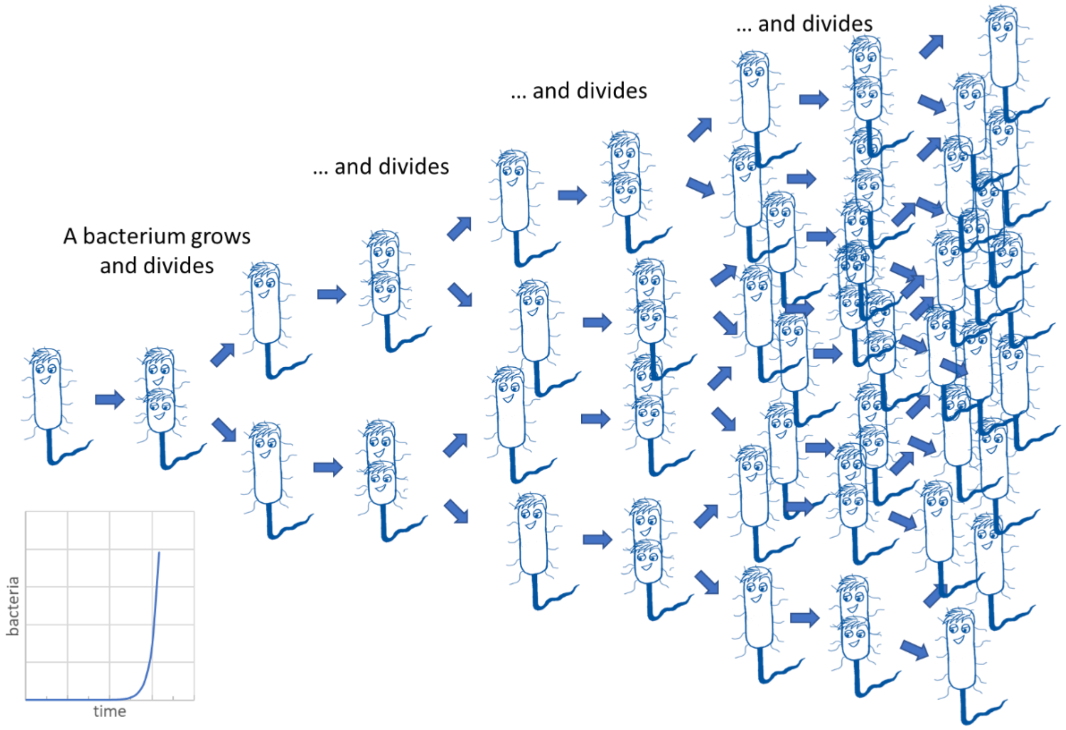
Storyline

All growth, qualitative and quantitative, requires material resources and energy, regardless of whether it is the growth of a child, the economy of a country, or a small bacterium like the normal inhabitant of the human and animal gastrointestinal tract, *Escherichia coli*. This bacterium, whose diameter is just one hundredth the diameter of a human hair, is unicellular like other microbes, and therefore growth is an increase in cell size followed by a simple division into two. With *E. coli,* this takes about 20 minutes under optimal conditions.

During growth, one *E. coli* cell becomes two cells after 20 minutes, 4 after 40 minutes, 8 after 60 minutes, and so on. This is *exponential* growth; if it would continue, this approx. 2 pg heavy bacterium (picogram – a trillionth of a gram), would form a bacterial mass with a total weight of 6 x 10^{27} g after just one day and 20 hours, a weight corresponding to the weight of our entire planet. An unimaginable achievement, but one that would understandably require a lot of resources and energy. Now one might think that if infinite resources and energy were available, an unlimited progression of exponential growth would be possible. But that this is not the case can already be seen in these smallest organisms, the microbes.



Exponential growth of bacteria.

Take, for example, the baker's yeast *Saccharomyces cerevisiae*, which we use to make our pizza dough or the dough for a yeast plait. This yeast does not multiply by dividing into two, but by budding and it does not double every 20 minutes but needs at least 90 minutes to do so, but again an exponential growth can be seen when all nutrients are provided. This exponential growth flattens out after some time and comes to a halt, and the cells devote all their energy and resources just to sustain themselves. Once the limits of the system are reached it collapses and the yeast will die. Even if additional nutrients are provided to the yeast during exponential growth, growth would still no longer proceed exponentially after a certain time because other limitations are successively reached: the *rate limiting parameters*. This can be, for example, necessary space or the accumulation of too many or toxic waste products. Here, in analogy to the yeast in our pizza dough running out of resources, we discuss the limitations of growth on our planet earth in the context of the recently identified planetary boundaries. Suggestions how the consequences of (microbial) growth can be taught are given.

The Planetary Boundaries and Societal Context

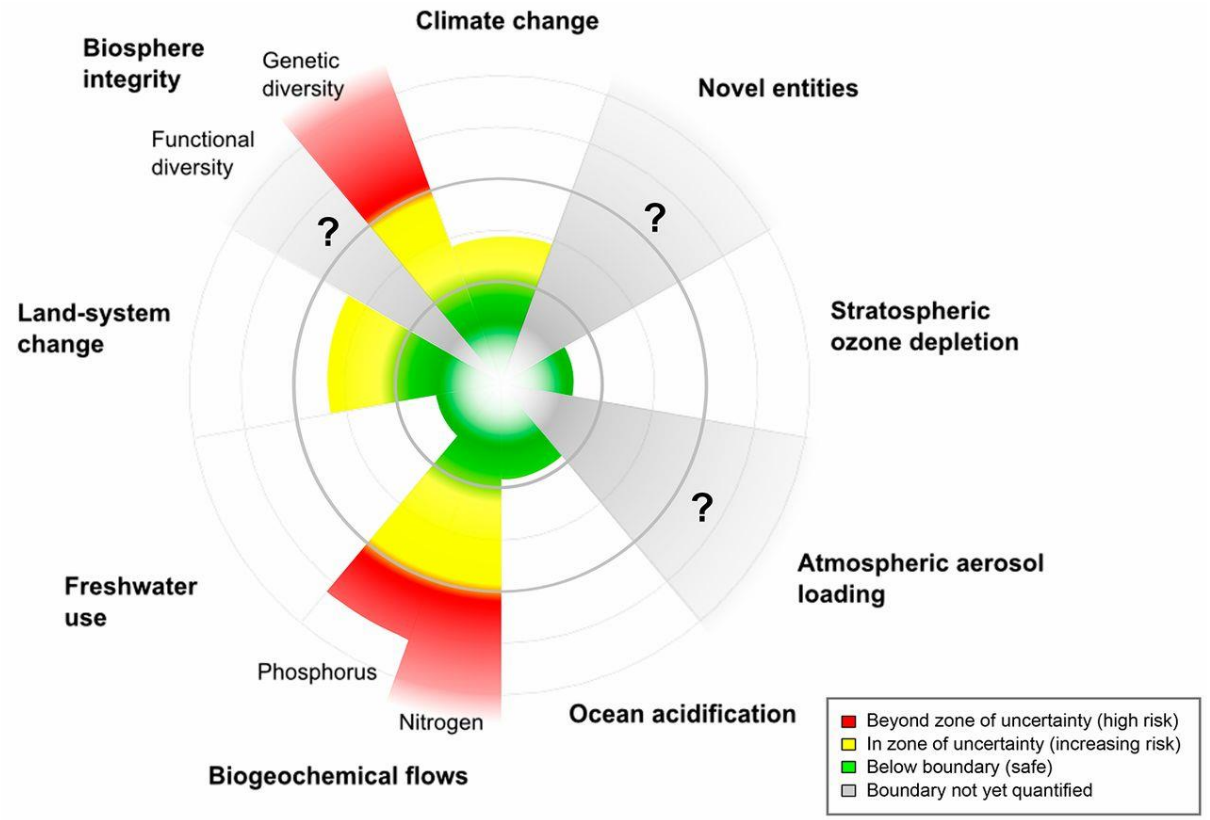
We are not living in a closed system, but rather get additional energy for "free": sunlight, (in the future also our own fusion?). Hence, every process that requires energy can in theory be taken care of. But already the 1972 report "The Limits to Growth" concluded that the absolute limits of growth on earth will be reached over the next hundred years if the current increase in world population, industrialization, environmental pollution, food production, and the exploitation of natural resources continues unchanged. And even 40 years later, nothing had really changed in these forecasts, except that the simulations had become more precise and realistic, due to the improved data situation and the better computer technology.

But nowadays, in contrast to the situation 50 years ago, the prognoses and their causes are taken seriously by many societies and governments, documented in the Paris Climate Agreement (2015), the formulation of the Sustainable Development Goals (SDGs), and first steps taken towards a circular bioeconomy. Examples of technological approaches to remove carbon dioxide from the atmosphere are, in addition to simple measures such as afforestation, carbon capture and storage, and carbon capture and utilization. The cost of such technologies is coming down as well, although reducing carbon dioxide (CO_2) release is still far less expensive. However, since CO_2 emissions cannot be effectively reduced in some processes, technologies for CO_2 capture are necessary in order to achieve the corresponding climate targets. Rapidly reducing methane emissions would arguably be a rather quick option to change the trajectory of climate change, as the half-life of methane in the atmosphere is with 12 years rather short compared to 20-200 years of CO_2 (IPCC, 2014), an option favoured by the November 2021 UN COP26 meeting.

Planetary Boundaries

1. ***What are planetary boundaries? - Ecological limits within which the stability of the Earth´s ecosystem can be preserved.*** With the establishment of planetary boundaries, an attempt has been made to establish ecological limits within which the stability of the Earth's ecosystem can be guaranteed (https://doi.org/10.1126/science.1259855). This can be imagined in a similar way to speed limits on our roads. These limits are chosen differently, depending on the environment and the road conditions, and should always ensure that the probability of an accident is as low as possible without making it impossible to drive at all. Staying below this speed limit does not guarantee that accidents will not happen, but it becomes less likely. Likewise, it is not certain that an accident will occur if the speed is exceeded, but the likelihood increases. It is similar with planetary boundaries.

Based on scientific understanding of the Earth system's functioning, nine different areas have been defined and, within them, limits have been defined whose adherence would make the risk of the planet being destabilized by anthropogenic disturbances low. Defining these boundaries is the biggest problem in creating planetary boundaries. For example, a variable needs to be identified that is directly related to the boundary and measurable. In addition, the complexity of the environmental system is so extensive that it is difficult to precisely define the parameters used. Furthermore, complete data is not always available or obtainable. Therefore, planetary boundaries are to be understood as borders with blurred edges rather than exact lines. For this reason, when depicting boundaries, there are regions of indicated by yellow, which indicates the uncertainty due to weaknesses and gaps in scientific knowledge.



The current status of the control variables for seven of the nine planetary boundaries. The green zone is the safe operating space, yellow represents the zone of uncertainty, and red is the high-risk zone. The planetary boundary itself is indicated by the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity. (From Steffen *et al.*, 2015, reprinted with permission from *Science*).

Regional differences may also be a problem, as the boundaries were considered purely at a global level when first compiled in 2009. This is again similar to road speed limits. These limits are adapted to the various given environmental situations. So, you can drive much faster on highways than within a town, where for example pedestrians are to be expected. Such a regional, more precise limitation would also be advantageous for the planetary boundaries and was partially incorporated by the authors in the new edition of the planetary boundaries in 2015. However, it is difficult and often impossible to consider all regional and sectoral impacts of global change. With all their shortcomings, the planetary boundaries can aid decision-makers by defining a safe operating space for humanity.

2. ***Four of the nine planetary boundaries have already been exceeded due to human activity.*** According to an international team of 18 researchers, four of the nine planetary

boundaries have already been exceeded due to human activity. Two of these planetary boundaries, the biosphere integrity and the biogeochemical flows, have not only left the safe operating space, but have already reached the "high risk zone", in which unacceptable environmental changes could be generated that could promote destabilization of the Earth system. According to the assessment of the scientists, we are in the uncertain zone for the other two planetary boundaries, climate change and land use change.

When considering the exceeding of planetary boundaries, it should be noted that not all transgressions necessarily lead to immediate or extreme reactions; rather moderate or continuous consequences can also occur. Furthermore, global transgressions are considered in these assessments, but local transgressions, if they occur cumulatively, can also pose a risk for the Earth's system. However, every transgression, whether global or local, implies that society, politics, and every individual must do something more to keep the planet in a state that allows continued existence of eight billion and more humans.

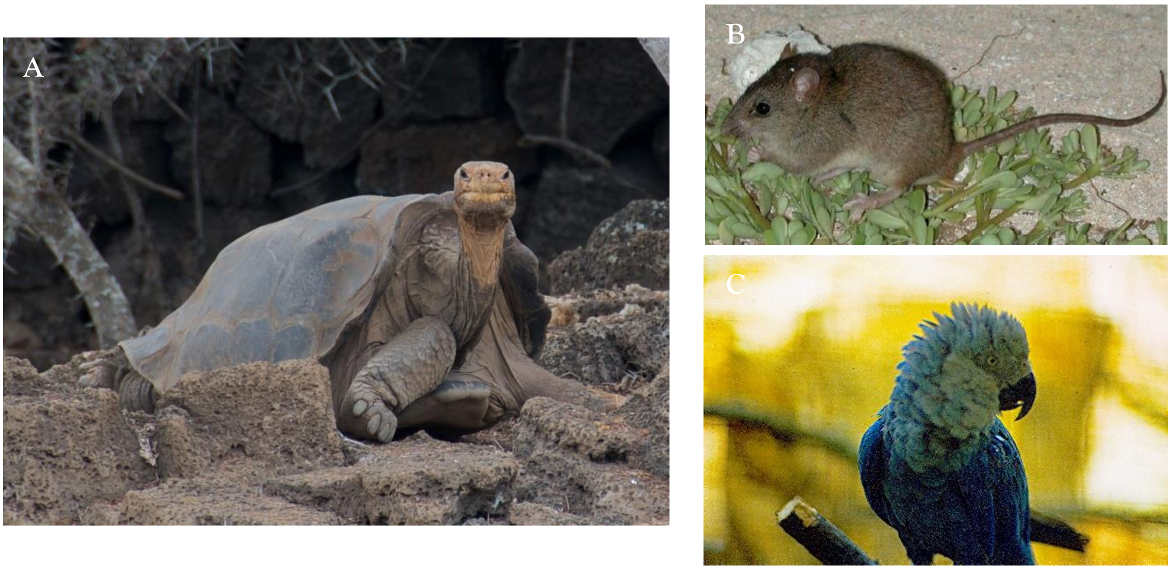
The best prerequisite for concerted action and rethinking in society and politics is an understanding of the interrelationships of the planetary boundaries and a knowledge of the effects of exceeding the boundaries. It should be noted that the changes also provide opportunities for new innovations and developments that enable and promote human and social development as we know it. **The knowledge provides us with opportunities to bend the curves.** In this article, we cannot be comprehensive, but rather focus on aspects in which the role of microbes can be highlighted.

3. ***Scientists designate climate change and biosphere integrity the core boundaries, boundaries which on their own have the potential to drive the Earth system to a new state.*** The two planetary boundaries climate change and changes in the biosphere integrity interact with all other boundaries – the other boundaries operate through these boundaries – so they have a particular significance for the function of the earth system. For this reason, some argue that these thresholds should be tackled more intensively than the others. It remains to be seen whether such a prioritization makes sense or whether the focus should be on the boundaries that are in the high-risk zone.

To assess the integrity of the biosphere, the genetic and functional diversity of all organisms should be determined. Therefore, two critical values are used, on one hand the biodiversity intact index (BII) and, on the other, the global extinction rate per million per year (E/MSY). BII is a recognized indicator of the average abundance of wild species in an area compared to the pre-modern era or primary vegetation under the current climatic conditions. Due to the inadequate data situation, this value is marked with a question mark in the diagram. Since it is also difficult to establish the relationship between BII and the earth system response, the uncertain range for this critical value was set from 90 to 30%.

The second critical value, the global extinction rate, is easier to record and the serious consequences of the extinction of specific organisms can be retraced. Nevertheless, not all consequences of biodiversity loss for the earth system can be estimated yet, since the earth system is very complex with many cross-links and interdependencies. For this reason, the first threshold was set relatively low with 10 extinctions per million species per year. However, the extinction rate is currently 100-1000 E/MSY and the consequences cannot be foreseen for the reasons mentioned.

The effects of extinctions are also difficult to assess because not only prominent examples such as the Pinta giant tortoise, whose last representative named Lonesome George died in 2016, are becoming extinct, but also other less prominent species and even unknown species disappear. In particular, when it comes to microbial diversity, it is difficult to determine whether it is decreasing like the diversity of the "macroorganisms" or not. One reason for this is that only a small fraction of the microbes occurring worldwide are classified. Even the fact that is now possible to estimate the microbial diversity of a specific sample by means of the different genomic DNAs present in it does not allow an exact statement about the worldwide microbial diversity.



Extinct animals in the 21st century. A. The last representative Pinta giant tortoise named Lonesome George died in 2016 (©A.Davey), B. Bramble cay melomys was officially declared extinct in 2016 due to human related climate change (©Ian Bell, EHP, State of Queensland, Creative Commons Attribution 3.0 Australia), C. Spix´s macaw, like Blu, the main protagonist in the movie Rio, were declared extinct in the wild in 2019 (©Rüdiger Stehn from Kiel, Deutschland - 71 Spix-Ara, CC BY-SA 2.0)

However, there are indications that microbial diversity is decreasing in specific areas. Studies of human gut bacteria, for example, have shown a decline in diversity. It is also evident that microbes that occur in a highly specific association with plants and animals become extinct when their host becomes extinct, because their habitats are lost.

But why is it interesting to know something about the influences of the human activities on the diversity of microbes? This is primarily due to the crucial role microbes play in maintaining a global, healthy ecosystem. Microbes are important in carbon und nutrient cycling, animal and plant health, agriculture, and the global food web simply because of the variety of the microbial metabolic pathways, their extreme diversity, and their large number. If you look at the Earth´s biomass, most of it isn´t composed of plants and animals, but rather of microscopic organisms found almost everywhere. You could even say we live in a microbial world, and it is precisely this influence of microorganisms that is important.

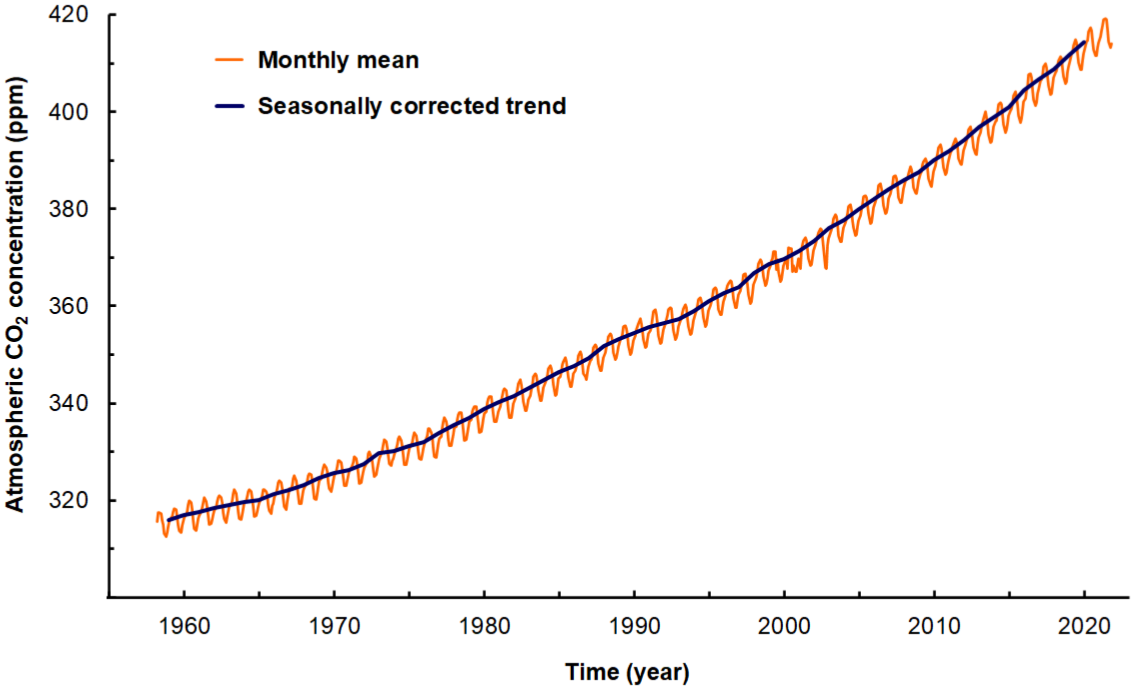
4. ***The atmospheric carbon dioxide (CO_2) concentration is already above the widely recognized ceiling for acceptable climate risk and the world already feels the impact.*** One of the planetary boundaries that has an impact on all others is climate change. Therefore, this is considered by scientists to be one of the two core boundaries which, if transgressed, have the potential to change the earth system intensely and irreversibly on its own. The second of these core boundaries is the biosphere integrity, which addresses changes in genetic or functional diversity, and which has already been mentioned.

To assess the change in climate, two variables are considered. The first commonly accepted control variable that we encounter every day in discussions about the climate is the CO_2

concentration in the atmosphere. CO_2 was chosen as this is the greenhouse gas released in greatest quantities by humans and because of its long lifetime in the atmosphere. Therefore, the change in the atmospheric CO_2 concentration can indicate the anthropogenic influence on climate change. However, in order to include all anthropogenic factors in the assessment, and not just the CO_2 concentration, scientists use global radiative forcing, a kind of world energy balance, as a second reference variable. However, for the sake of familiarity and simplicity, only the atmospheric CO_2 concentration is discussed here.

The threshold for atmospheric CO_2 concentration was set in the concept of the planetary boundaries at 350 parts per million (ppm), a value that was already exceeded in the 1980s. The zone of uncertainty was narrowed in 2015 from the range of 350-550 ppm, defined in 2009, to 350-450 ppm CO_2. This narrowing of the original choice was done because of the observed climatic changes, such as the frequency and duration of global heat waves. This update of the planetary boundaries and the unanimous opinion of the experts that transgressing 400 ppm atmospheric CO_2 leads to unacceptable climate risks, was incorporated into the goal of the Paris Agreement to limit global warming below 2°C, compared with pre-industrial levels.

In March 2021, a concentration of 417.64 ppm was measured at the measuring station of the Mauna Loa Observatory on Hawaii and the values continue to rise yearly. According to experts, exceeding the 450 ppm threshold will increase the risk of irreversible climate change and lead to global warming, melting glaciers, rising sea levels, and changes in forestry and agriculture.



Surface average atmospheric CO_2 concentration. The data is from Dr. P. Tans, NOAA/GML (*gml.noaa.gov/ccgg/trends/*) and Dr. R. Keeling, Scripps Institution of Oceanography (*scrippsco2.ucsd.edu/*), and are based on an average of direct atmospheric CO_2 measurements at the Mauna Loa station. Measurements are made at an altitude of 3400m in the northern subtropics. (Keeling *et al.*, 1976)

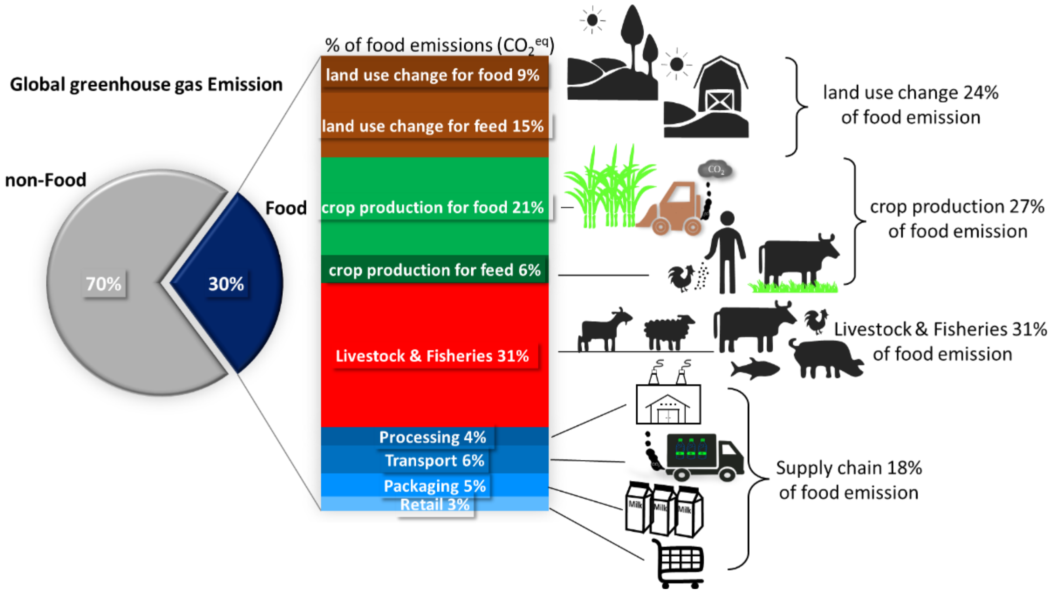
5. ***The food sector is responsible for a third of global greenhouse gas emissions: politics, industry and every individual need to contribute to a revolution in this sector.*** But what are the sources of greenhouse gas emissions? These sources can be found in many areas, but the food sector, and therefore agriculture, is estimated to be the major source, accounting for around 30%

of global annual emissions. Therefore, a revolution in the food production sector would likely lead to a significant reduction in global greenhouse gas emissions.

Next to CO_2 emissions, methane (CH_4), and nitrous oxide (N_2O) emissions are of particular importance in this sector. Their emissions are caused, for example, by livestock farming and the use of synthetic fertilizers. To get a better estimate of the greenhouse gas emissions, the other greenhouse gases are converted into CO_2 equivalents. CH_4 has a global warming potential of 86 times that of CO_2 over a 20-year timescale, and N_2O is even 286 times more harmful than CO_2. In this conversion, a fixed period is considered because the gases have different lifespans: CO_2 has a lifespan of several centuries, whereas N_2O has a lifespan of about 100 years, and CH_4 about 12 years.

The revolution in the food production sector should, on the one hand, include a revolution in the agricultural sector itself. For example, increasing production efficiency through more precise use of fertilizers or additives in animal feed, could simultaneously minimize the anthropogenic impact on the nitrogen and phosphate cycle and lead to a lower input of these two nutrients into water bodies.

A change in consumer behavior could drive such a revolution in the food sector. For example, a switch to a mainly plant-based diet with moderate consumption of animal products, such as milk, meat, and eggs, would reduce the agricultural impact on the world.



Global greenhouse gas emissions associated with food. Based on data from the meta-analysis by Poore & Nemecek (2018, Table S17). Land use change includes savannah burning (2%) and cultivated organic soil (4%). Livestock & Fisheries includes livestock/aquaculture (30%) and capture fisheries (1%).

6. ***Not only plants but also microorganisms remove the greenhouse gas CO_2 from the air and fix it through their metabolism.*** The concentrations of greenhouse gases in the atmosphere, which have such a strong influence on the climate, of course not only depend on the formation of the gases – the sources – but also on how much of these gases are captured or ‘fixed’ – the sinks. Let's look at this for the carbon cycle.

Carbon (C) is bound in the soil, in plants, in the oceans and generally in biomass on land and in the oceans. This bound C is defined as dynamic carbon stores, which means that the fixed carbon is out of circulation for an undefined period and can therefore return to the C cycle in substantial quantities. Important carbon sinks are forests, in which there is a net increase in biomass, peatlands which are still growing, and the oceans in which there is a biomass input. (The sinks should not be confused with the carbon reservoir, the carbon that is mainly bound in the earth's crust (mainly lithosphere) and does not naturally enter the C-cycle in significant quantities.)

Terrestrial and marine ecosystems together serve as sinks for around 50% of our global CO_2 emissions. This is not achieved by trees and plants alone: microorganisms play a major role in CO_2 fixation. For example, marine bacteria, especially *Prochlorococcus* and *Synechococcus*, remove about 10 billion tons of carbon every year from the air through photosynthesis and store it as biomass in the oceans. This represents 2/3 of the entire C-fixation of the oceans. A small part of the biomass produced by photosynthesis sinks before remineralization processes can break it down and recycle it into CO_2 and nutrients. So, this part of the carbon becomes sequestered in the deep sea.

Boosting microbial photosynthesis in marine systems, by removing rate-limiting parameters like available iron, through large scale addition of fertilizers, as an approach to increase the activity of this particular C-sink has been discussed. However, collateral and the long-term effects of addition of fertilization, which is necessary to promote the growth of the corresponding microorganisms, cannot yet be estimated. Other approaches include, for example, afforestation, agricultural practices to store carbon in soils (e.g., use of biochar), or bioenergy with carbon capture and storage.

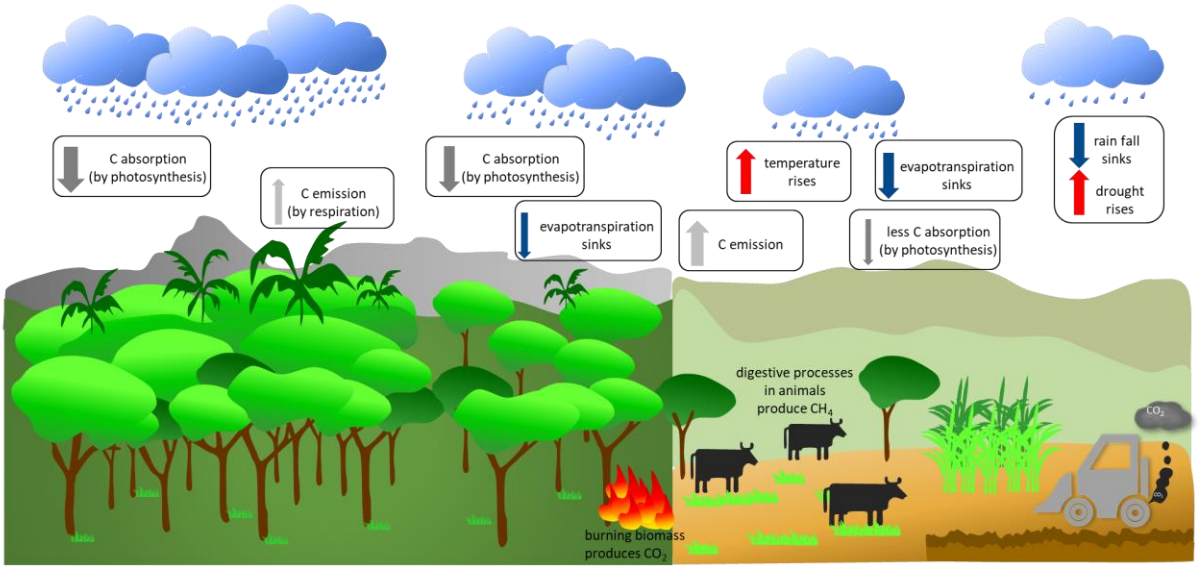
However, microorganisms are not only involved in fixing CO_2, but also in its formation. It is the same with the greenhouse gas methane. In a complex, self-regulating system such as the earth, fixation and release are parts of the natural cycles and ordinarily would not lead to any problems. Due to anthropogenic activities, however, such as burning fossil fuels to create energy, imbalances are caused, resulting in prejudicial environmental changes. For example, increased atmospheric CO_2 concentrations can lead to increased photosynthesis on land. This in turn results in more forest litter, which is degraded by microorganisms, producing more CO_2. At the same time, a higher atmospheric CO_2 concentration leads to global warming and this in turn increases the rate of degradation of the terrestrial material and thus leads to faster release of CO_2.

7. ***Changes in land use und climate have far-reaching consequences – the Amazon rainforest has become a source of CO_2, rather than a sink.*** The feeding of more than 8 billion humans not only generates large amounts of greenhouse gases, it also contributes to the change in land use, also a defined planetary boundary that has already left the certain zone (see first figure). As a critical and measurable variable to estimate the land-system change, the relative proportion of remaining forest cover (in percent) was used. The threshold in the land-system change was set at 75% of the original forest cover and leaving the zone of uncertainty at 54%. In 2015 the value was 62%.

The two planetary boundaries climate change and land use change clearly show how these defined boundaries are interlinked. On one hand, every ecosystem on earth is affected by the increased emission of greenhouse gases and the associated global warming. On the other hand, many ecosystems are changed by humans and this in turn has an impact on climate change, and also other key parameters, for example, like biodiversity.

A vivid example is the Amazon rainforest, which is a hot spot for biodiversity and in addition a large terrestrial carbon sink, or has been over decades. Threatened by agricultural conversion and climate change, this carbon sink seems to be in decline and the Amazon rainforest has become a source of CO_2, rather than a sink. The CO_2 emissions are largely driven by fires, which are often deliberately ignited to destroy the rainforest and enable its conversion into pasture or agricultural land, but also caused by the higher temperatures and droughts. For example, the east, which makes up 24% of Amazonia, is responsible for 72% of the total Amazonian carbon emissions, 62% of which are due to fires. Generally, about 10% of anthropogenic CO_2 emissions over the last decade, ~1 Pg C yr^{-1} (petagram carbon per year), were released by deforestation of the rainforest (IPCC 2013).

However, deforestation is not the only reason for increasing net CO_2 emissions. Also, degradation of the forests adjacent to the deforested regions contributes to this. These degraded forests absorb less CO_2 than before and thus the CO_2 emissions caused by deforestation cannot be compensated. This degradation is due to rising temperatures and reduced evapotranspiration, which in turn leads to less rain and thus more droughts. In addition to higher CO_2 emissions, this also makes the remaining forests more susceptible to fires or further degradation. Furthermore, the reduced rainfall and the droughts lead to lower crop yields. That means that newly-created farmland has lower than normal productivity.



Forest, e.g. primary rain forest provides soil protection, reduces temperature by evaporation cooling and consumes more CO_2 than it releases by respiration.

Degraded forest leads to lower CO_2 absorption (also in neighboring areas) and decreasing evapotranspiration, thus increasing temperature.

Conversion to pasture or agricultural land reduces CO_2 absorption, O_2 production and evapotranspiration. In addition, these land use changes increase CH_4 emission from the soil, temperature, and drought.

Some effects of change in land use. Conversion of forest to pasture or agricultural land reduce the absorption of greenhouse gas and cause higher temperatures and droughts.

8. ***Changes in land use also boost the formation of other potent greenhouse gases - rainforest-to-cattle pasture conversion boosts methane release.*** The conversion of primary rainforest (i.e., a naturally regenerated forest of native tree species where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed) into pastures alters not only the flora, but also the microorganisms that drive the biogeochemical cycle of the soil. It was found that in the pastureland, in comparison to primary and secondary rainforests, the occurrence and diversity of active methanogenic microorganisms in the soil increased.

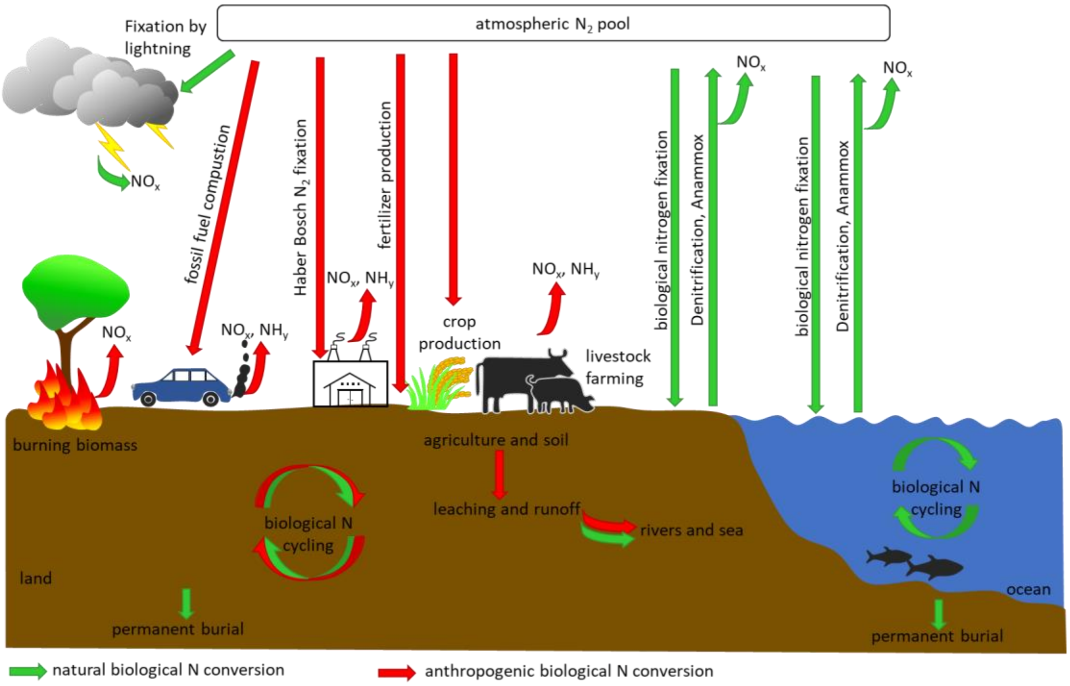
However, what influence do methanogens have on the biotic CH_4 cycle? Methanogenic microorganisms, mostly methanogenic archaea, produce CH_4, whereas methanotrophic bacteria consume CH_4. Through these activities, these two functional groups of microorganisms control the biotic CH_4 cycle and the balance between them decides whether a soil functions as a CH_4 source or as a CH_4 sink. Therefore, an increase in the occurrence and diversity of active methanogens in in newly-created pastureland is likely to cause increased CH_4 emissions of the soil. Indeed, measurement of infield gas fluxes have shown CH_4 consumption over the seasons in mature rainforests, while pasture soils emit CH_4. Thus, terrestrial CO_2 removal (tCDR) via afforestation would simultaneously lead to a reduction in the release of CH_4.

9. ***All life needs nutrients such as nitrogen and phosphate – however, disturbing the biogeochemical flows could cause dramatically changes in some ecosystems.*** The nitrogen (N) and phosphorus (P) cycles are used as critical variables for biogeochemical flows, which is the second planetary boundary, whose thresholds have already been clearly exceeded. There are other biogeochemical cycles that are important for the stability of the earth system besides these two, but the anthropogenic influence on the nitrogen and phosphorous cycles is consequential. The C cycle is not taken as a critical value for the biogeochemical flows because it is considered in the planetary boundary climate change.

Nutrients such as nitrogen (N) and phosphate (PO_4) are an important part of all living organisms, as they are a part of such cell constituents as lipids, proteins, and DNA. Therefore, they have to be acquired by all organisms in order to enable growth and maintenance. Also, the crops grown by humans need N and PO_4, in addition to various other nutrients, for good growth. But since PO_4 in particular is not available in sufficient quantities in many soils, and is also often the growth-limiting factor in plants, P and N are added as fertilizer.

However, most agricultural practices fertilize the soil and not the plant *per se*. As a result, the plants consume only a fraction of the fertilizer applied and the rest, including P and N, resides in the soil or is washed out of the soil and ends up in surface waters. This human input of P and N into water bodies can lead to eutrophication – unwanted growth of photosynthetic, sometimes toxic, microbes in affected water bodies and a resulting reduction in oxygen levels that kills animal life: dead zones.

Even if there is no eutrophication, an algal bloom can have far-reaching consequences. For example, they can reduce the extent of the biological CO_2 sink by inhibiting the growth of seaweed. These and other nutrient-related effects justify using a sustained flow of N or P as a critical variable in the planetary boundary of biogeochemical flows.



Global nitrogen cycle in the 21st century. The arrows indicate a transfer from the atmospheric N_2 reservoir to terrestrial and marine ecosystems or the transfer of nitrogen oxide (NO_x) or ammonia (NH_y) to the atmosphere. Green arrows represent natural N conversion, red arrows represent anthropogenic N conversion.

10. ***Nitrogen, an element with an unlimited supply, and phosphorus, an element that might see peak production soon, both with a distribution challenge.*** Unlike many of the other resources humankind relies on, N is almost an unlimited resource as we have huge amounts of molecular nitrogen (N_2) in the atmosphere, requiring “only” energy to convert chemically inert N_2 into a reactive, plant-ready N fertilizer. However, the energy demand is a major contributor of the CO_2 footprint of industrial agriculture, asking for a rapid replacement of fossil resources by renewable energy for N-fertilizer synthesis.

The planetary boundary of nitrogen is set at a sustained flow of 62 Tg N per year (1 teragram = 1 megaton), while the current rate is 150 Tg N per year and growing. However, the additional N in the environment has extreme consequences, visible with every increasing dead zone in front of the Mississippi delta, the Caspian Sea, or the development in the Marmara Sea in 2021. The natural nitrogen cycle has many roles for microbes and with its complexity is also still under research investigation. Absolutely clear are however the need to reduce nitrogen fertilizer use, despite the fact that many agricultural lands are inadequately fertilized, e.g. in developing regions, where fertilizers can be too costly.

As some technologies do apply also for phosphate, we briefly introduce this planetary boundary, while discussing possibilities for fertilizer reduction afterwards.

A sustained flow of 11 Tg P per year from freshwater systems into the ocean was set as the threshold for the planetary boundaries. With a current rate of 22 Tg P per year, this has already been clearly exceeded, and many countries are expected to use significantly more P-fertilizer in the future. In contrast to N, excess P is not directly lost into the groundwater or next lake or river, because it readily complexes with metals, such as iron, to form insoluble salts that are not or only very slowly accessible to plants.

Moreover, P also diffuses poorly in the soil: whereas N can diffuse centimeters, P often diffuses not even millimeters, making it very hard for plants to reach this essential element. As a consequence, although regions with a long history of P-fertilizer use contain amounts of P in the soil that can last an estimated two centuries, P-fertilizers nevertheless still have to be used for such soils, although in reduced amounts. How then does P contribute to water pollution and is finally lost to the ocean? All fields lose soil by wind and water and direct runoffs are also possible.

Like most resources, P is available in limited quantities: an estimated 100 to 300 years’ supply of phosphate rock, mainly in Morocco which contains an estimated 75% of all P-reserves in the world.

Thus: the challenges of N and P fertilizer ask for change, as the planetary boundaries are already seriously exceeded. “Fertilizing the plant and not the soil”, “precision agriculture” and “site-specific crop management” are phrases easy written, but the technology required is neither easily developed nor applied in the field. For example, where possible, slow release fertilizers next to the (developing) roots should be used, avoiding excess fertilizer use on the field, while reducing peak concentrations. Another obvious, and much required technology is greenhouse farming of high value crops, such as vegetables and fruits in soil-free systems. Here, the nutrient use can be maximized, while the water and land use can be minimized. However, the systems are material intensive - the greenhouses and associated equipment - and energy intensive, for light generation and to some extent temperature control, thus needing renewable energy (i.e., sun and wind). On the other hand, N- and P-fertilizer use can easily be reduced by a factor of ten compared to traditional farming.

11. ***Can microbes help us to reduce the anthropogenic impact on the biogeochemical cycles? Indeed, they can.*** For example you might have read that legume plants live in a symbiosis with bacterial partners that capture N_2 from the air. These bacteria have a particular enzyme,

nitrogenase, that catalyzes the conversion of plant-unusable atmospheric N_2 to plant-usable ammonium.

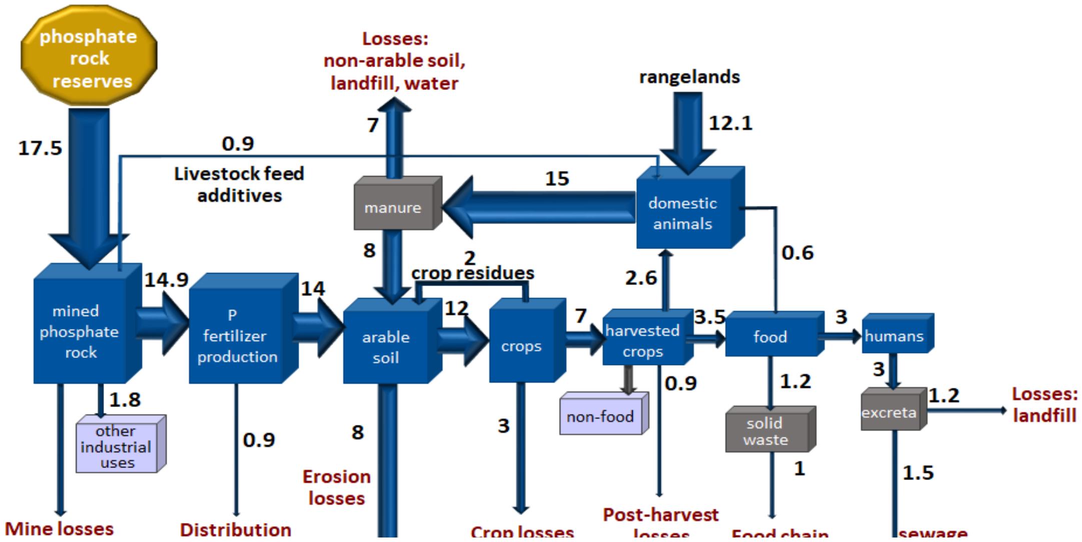
Soybean is the legume with the largest land use and harvest profiting partially from this symbiosis. While researchers investigate how this natural N-fertilization can be improved, the idea was exploited for example by the company Azotic to use microbes for growth of corn. In fact, up to 50% N-fertilizer reduction is achieved with this technology and other non-legume crops might benefit from N_2 fixation.

For reduction of P-fertilizer use, researchers work on plants that secrete organic acids which solubilize P in insoluble P-salts and thereby mobilize it. Similarly, an N-fixing microbe, *Paenibacillus sonchi*, has been described that could utilize a highly insoluble P-salt as sole P source, opening up new possibilities for soils that contain significant insoluble P.

The application of N- or P-providing microbes is often via seed encapsulation, an area experiencing many new developments. *Paenibacillus* members, such as *P. sonchi*, have been isolated from the rhizosphere of various crops. In addition to phosphate-solubilizing bacteria such as *P. sonchi*, arbuscular mycorrhizal fungi are found in the rhizosphere of crop plants. They are known to provide nutrients such as P to plants, thus enhancing plant growth. For this, they often use the help of bacteria. Mycorrhizal fungi have been used for some time in organic farming to support the uptake of phosphate into the crop and thus their growth.

The N and P used to improve plant growth and ending up in the plant biomass has a number of fates, depending on the plant and plant material. For N it is rather simple, mostly being recycled back to N_2 and returned to the atmosphere. The conversion of N in biomass, as proteins, nucleotides, sugars, to N_2 is catalyzed again by the microbial nitrogen cycle. A major source of N-release is the biomass left on the field and in the water treatment plants.

However, in human timelines there is no P-cycle, as the natural one is estimated to last 10 to 100 million years. The general P-use network was early sketched by Elser (see below), highlighting the unsustainable loss of P that exceeds the input P amounts, as additional P is used by grazing animals from non-fertilized pastures. The author concluded 10 years ago "Given the scale and scope of the needed changes in coming decades, concerted efforts in research, technology transfer, and regulatory and institutional innovation should already be well underway. I end this piece by expressing my concern that they are not."



Simplified P flow through the global food production and consumption system (adapted from Cordell *et al.*, 2009, with permission from *Elsevier*). Usage, losses and recovery are indicated. Units of the fluxes are in million tons per year. Largest losses are associated with crop and livestock production.

12. ***Which developments have been made that help to reduce P-rock use and to close the loop?*** P is on the list of crucial elements in many countries, not least because it is a limited resource. The fact that a lot of P is lost via erosion and leaching at the field can also be seen in the simple flow diagram of the global P system.

Apart from efforts to avoid this loss and to improve the P uptake in crops, adding phosphate to the list of natural resources to be recovered from wastes is an important development. For example, the exploitation of phosphate-accumulating microbes for the recovery of P from waste water in waste water treatment plants is in development, and indeed a commercial plant started in Hamburg in 2021, that has the capacity to recover around 7,000 tonnes of high-purity phosphoric acid annually from ~20,000 tons of sewage sludge ash.

Another approach is based on the fact that much P is bound in agricultural side streams, like canola press cakes. These press cakes are used as animal feed, although monogastric animals like pigs cannot utilize the P which is present as phytate. To release the P in phytate, enzymes called phytases can be deployed which mobilize significant amounts of P from a range of press cakes, amounts that would cover the polyphosphate (PolyP) market easily. P-polymers are used in the food and industrial sectors in the low million ton scale but, importantly, in high purity and at high prices. Hence, novel recycling technologies for P might be first installed in the PolyP market, as it is less price sensitive. One such idea is using baker's yeast as polyP producing microbe. After P starvation, baker's yeast hyper-accumulates up to 30% of its cellular dry weight as PolyP in less than 3 hours. The yeast biomass can then be used for manufacturing polyP-rich yeast extract or for isolating the polyP.

Relevance for Sustainable Development Goals and Grand Challenges

The prerequisite for achieving the SDGs is a stable Earth system. As the planetary boundaries are meant to represent such a stable earth system, it is inevitable the planetary boundaries are pivotal to the ambitions of the SDGs, and indeed were taken into account in the definition of the goals. For example, the concept of planetary boundaries is based on the 2° climate protection guardrail, the main report of the German Advisory Council on Global Change (WBGU) in 2011 and the concept of planetary health. In order to use the planetary boundaries framework in a meaningful way to achieve and define the SDGs, these thresholds must be constantly supplemented or renewed according to the state of research. And in addition to the global effects, regional effects should be given more attention and recognition. The greatest challenge is and will remain a global rethink and acceptance of necessary change. For this it is absolutely necessary to create or expand the understanding of the relevant level of the complex system planet in the population, the economy, and politics. In addition, everyone should be made aware of the recognizable effects of the pressure created by humans on the planet, so that ideas and innovations can lead humanity to live a comfortable life for a long time.

Potential Implication for Decisions

1. ***Individual***
   a. Should we change our diet preferences? (e.g., reducing intakes of ultra-processed foods, red meat, unsustainable plant oils)
   b. Which of the three R´s – reduce, reuse or recycle – should we focus on? Why?
   c. Do we need to overcome aversions to genetically modified crops, animals and microbes?

   d. Should we support soil diversity in our own garden, e.g. by enhancing insects and other organisms' habitat and allowing biomass, branches and leaves, to rot naturally?

2. ***Community policies***
   a. Implement education and awareness programs
   b. Political decisions to support new P recycling technologies
   c. Infrastructure to minimize the amount of food that is unnecessarily discarded, as the causes for this vary depending on the region and/or the country

3. ***National policies relating to Planetary Boundaries***
   a. National certification to offer the consumer a reasonable basis for their decisions
   b. Legislation and support to improve agricultural efficiency and sustainability
   c. Legislation and support to manage plant nutrient cycles more efficiently
   d. Political decisions to support recycling in general
   e. Regulatory frameworks to support (or not to inhibit) the evaluation of genetically modified crops, animals and microbes

Pupil Participation

1. ***Class Discussion of the issues associated with planetary boundaries***

2. ***Pupil stakeholder awareness***
   a. What is the impact of my own diet preferences on the planetary boundaries?
   b. What is the impact of my decisions on the C, P, and N cycle?
   c. How might the sustainable production of products (e.g., food) be incentivized?
   d. Is today´s infrastructure sufficient to bend the curves?
   e. Does knowledge of climate change etc. influence my behavior and my purchasing decisions?
   f. Does packaging, production method and product description have an influence on my purchase behavior?
   g. Does my behavior as an individual have an impact on climate change?

The Evidence Base, Further Reading and Teaching Aids

https://www.youtube.com/watch?v=SieN0IrZ5wg

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Glossary

Anthropogenic: is caused or influenced by humans or their activities
Biodiversity intact index (BII): BII is a recognized indicator of the average abundance of wild species in an area compared to the pre-modern era or primary vegetation under the current climatic conditions.
Carbon reservoir: A carbon reservoir contains an amount of carbon, that is not naturally enter the C-cycle in significant quantities
Carbon sink: A carbon sink is a natural or artificial system that absorbs more atmosphere´s carbon with physical and biological mechanism for an undefined time period than it releases.
CCS: carbon capture and storage
CCU: carbon capture and utilization
CDR: carbon dioxide removal
pg: picogram; 1 pg = 10^{-12} g
Pg: petagram; 1 Pg = 10^{15} g
Polyphosphate: A polyphosphate is a highly anionic inorganic polymer composed of many repeating units of orthophosphate linked by high-energy phosphoanhydride bonds. It is a ubiquitous metabolite in microorganisms.
Primary forest: a naturally regenerated forest of native tree species where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (FRA, 2020)
Radiative forcing: Radiative forcing is a measure defined by the IPCC (Intergovernmental Panel on Climate Change) for the influence of a certain climate factor on the amount of downward radiant energy that hits the earth's surface.
Rhizosphere: The rhizosphere is the narrow region of soil or substrate that is directly affected by root secretions and associated soil microbes.
Secondary forest: a forest which, after significant removal or disturbance of the original forest vegetation by human or natural causes, regenerate largely through natural processes at a single point in time or over an extended period of time and which show a significant difference in forest structure and/or canopy species composition with respect to pristine primary forests.
Tg: teragram; 1 Tg = 10^{12} g