Planetary boundary pioneer Johan Rockström awarded 2024 Tyler Prize

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Mongabay Series: Planetary Boundaries

by Glenn Scherer on 29 February 2024

- *The 2024 Tyler Prize for Environmental Achievement will go to Johan Rockström who led the team of international researchers who originated the planetary boundary framework in 2009.*
- *The theory defines a scientifically based "safe operating space for humanity" to safeguard stable Earth conditions established in the Holocene when civilization arose, with the intention of preventing dangerous tipping points in the Anthropocene — a new era in which humanity has the capacity to wreak havoc on Earth systems.*
- *In a new interview with Mongabay, Rockström discusses how the planetary boundaries framework formulates quantified safe limits to protect nine Earth systems (including climate, biodiversity, freshwater and more), all vital for sustaining life and he shares some updates on this cutting-edge research.*
- *"Planetary sustainability is a security issue because staying within planetary boundaries gives us stable societies, food security, water security and reduces conflicts," says Rockström. "Placing planetary boundaries at the UN Security Council positions sustainability, climate, biodiversity, water, where it belongs — in security."*

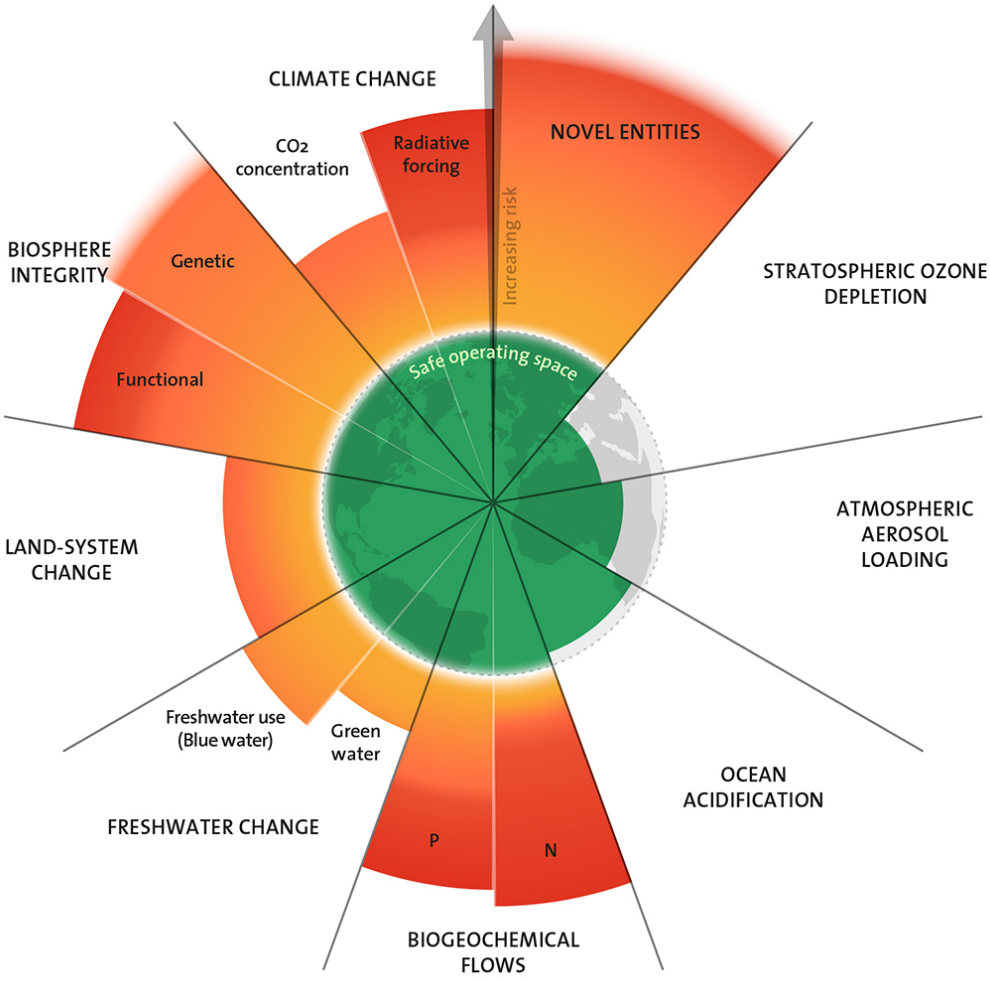
The 2024 Tyler Prize for Environmental Achievement has been awarded to Johan Rockström for his pioneering work leading the international research team who originated the groundbreaking planetary boundary framework in 2009. The theory, updated in 2015 and 2023, is founded upon decades of Earth System Science and the work of researchers worldwide.

The planetary boundary framework was conceived while Rockström was director of the Stockholm Resilience Centre, which he co-founded in 2007. The theory delineates planetary boundaries for nine Earth systems, whose stability and resilience are vital to maintaining life as we know it.

The framework establishes scientifically quantified thresholds — limits for environmental impacts from human activities in order to maintain a "safe operating space for humanity."

By respecting planetary boundaries, the hope is that the world can sustain an environment similar to the Holocene epoch during which civilization emerged, and avoid more of the extreme environmental harm that has arisen in the Anthropocene — a new geological epoch in which human consumption and pollution are dangerously destabilizing Earth life support systems.

In 2023, scientists published a new study finding that humanity is “well outside of the safe operating space” for six of the nine planetary boundaries. Transgressing multiple planetary boundaries could, according to Rockström, risk “reaching tipping points that will undermine the Earth’s life-support systems.” Researchers warn that tipping points are looming in the Arctic, Amazon, the world’s oceans and elsewhere.



The 2023 planetary boundaries update showing 6 boundaries transgressed. The nine boundaries are counterclockwise from top: climate change (CO2 concentration and radiative forcing), biosphere integrity (genetic and functional), land-system change, freshwater change (blue water use and green water), biogeochemical flows (nitrogen and phosphorus), ocean acidification, atmospheric aerosol pollution, stratospheric ozone depletion, and novel entities pollution (including tens of thousands of synthetic chemicals including plastics plus heavy metals, radioactive materials, and more). Image courtesy of Azote for Stockholm Resilience Centre, based on analysis in Richardson et al. 2023 (CC BY-NC-ND 3.0).

While Rockström emphasizes the great urgency with which humanity must respond to the Earth emergency, he says he believes the unfolding crisis offers the opportunity for a “global sustainability transformation.” Today, the tenets of the planetary boundary framework have been embraced by scientists, international policymakers at the U.N., countries and corporations as a means of gauging environmental risk, avoiding further harm and achieving a sustainable circular economy.

“We need to listen to scientists like Johan Rockström … a trailblazer,” said Harrison Ford, the vice chair of Conservation International, responding to the award. The Tyler Prize Executive Committee gave the $250,000 Prize to Rockström for his “science-based approach to sustainable development for people on a stable and resilient planet.” He joins a group of eminent scientists honored by the award since 1974, with many recently profiled by Mongabay.

Rockström has co-authored books such as *Breaking Boundaries: The Science of Our Planet*, which became a Netflix documentary narrated by Sir David Attenborough. He also appeared with actor Leonardo DiCaprio in the documentary *Before the Flood* and has presented TED Talks. Rockström’s work also inspired Mongabay’s ongoing Planetary Boundary reporting series, totaling more than 190 articles to date.

The Earth System scientist’s unwavering dedication to environmental stewardship and to humanity’s well-being continues to inspire, inform and shape the trajectory of global efforts to preserve our living planet for generations to come.

What follows is an exclusive Mongabay interview with Johan Rockström, where he outlines the evolution of the planetary boundaries theory, offers a glimpse of future cutting-edge research and delineates risks humanity faces and opportunities for what he calls a “global sustainability transformation.” (This interview has been lightly edited for clarity.)

Johan Rockström, director of the Potsdam Institute for Climate Impact Research, professor in Earth System Science at Potsdam University, and professor in Water Systems and Global Sustainability at Stockholm University. He also co-founded the Stockholm Resilience Centre. Earlier, Rockström spent 25 years doing applied water field research in the tropics. Image courtesy of the Potsdam Institute for Climate Impact Research.

Mongabay: **You've long been a global pioneer in Earth System Science and led the international team that originated the planetary boundary framework theory in 2009. Can you briefly relate how you and other scientists around the globe came to realize the need for the framework and say why it is so important to the world?**

Johan Rockström: There were essentially three strands of scientific evidence that came together [in Earth System Science] in the beginning of the 2000s.

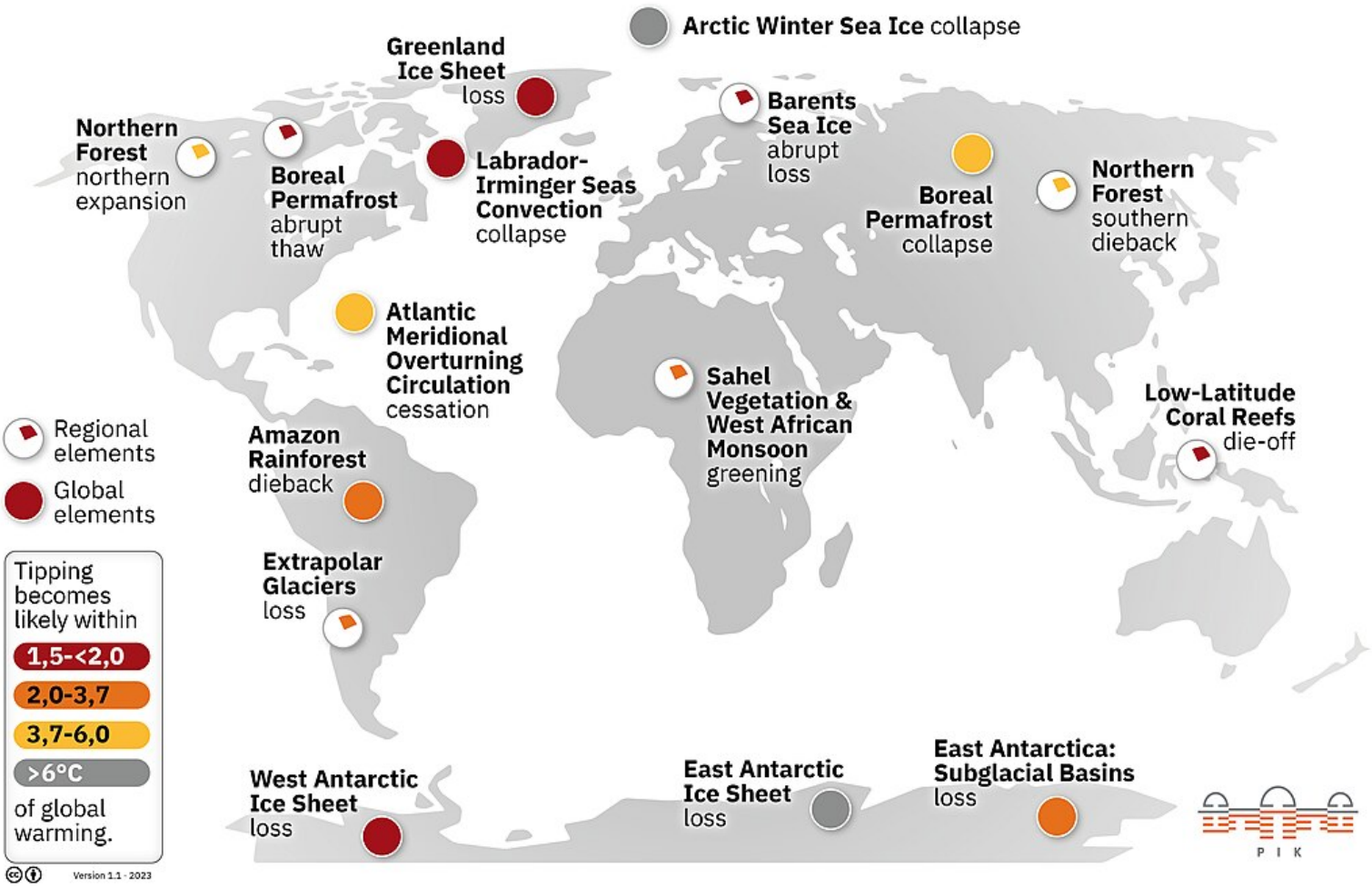
Number one was the evidence behind the great acceleration [in consumption and environmental harm] and the [transition to the] Anthropocene. I would argue that this was a foundational piece of science, a major piece of work led by Will Steffen and published in 2006 through the International Geosphere-Biosphere Programme.

It showed that all the evidence of the great acceleration — with all the hockey sticks [which illustrated consumption and pollution trajectories] — point to the conclusion that we've entered a whole new geological epoch, where we are not only the largest force of change on planet Earth, but that we're starting to hit the ceiling of hard-wired biophysical processes that regulate the functioning of the Earth system.

The Anthropocene evidence was one important piece of research that showed that we need to start addressing the boundaries for human development at the planetary scale.

The second piece of science comes from resilience theory and tipping point science. Resilience theory … is based on this premise that systems — both social and ecological systems — have multiple stable states separated by thresholds. And what keeps them in one attractor [and stable] are feedbacks and interactions determined by their resilience. A system in a very healthy state is dominated by feedback that keeps it in a rainforest state, or in a clean lake state, or in a frozen ice sheet state. Push that system too hard, and the system tips over and will be dominated by whole new types of feedback.

That science was published fully for the first time in 2008 in the Tim Lenten et al. paper, proposing the existence of tipping elements — that if you push big biophysical systems too hard, they can flip over and undermine the entire functioning of the climate system.

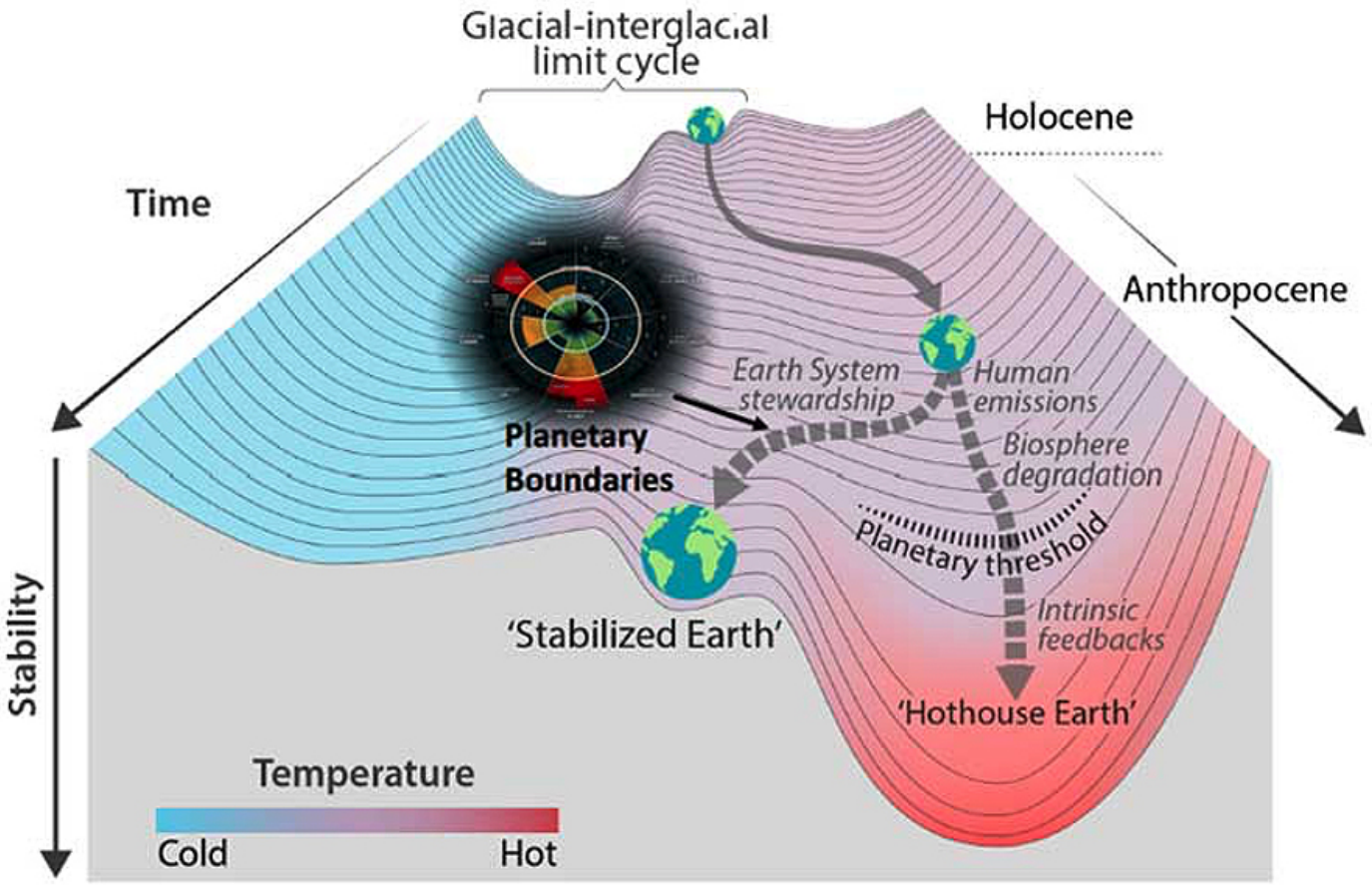


Major possible tipping points in the climate system, based on global temperature increase, as understood in 2022. The Arctic, Antarctic, Amazon and other regions are already showing significant signs of irreversible tipping points due to the transgression of the climate change boundary, along with other planetary boundaries. Should the Arctic and Amazon tip, they will add significant amounts of carbon stored in permafrost and the rainforest to the atmosphere. Image courtesy of Potsdam Institute for Climate Impact Research (CC BY 4.0).

The third, and in my mind almost the most foundational piece of research behind the basis for the planetary boundary theory, is paleoclimatic research — derived from ice core data, which showed at the time, in the mid 2000s, that the Holocene (the equilibrium interglacial state that we've been in since we left the last ice age) is not only an attractor, an interglacial equilibrium state. It's [also been] extraordinarily stable.

We have the [Antarctic] ice sheet … Vostok ice core data showing us 1 million years back, of how the Milankovitch [orbital] cycles have been taking us in and out of ice ages and short interglacials. But then we started to get the evidence of this unique feature of the most recent interglacial: Knowing that we've been modern humans over just the last 250,000 years, two ice ages, one interglacial, always at just a few million people, hunters and gatherers, [enduring] extremely variable life conditions and environmental conditions, varying tremendously during this entire period, until we reach the Holocene. Then we barely enter the Holocene, and we go through the Neolithic revolution some 8,000 years ago, which we know today is a result of the stable environmental conditions on Earth [that occurred then].

If you put all this together — the fact that the Holocene finally gives us a reference point for a desired state of the planet to support the modern world as we know it — then we can measure [current conditions] against the Holocene.



Imagine Earth's climate taking different trajectories through time — pathways weaving between extremely different climate states. Various paths through all the possible climates can be greatly influenced by distinct tipping points. Self-reinforcing feedback processes can lock the planet into a particular trajectory for centuries or millennia. There is no evidence modern societies can exist, let alone thrive, in conditions substantially different from the relatively climate stable Holocene, an epoch that began about 11,500 years ago, only to be disrupted by the recently recognized Anthropocene, an epoch characterized by planetwide human impacts. Image courtesy of Steffen et al. (2018).

Secondly, tipping points are real, so we need to have boundaries, and we can use tipping point risks as a piece of evidence to quantify where to put those boundaries, because you don't want to go too far, because you risk causing feedback shifts that can trigger irreversible changes.

We use tipping point science as the first, and so far, most powerful way of defining where to place the planetary boundary. And, of course, the [changes seen in the] Anthropocene being why we have the justification for now lifting up sustainability to the planetary scale.

All of this came to the fore in those years between 2005 and 2008, and the planetary boundary science was published in 2009. It was some 30 years of major Earth System Science advancements that came together so that we could stand on the shoulders of giants, to quote Newton, and bring us to the level of the

planetary boundary science.

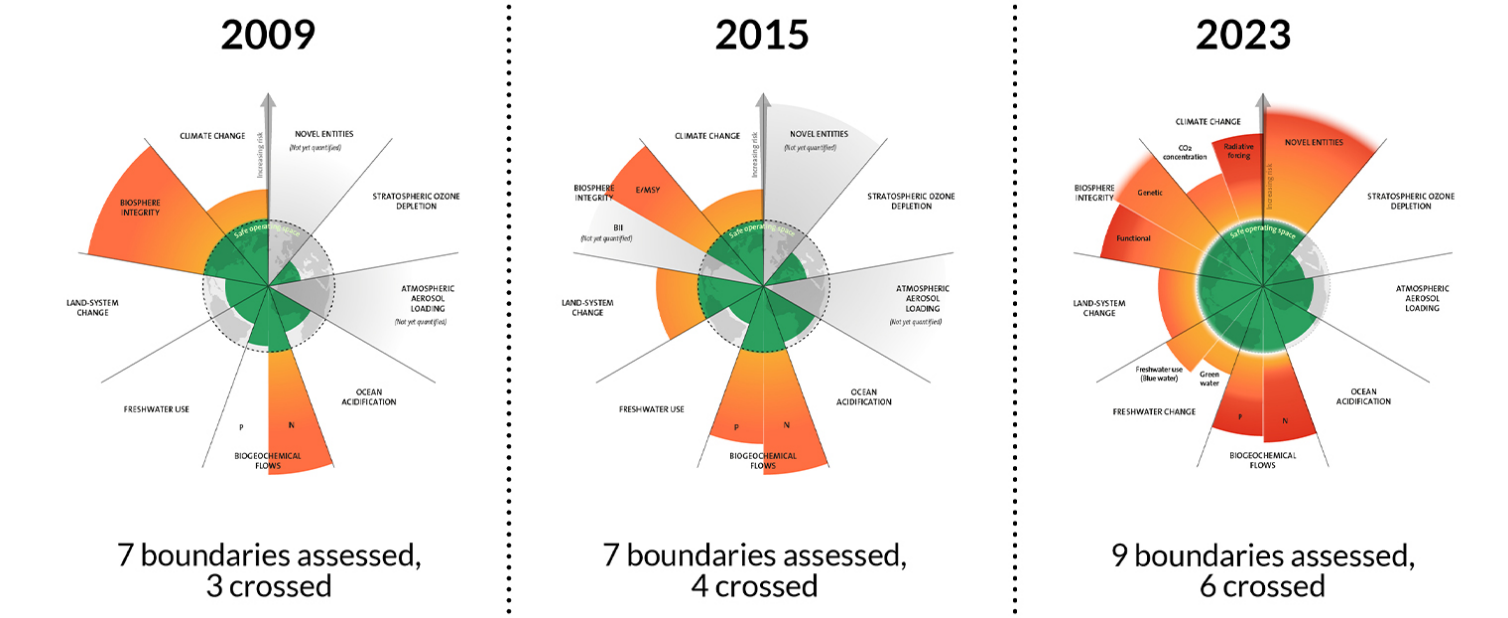
Mongabay: And standing on those shoulders, I guess you were able to look far enough ahead to see the impending planetary disaster awaiting humanity, which must have brought your sense of urgency to the fore.

Johan Rockström: Correct. Of course, all this scientific work came about based on a sense of urgency — a rising significant degree of nervousness. At the time — in 2007, 2008 — I could not say it clearly, but we were concerned that humanity was putting life support systems on Earth at risk.

Today, 15 years later, I don't have to hesitate. We're putting the stability of the planet at risk. We are risking to destabilize the entire Earth system. We're risking to push the whole planet on a drift away from livable conditions for humanity. It's an existential risk we're facing.

Over the past 15 years, not only have we been able to get much better precision on the [boundary] quantifications, and get much more robust assessments of the degree of breaching — of transgressing boundaries — we also, unfortunately, have so much more evidence [showing] that what we proposed in 2009 has been confirmed. The risks are real.

And now, here I'm quoting the Intergovernmental Panel on Climate Change, which in its sixth assessment [in 2022], confirmed the planetary boundary science by concluding, not only are we in the middle of the climate crisis threatening human health, we're also risking the stability of the planet.



The scientific evolution of the planetary boundaries framework from 2009, to 2015, to 2023. Image courtesy of Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009 (CC BY-NC-ND 3.0).

Mongabay: In a paper published in September of last year, you and an international group of scientists found that the safe Earth system limits for all nine boundaries have now been quantified, and by that reckoning, it was also determined that six of the planetary boundaries have now been transgressed.

Johan Rockström: Yes. Correct. To begin with — just to show the challenge of quantifying the boundaries — it isn't until this third scientific publication on planet boundaries in 2023 that we're able to quantify all nine boundaries for the first time. In 2015, which was the second [planetary boundaries] scientific paper, we were only able to quantify seven of the nine.

In one important breakthrough [in 2023], we were able to put quantifications on [the remaining two boundaries], aerosol loading and novel entities (chemical pollution), based on research originating from other research groups around the world, which we synthesized into the planetary boundary framework.

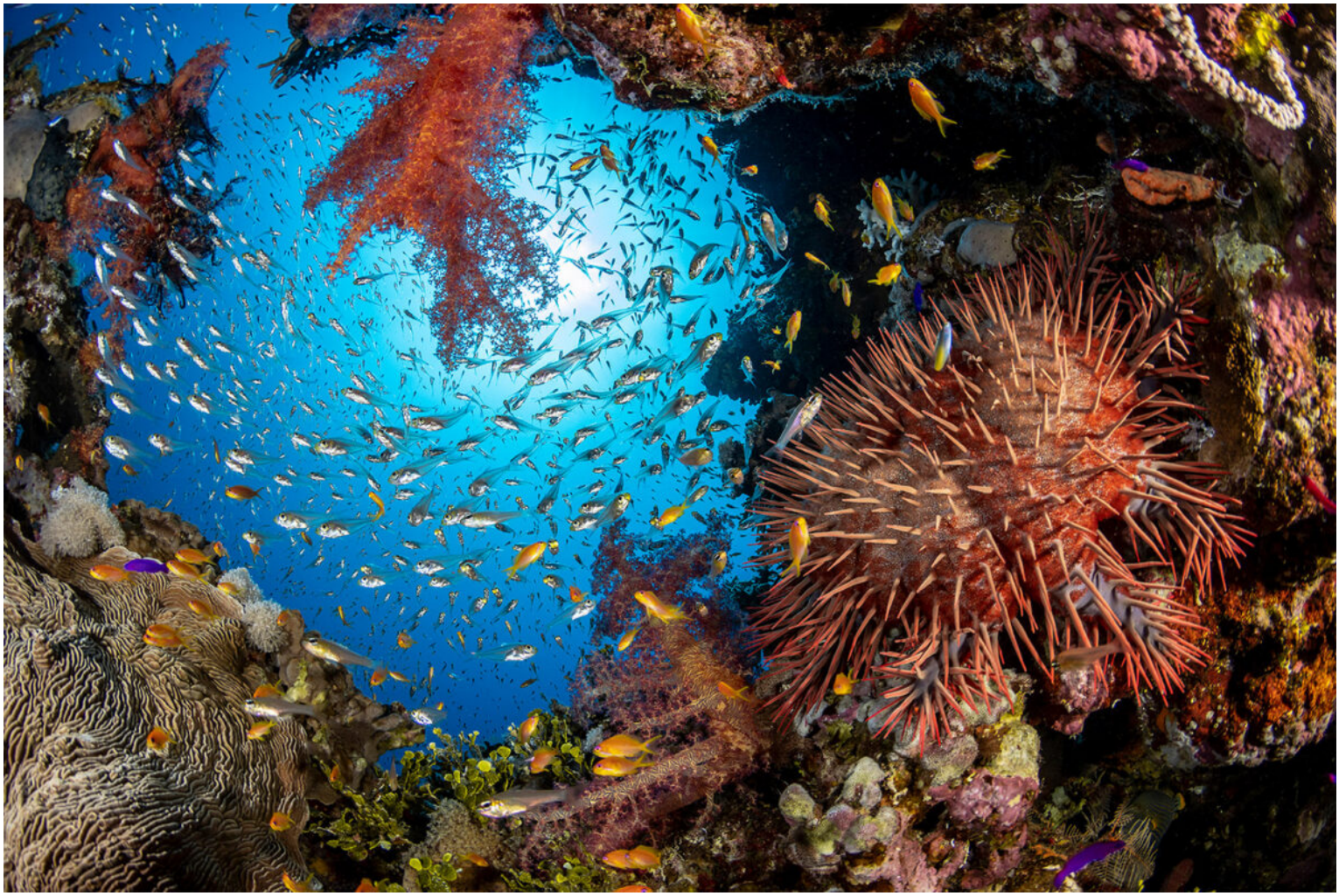
Not surprisingly, but really depressingly and concerning, is that six of the nine boundaries are outside of the safe Earth operating space for humanity.

There are many ways of articulating what this means. But one way, which I find to be, let's say, the sharpest — and the one that reaches deepest into the heart of policy in the world today — is that we know we're in the midst of a climate crisis, and it's costing us. And when you're disturbing the climate system — causing a massive energy imbalance, which is the result of burning fossil fuels and cutting down trees in an unsustainable way — then you at least want to have a healthy planet that is able to buffer and dampen the massive stress caused by that crisis, by that [climate] problem.

Unfortunately, instead, we are doing a double mistake. Not only are we causing the climate crisis, we are reducing the health, the resilience, the buffering capacity of the biosphere — nature on planet Earth.

So when we transgress the boundaries on biodiversity, on freshwater, on land use and overloading of [nitrogen and phosphorus] nutrients, we weaken the ability of the planet to buffer the stress caused by climate change. And that is not a good combination. If you punch the planet on climate, you at least want to have a strong planet [to resist that punch].

We know that over the last 250 years that half of the stress caused by our emission of greenhouse gases have been absorbed very persistently by a healthy biosphere — 25% of carbon dioxide on land, 25% in the ocean. Consistently, year after year after year, 90% of heat has been absorbed in the ocean. But we now see the first cracks of reducing that capacity, which has all to do with our breaching of the other planetary boundaries.



Coral Reef at Sharm el Shekh, Egypt. The world's oceans absorb tremendous amounts of carbon, buffering humanity from climate change's worst effects so far. But there are heavy costs: Reefs are dying in intensifying marine heat waves, while ocean acidification is worsening due to seawater's absorption of CO_2 from fossil fuel burning — a threat to marine life. Image by Renata Romeo / Ocean Image Bank.

Mongabay: Do you think the planetary boundary framework to date has been successful in promoting positive change with scientists, policymakers and the public, and can you offer a couple examples?

Johan Rockström: The planetary boundary framework itself merely gives us the 1.5° Celsius [2.7° Fahrenheit] equivalence [demarcating the climate change boundary, the transgression of which affects] all the environmental systems that regulate the health of the planet. But it's not a technical or practical solution in itself.

But we see that many companies, like, for example, IKEA, H&M, L'Oréal and Unilever, have been over the years adopting the planet boundary framework to guide their businesses. We see countries like Finland, Switzerland, the Netherlands, New Zealand, Germany, Sweden and the European Environment Agency adopting the planet boundary framework and using it as a way of quantifying in a more comprehensive way what is a safe operating space for societies to be really, truly sustainable.

We have also seen more work in economics, like, for example, when Sir Partha Dasgupta, on behalf of the U.K. government, wrote a really seminal work on the economics of biodiversity in the run-up to COP26 [the climate summit] in Glasgow. He concluded that we now need an economy that operates within planetary boundaries, within strong sustainability measures, which means quantifying boundaries within which you can have economic development. …

We see [the planetary boundary theory] more and more inspiring actions toward a more integrated sustainability framework.

One thing I find to be perhaps most promising regarding the planet boundary framework is that we rightly talk continuously about concerns over doing the wrong investments in this transition away from fossil fuels. For example, on biofuels, we [currently] replace oil with ethanol or different tree-based biomass [energy] products and thereby cause tradeoffs with food production or accelerated deforestation of natural forests. Well, that's always a risk if you focus only on climate. If the only thing you focus on policy-wise is your 1.5°C boundary, then, of course, you're always at risk of missing [and impacting other boundaries], of overconsuming water or ecosystems. But the planetary boundary framework becomes a comprehensive accounting system, which enables you to avoid doing such mistakes.

Rockström points out that paying attention only to climate change solutions, while ignoring the other eight boundaries, can be dangerously counterproductive. This aerial view shows a wood pellet production mill in Ahoskie, North Carolina in 2022, where massive heaps of wood chips are pressed into pellets and heat-dried before being shipped overseas. The EU, UK, Japan, and other nations are burning wood pellets as a replacement for coal to try and achieve their carbon reductions goals. But this is a false solution, as deforestation, and the use of fossil fuels to make the pellets and to transport them overseas, along with power plant carbon emissions at the smoke stack significantly add to the climate problem. Image courtesy of the Dogwood Alliance.

You can check upfront whether your investments — be it in mining for rare earth metals, for battery technologies or for EVs, or if it is biofuels or bioenergy systems. You cannot go wrong if you take a planetary boundary framework [approach] and measure upfront against quantitative, hard sustainability boundaries.

We increasingly see how the framework [is being integrated, though not fully] adopted in policy regimes. You could argue that the COP15 on biodiversity [in 2022] and the Kunming-Montreal Global Biodiversity Framework now have the planetary boundaries [in mind]. It's entirely aligned with the planetary boundary

science of halting the loss of biodiversity, but it's an independent framework. It's showing that we're moving in a direction where we recognize the need to quantify boundaries at the global level, that we then need to operationalize in different sectors. And I think that's a mainstreaming that is very positive.

Mongabay: I was reading recently about the Earth Commission. Is that sort of equivalent to an Intergovernmental Panel on Climate Change for the planetary boundaries, or is that an overstatement?

Johan Rockström: Well, that's your words. I wouldn't want to be quoted saying that it's an IPCC for the planet. But definitely, the Earth Commission represents an effort to create an independent global science assessment mechanism such as the planetary boundary framework. It's asking the question: What do we know today, and how do we define stability and resilience at the planetary scale and synthesize all the scientific sources for those kind of quantifications? And the planetary boundary framework is the very inspiration, the kind of the source inspiration for that assessment.

But as you know, the Earth Commission has also gone one step further to say we want to not only quantify the state of scientific knowledge on planetary boundaries, on the safe boundaries, but also on justice — on just boundaries. It's trying to get a handle on what's the maximum allowed significant harm levels that people can tolerate for each of the control variables behind the planetary boundaries.

So, the planetary boundaries still rule on the fundamental control variables for each of the boundary domains. And then the justice levels are measured along the same control variables, which is a unique breakthrough, and that's what the Earth Commission is doing.

Yes, the planet boundaries framework inspired this global assessment mechanism, and I would like the vision with the commission to be that it becomes a permanent institution that continuously updates our level of science, just like the IPCC does.

This satellite view of Earth lit up at night offers strong proof of humanity's transition from the Holocene to the Anthropocene — with its intensive use of energy. The planetary boundaries framework warns that if we continue to consume and pollute at accelerating rates, then we may not achieve a global sustainability transformation in time. Image courtesy of NASA.

Mongabay: **Can you share some of the latest frontiers of planetary boundary science and tell us what direction your research is now taking?**

Johan Rockström: I'm just now finishing my last review step on a paper for the *Nature Reviews Earth & Environment.* We'll be publishing a review paper where we've mapped 15 years of planetary boundary science, both in terms of the advancements in the science, but also in the implications it has had for science policy and an uptake in society. I think that's quite significant. We show, for example, that there's been approximately 1,500 peer-reviewed scientific papers specifically focusing on, criticizing and advancing the planetary boundary science since it was first published [in 2009]. …

In the very heart of the science, at the frontier of the science today, there are a few exciting things going on. One thing I would like to see — and we're working on this — is to get more Earth system modeling of interactions between planetary boundaries. This is one of the big questions: What happens if you are in the red, for example, with land and climate; how does that impact the safe boundary for water? Or do we change the climate boundary if we are losing the resilience in the biosphere boundaries? How do interactions between boundaries potentially shift the position of the boundaries? And what are the impacts of transgressing boundaries because of interaction?

The other really exciting development right now is that we are inviting a core group of Earth observation actors —in the European Space Agency but also private actors like Planet.com — who run satellites observing environmental parameters on planet Earth. The very ambitious objective is to get Earth observation data and analytics of post-processing to quantify all the nine boundaries, and to do it with high-resolution maps, to get spatial assessments and be able to present an annual planetary boundary health check.

We would do annual scientific updates of the boundaries quantification but also get an assessment of the degree of breaching, and have that as a health check at a much more frequent time step. We currently do an assessment roughly every seventh year, and now we want to transition to do it every year.

A third, really important piece of science needed is to further define the nine boundaries to develop more control variables within each. We have already done this for some boundaries. For example, for climate, we evaluate both carbon dioxide ppm levels, and also climate forcing in watts per square meter. For the biodiversity boundary, we now have four control variables: the extinction rate (the number of species gone extinct), the human appropriation of net [ecosystem] production, the percentage of intact nature and the minimum amount of intact biodiversity needed to maintain nature. In other words, what percentage of an agricultural field must still have corridors, a pollinator and wildlife trajectory?

I think it's important that we recognize that the nine boundaries, after 50 years of science, have been quite well confirmed. I would argue today that there's very little debate around the nine boundaries themselves. The scientific discussions [are primarily] around the control variables, and not only which control variables, but also the exact quantification of the safe boundary levels and the uncertainty ranges for each of these.

But I foresee, if you ask me to look in the crystal ball, where we'll be in the next 10 years: I think each boundary will receive probably up to four, between two and four, control variables.

Why? Because boundaries are really complex. The ocean planetary boundary, for example, has only one [quantified] control variable today: ocean acidification. That is scientifically and operationally very unsatisfying, because ocean acidification is really just a physics chemical representation of the ocean. We presently have no control variable for the biology in the ocean. So, there is a quest to find a twin control variable that can capture biology there — all phytoplankton, zooplankton, the food webs and the nutrient cycling in the ocean, so we'll not only be able to [evaluate] the heat and chemistry of the ocean as we do today, but changes in biology too.

The ocean planetary boundary currently has only one control variable: ocean acidification. Scientists are working to provide other metrics for measuring ocean health, including a control variable for biodiversity. It's important to note that the planetary boundary framework is not a static theory, but dynamic and changing as new knowledge arises. Image by Olivier Roux via Flickr (CC BY-NC 2.0).

Having multiple control variables for each boundary not only shows us the complexity of the Earth system, but also [gives] us multiple ways of measuring the planetary boundary process.

And finally, why do all this? Well, it's because satellites and remote sensing and Earth observations, and also field measurements, capture different things. And countries and businesses and policymakers can respond to different control variables.

For example, on freshwater, we now have one boundary definition for green water, which is the maximum allowed level of deviation, both wet and dry, from soil moisture levels in any unit of land across planet Earth. But that is not a very easy control variable to implement. It works really good in science, but it's not obvious how you manage that in a river basin. But the other control variable, on the maximum allowed consumptive

blue water use (how much blue water can you withdraw from a river before you start risking aquatic ecosystems?), that's a truly operational control variable because every country and every ministry of water actually have data on river flow.

I think we are moving in a direction where we'll see more control variables that will not only confirm the boundaries but offer multiple ways of measuring where we are in relation to each boundary.

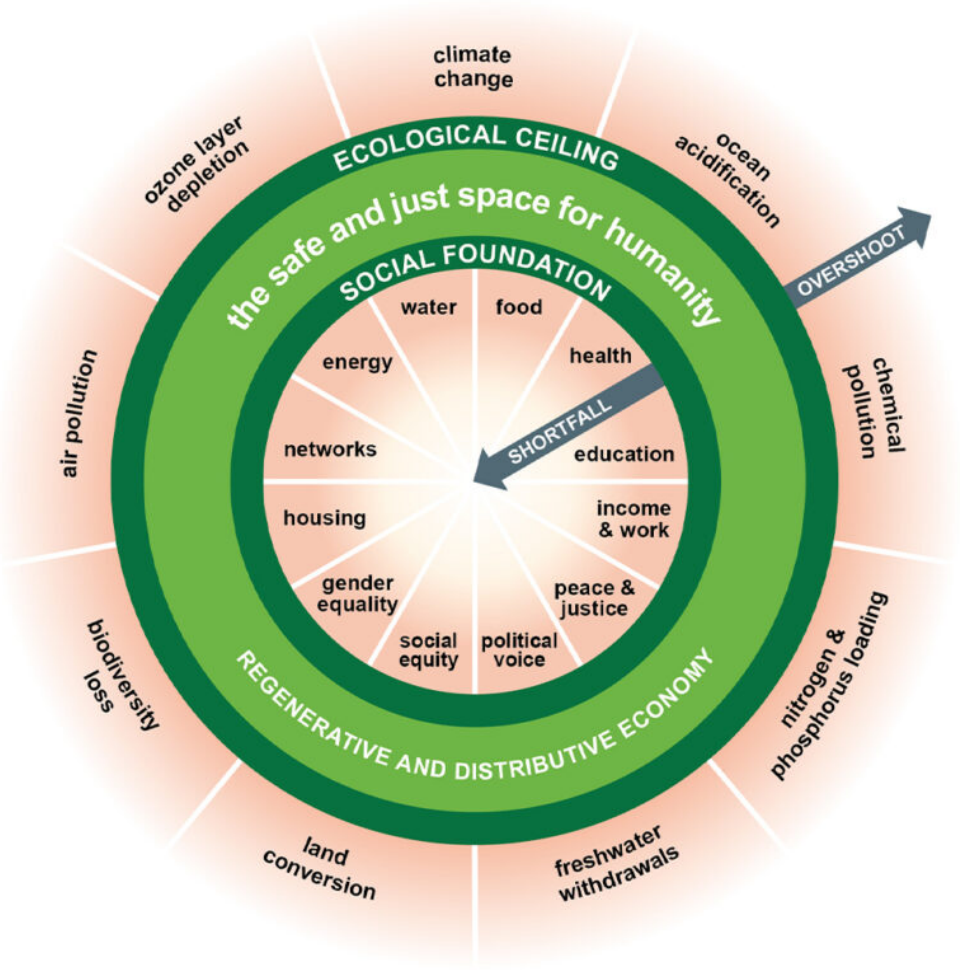
Mongabay: Many people already feel overwhelmed by climate change, and when first confronted with eight other problems which are equally, or even potentially more serious, what do you say to them regarding action and hope?

Johan Rockström: To begin with, I think it's reassuring that we today have come so far in science, that we can measure the whole planet and the health of the whole planet. The fact that we are in the red, that we have transgressed six of the nine boundaries, is of course a deep concern. But on the other hand, it's fantastic that we now have the tools and the data so we can keep an eye on the whole system. That is one level of hope.

Secondly, what I think is also reassuring is that when you look at the biosphere boundaries — the ones for freshwater, biodiversity, land and nutrients — we have a lot of opportunity to regenerate.

Of course, we cannot turn back [the clock] on the loss of species. That's a finite, terminal loss, which is really damaging. But [for the] functions of ecosystems, it's not too late to now turn back and move towards a safe space and build resilience into both food systems and ecosystems. There's a possibility here of turning things around.

And what I find to be really exciting is how the planet boundary framework is now being used for different scenario analyses: Can we think of [sustainability] transformation pathways for a safe landing back within a safe operating space? There are studies showing this is possible: We can both transition away from fossil fuels back into the safe space on climate for energy, but also on food system transition and circular resource models. That is a path towards a more desirable future.



A visual representation of the donut economy model combining planetary boundaries with the complementary concept of social boundaries. The center hole of the graphic depicts the proportion of people who lack access to life's essentials (food, shelter, healthcare, education, equity, and so on). The outside edge represents the ecological ceilings (planetary boundaries) that life depends on, which must not be overshot. Overshoot of boundaries leads to social deprivation, inequity, and injustice. A transition to a circular economy, where no resource is wasted, could prevent boundary transgressions and leads to a more just, equitable society. Image by DoughnutEconomics found on Wikimedia Commons (CC BY-SA 4.0).

I think we need to realize nothing less than a planetary boundary framework to navigate our future in the Anthropocene, now that humanity is this global force. And by doing so, it's not a sacrifice! It's not going backwards! Rather, it's going forward into a new type of modernity. That has to come across more clearly. And of course, this does not escape from the fact that urgency is there. The planet boundary science shows a very high degree of urgency. But it's reassuring that we now finally have this navigational chart that the boundaries provide.

Mongabay: In your October 2023 TB Macaulay Lecture, which was really informative, you said that a global sustainability transformation is needed if the world is to stay within a 1.5°C temperature rise and avoid a path to climate disaster. What actions must we take?

Johan Rockström: Look, considering all of the planetary boundary science — and even just the climate science alone — that lands us on the conclusion that we need nothing less than a global sustainability transformation.

As I mentioned earlier, I think we will fail on solving the climate crisis if we only phase out fossil fuels. We also need to have a transition back within the biosphere boundaries to have any chance of avoiding [climate disaster]. Even if we stop emitting carbon dioxide and other greenhouse gases from society's industrial sectors, we'll still have massive greenhouse gas releases from methane, nitrous oxide and carbon dioxide due to our transgressing the biosphere boundaries. So, however we twist and turn, we are in a realm of global transformation today.

What needs to be done? To begin with, in my view, it offers quite a lot of reassurance that the most straightforward, number one task is to get off fossil fuels. If you take a planetary boundary assessment, it tells you, which I know is provocative, but it tells you that one of the *easier* challenges we are facing is to phase out fossil fuels. It's the most mature policy area. We have most solutions there. We even have emission trading schemes and cap and trade systems and carbon pricing. We have the IRA [Inflation Reduction Act] in the U.S.

We just need to get on with it, because halting biodiversity loss, avoiding destroying freshwater and keeping land systems intact and avoiding overloading of reactive nitrogen and phosphorus are potentially even more challenging. So, getting off fossil fuels is one step in this transformation.

The second step is we need a food system transformation, and it's an equally important transformation as the energy transition. The reason for this is that the food system is the number one cause for transgressing planetary boundaries, due to its freshwater use, overloading of nutrients, biodiversity loss and land system changes.

And here, we have the solutions. Number one, we know we can feed humanity on current cropland without destroying the 50% or so of remaining intact land on planet Earth, if we just reduce food waste and start transitioning towards more healthy diets.

The world's crops now need to feed 8 billion people, and utilize largely unsustainable agricultural methods that put incredible pressure on the planetary boundaries for climate change, land-use, freshwater change, biosphere integrity, and biogeochemical flows (via nitrogen and phosphorus fertilizers). Rockström sees a necessity for a rapid shift to a sustainable global food production system, a transformation achievable with current technology and knowledge. Image by Albert Aschl via Flickr (CC BY-NC-SA 2.0).

Secondly, the technologies to shift from emitting greenhouse gases from unsustainable agricultural practices to sequestering carbon in sustainable agricultural practices is known. We know how to shift towards more zero tillage systems, water harvesting systems, better crop rotation, agroforestry systems. These are not utopian technologies. It's a question of getting the right price mechanisms, the right investments in place, and really embarking on these transitions.

Finally, what I find to be an obvious win-win — but also something that is quite depressing because we're not making more headway — is that we're still allowing the global economy to be a linear system. We exploit one source, we add value, we consume, we waste and then we cause pollution or different forms of impacts. But it's a linear system.

We need to close these systems and make them circular. Particularly when it comes to metals, because we see today that this transition away from fossil fuels to a green electric and renewable energy future will require massive amounts of rare earth metals. And this [accessing of metals] cannot be allowed to happen at the expense of planetary boundaries in the biosphere. This understanding in itself is a transformation.

Finland was the first country in the world to develop a circular economy roadmap in 2016. Since then, a government program aims to create a “carbon-neutral circular economy society” and has sparked various government measures and innovation from researchers, cities and companies. While these efforts have yet to translate into a decline in material consumption, it sets an example for other nations to follow. Image by French_landscape_photographer via Flickr (CC BY-NC-ND 2.0).

So, we need three transformations: The energy transition (get off fossil fuels), the food system transition (get into green food system technologies) and third, close cycles on resource use. If we can master those three, we will be moving decisively toward a safe landing within planetary boundaries.

In closing, we know that this global sustainability transformation is not only about safety, it’s also about justice. Because in the end, every planetary boundary translates into a budget. And that budget has to be fairly distributed. To do that, whatever methods you apply, it means that you need to have a very big shift in

how to fairly redistribute nitrogen, or phosphorus, or land, or biodiversity, or carbon to all human beings in the world.

And, when one applies planetary boundary framing, [justice] is an implication, which many want to escape. But it's a reality. It's a reality of living in the Anthropocene. Operating within planetary boundaries means we have to account for absolute budgets, and they have to be distributed in a way that is fair. And this is, in itself, a part of the transformation.

Banner image *of Johan Rockström courtesy of the Potsdam Institute for Climate Impact Research.*

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