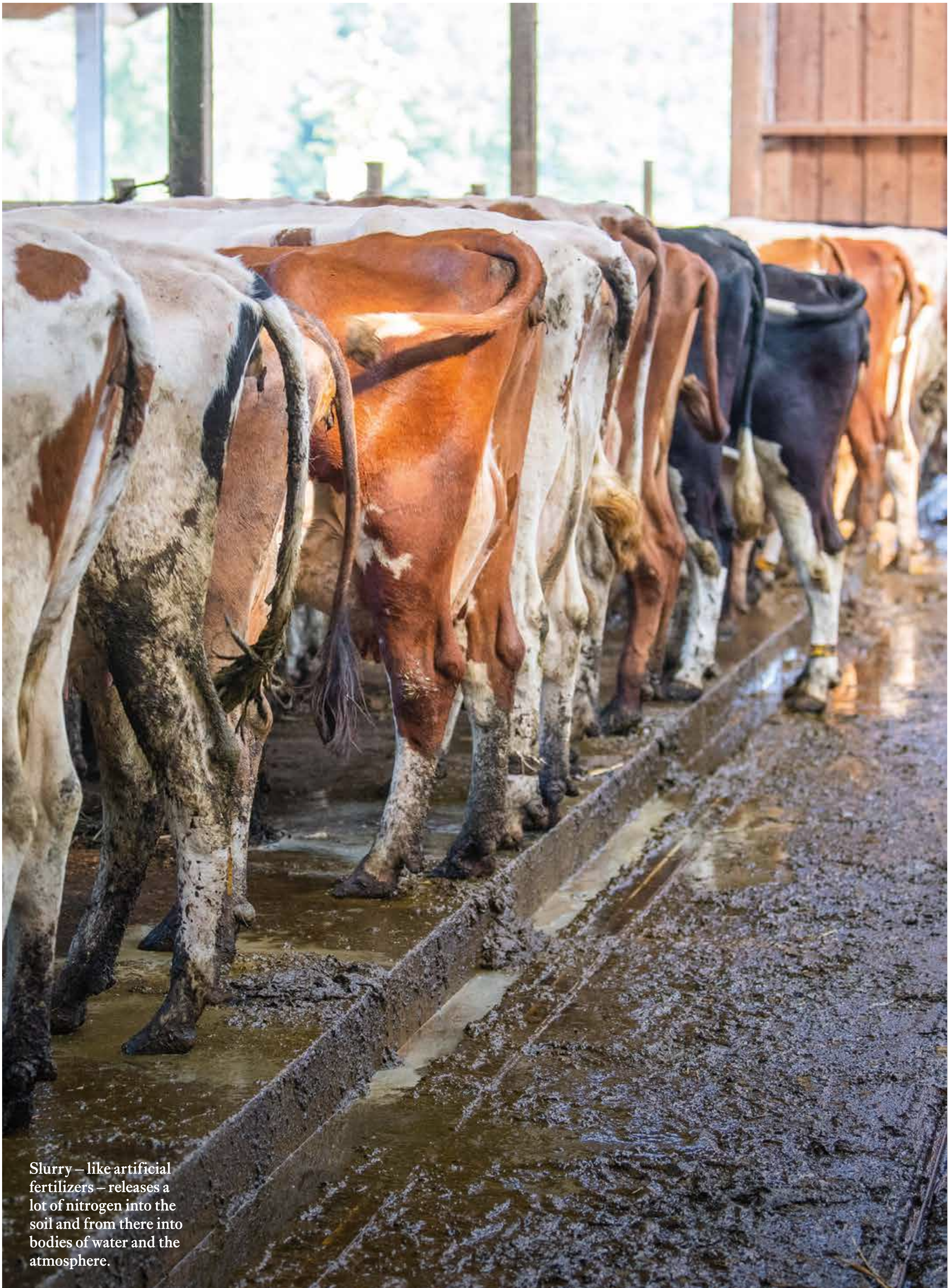

Slurry – like artificial fertilizers – releases a lot of nitrogen into the soil and from there into bodies of water and the atmosphere.

PHOTO: PICTURE ALLIANCE/DPA | LINO MIRGELER

THE OVERFERTILIZED EARTH

TEXT: KLAUS JACOB

No animal, plant, or single-celled organism can do without nitrogen, but humans are putting more and more of it into circulation – with various consequences for health and the environment. Sönke Zaehle, Director at the Max Planck Institute for Biogeochemistry in Jena, is studying the nitrogen cycle and its relationship to the climate. The findings are important for environmental policy.

If awards were presented for the importance of chemical elements to life, carbon would be the big winner. It plays the lead role in organic chemistry, after all. Meanwhile, nitrogen is often overlooked, but such disregard is anything but justified, since life would be unthinkable without it. There is no protein that does not contain nitrogen. Every plant and every animal needs it to thrive. No biochemical reaction is conceivable without nitrogen. And when people eat meat or vegetables, they consume nitrogen in the process. In pre-industrial times, there was a nearly constant, marginally increasing amount that circulated through the air, soil, waters, and living creatures in its biologically usable form. In this virtually closed cycle, changes occurred, at most, on a local level – however, this has been disrupted by massive human intervention, for example, the fertilization of fields. The way in which the cycle is disrupted by this intervention and how this affects the climate is being studied by Sönke Zaehle, Director at the Max Planck Institute for Biogeochemistry.

But first things first: although nitrogen is the main component of air at 78 percent, it is by nature rare as a building material for biomolecules. This is because, in its very stable elemental form, in which it occurs for the most part within the atmosphere, it cannot be utilized by most plants and animals. Nevertheless, lightning has the power to transform it into a biologically available form – something geoscientists refer to as reactive nitrogen. Consequently, every time there is a thunderstorm, this also has a fertilizing effect. Yet, in the course of evolution, some organisms have also found a way to obtain this rare, basic substance themselves: nodule bacteria, which live in symbiosis with legumes such as clover, vetch, or soybean, and dock onto their roots, supply these plants with nitrogen compounds. Hence, before there was artificial fertilizer, people often practiced three-field crop rotation and grew legumes for a season to enrich the soil with nitrogen. The cards were entirely reshuffled, however, with the invention of artificial fertilizers. Just over a century ago, German chemists Fritz Haber and Carl Bosch developed a process to produce saltpeter from atomic nitrogen and hydrogen, a precursor of artificial fertilizers such as ammonium nitrate – but also of explosives. And that's not the only reason why the Haber-Bosch process is both a blessing and a curse. In other respects, too, it has had both a positive and negative impact. On the one hand, it has led to an agricultural revolution that has made it possible to feed the world's rapidly growing population. On the other, it has substantially altered the nitrogen cycle – with far-reaching consequences for ecosystems and health.

As with fossil fuels, the problem is the sheer volume. Production of artificial fertilizers has virtually exploded since the Second World War. To get an idea of the dimensions: the Haber-

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Bosch process gobbles up about 1.4 percent of the world's energy because it requires elemental hydrogen, heat, and high pressure. And according to Sönke Zaehle's calculations, use of synthetic fertilizers adds around 90 to 100 million metric tons of reactive nitrogen to the global cycle every year. But that's not all: the combustion of fossil fuels in coal- and gas-fired power plants, and not least in diesel engines, also produces nitric oxides, from which harmful particulate matter is formed. Added to this are forest fires, which also release some of the nitrogen from biomass in the form of nitric oxides.

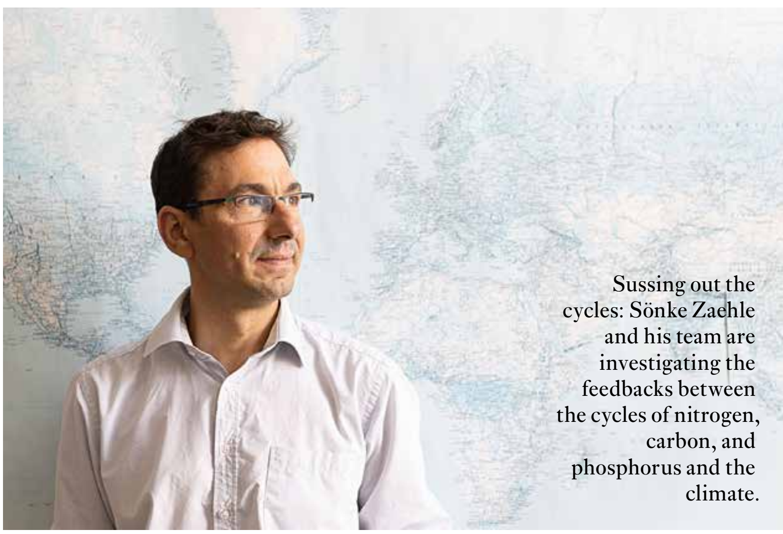

PHOTO: STEFFEN WALTHER FOR MPG

Sussing out the cycles: Sönke Zaehle and his team are investigating the feedbacks between the cycles of nitrogen, carbon, and phosphorus and the climate.

Determining how much nitrogen is in circulation, where it accumulates, and in what quantities it flows back and forth between the biosphere, the geosphere, and the atmosphere is quite an undertaking. Describing the entire cycle in a model and simulating it on the computer is so complicated that Sönke Zaehle's team has divided up the problem: first, into the path that leads from ecosystems to the atmosphere, and second, the reverse. To determine the amounts of the various nitrogen compounds that enter the air from diverse sources, the researchers divide the earth into grid cells with edge length of about 50 kilometers. For each of these fields, their model calculates how much nitrogen is released by the ecosystems there, i.e., forest, grassland, or agricultural land. During this process, the researchers take into account the role played by the rising concentration of CO_2 in the atmosphere, which also stimulates plant growth, and phosphorus fertilization. They likewise investigate how material cycles change with climate change. The researchers feed the model additional data from other research groups on manmade nitrogen emissions from vehicle traffic and industry, for example, and this gives them a precise overview of where and how much reactive nitrogen escapes into the atmosphere. With all this, they are arriving at the same outcome as studies by other groups that use the global distribution of ammonia, nitric oxides, and nitrous oxide to infer emissions of the substances: "Humans have more than doubled the input into the nitrogen cycle since the beginning of the industrial revolution." That's a massive intervention, especially since there appears to have been little globally significant change over many millennia.

The researchers from Jena also calculate the input of nitrogen from the air into waters, soils, and ecosystems with models that likewise take the local climate into account. For this, they use data on how nitrogen compounds are distributed in the atmosphere worldwide, and the results reveal where the nitrogen accumulates and in what quantities. But they're not stopping at these two, one-way observations. "As part of a major EU project, we are working with international colleagues to model the entire nitrogen cycle," says Sönke Zaehle. A particularly complex aspect is the interactions between the different parts of the Earth system, i.e., the oceans and other bodies of water or the terrestrial ecosystems and the atmosphere, but also the very different lifetimes of the globally relevant nitrogen compounds – which can range from fractions of a second to centuries.

Consequences for ecology and health

Just as diverse as the atmospheric chemistry of nitrogen are the harmful effects that each of its compounds can unleash in turn. They alter ecosystems, cause eutrophication and sometimes even collapse water bodies, harm drinking water and the respiratory tract, influence the climate, and destroy the ozone layer. Humans bringing nitrogen into play are like Goethe's sorcerer's apprentice, who thought he had a clever idea bewitching a broom to do his chores for him, but was then unable to stop it as it went completely berserk.

First of all, there is the impact on health: a study by the organization Environmental Health Analytics (LLC) in Washington has shown that every year around 100,000 people die prematurely due to nitric oxides, although such analyses are subject to some uncertainties due to the large number of influencing factors. As they are hazardous to health, there are limits set on air pollution with nitric oxides and particulate matter. Where these have been exceeded, some German cities have already temporarily banned the use of diesel vehicles.

But why does reactive nitrogen harm the environment if it is also an effective fertilizer? The answer is a recurring topic in the media and politics. Plants typically cannot take up all of the large amounts of fertilizer, partly be-

PHOTO: STEFFEN WALTHER FOR MPG

SUMMARY

It is mainly thunderstorms and nodule bacteria that naturally convert elemental nitrogen into a form in which plants can absorb this vital element.

Primarily through fertilization and the burning of fossil fuels, humans have doubled the amount of nitrogen that is cycled between the atmosphere, bodies of water, soil, and terrestrial ecosystems.

Nitrogen compounds stimulate plant growth, but their excess reduces biodiversity, is harmful to health as well as the ozone layer, and affects the climate.

cause rain washes it out before growth starts to speed up. This means nitrogen ends up in rivers and groundwater, and eventually in the sea, mainly in the form of nitrate. In the body, however, nitrate can be converted into the related nitrite, which is harmful to health, so limit values also apply to drinking water. Some drinking water wells in Germany have already had to be shut down because of excessive contamination, with the problem particularly acute in northern Germany where there are large fattening farms with heavy manure production.

Overfertilization also harms natural ecosystems; not all plants like a lot of fertilizer. Vegetation that thrives on poor soils suffers as a result of this unwanted gift, and this is an area where species diversity is particularly high, perhaps because these plant specialists were able to find ways to live with a lack of nitrogen. Even carnivorous plants, such as the Venus flytrap, have evolved to meet their nitrogen requirements by catching insects. Such diversity is in danger of disappearing as a result of the fertilizer glut, and overfertilized regions are dominated by just a few nitrogen-loving species such as stinging nettles or dandelions. When plant species disappear, so do numerous animals that depend on these masters of eking out a living for their own survival. The oversupply of nutrients is equally harmful for rivers and lakes, since eutrophication leads to an overproduction of biomass, which, in the worst cases, can cause ecosystems to collapse.

The oversupply of nitrogen also has an impact on the climate. The nitrogen cycle inevitably produces nitrous oxide, a potent greenhouse gas, because soil organisms convert nitrate into elemental nitrogen and nitrous oxide in the absence of oxygen. This is why a particularly large amount of nitrous oxide is released into the atmosphere

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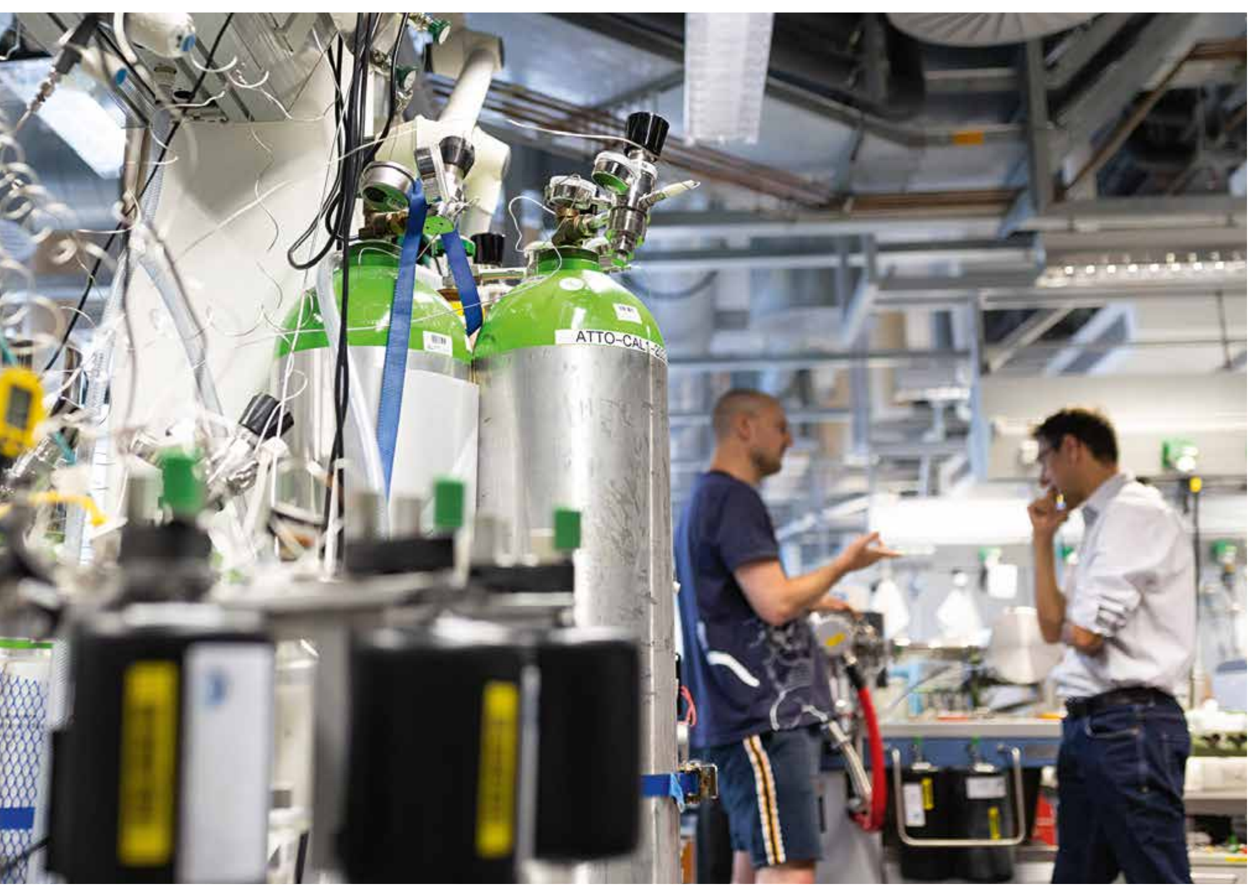
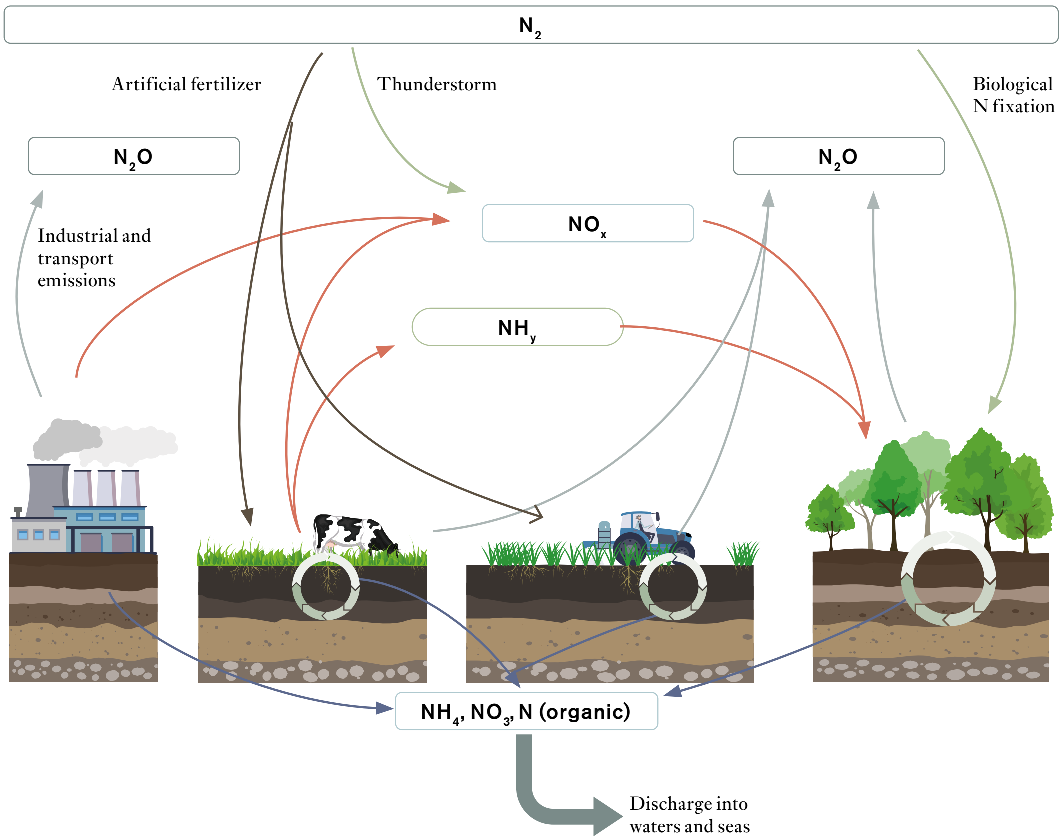


Hot on the trail of greenhouse gases: Heiko Moossen (left) and Sönke Zaehle are researching the increase and decrease of nitrous oxide, as well as carbon dioxide and methane, in the atmosphere, and analyzing their isotope ratios with mass spectrometers for this purpose. The pure substances from gas cylinders serve as a reference here.



Through thunderstorms, biological fixation by bacteria, or conversion into artificial fertilizer, elemental nitrogen N_2 is converted into a reactive form such as NO_x nitric oxides that plants can utilize. Nitric oxides NO_x and N_2O from industry and traffic as well as emissions of NO_x, N_2O, and NH_y from agriculture are also involved in the nitrogen cycle.

after each rainfall, when water cuts off the oxygen supply to the soil. The greenhouse effect of nitrous oxide is almost 300 times that of carbon dioxide, and it remains in the atmosphere for an average of around 110 years, about ten times longer than methane. Nitrous oxide concentrations in the atmosphere have increased by 33 percent since 1750, Zaehle's team has calculated. Analyses by various research groups, including the group working under Sönke Zaehle, agree that most of it comes from agriculture – close to 80 percent in Germany.

Yet nitrogen doesn't just affect the climate in the form of nitrous oxide. Other nitrogen compounds also affect the climate because they boost plant growth. This removes carbon dioxide from the atmosphere, which has a cooling effect. In addition, nitric oxides form aerosols near the ground, creating fine dust. These act as a shield against sunlight and thus also have a cooling effect. All of these sometimes opposing effects are currently being captured by Zaehle's team in models in order to estimate the net effect of nitrogen on the climate. The calculations are complicated by the fact that nitric oxides are distributed very inhomogeneously: they reach high levels over conurbations, but low levels over large, forested areas. "Initial analyses suggest that the effects of reactive nitrogen that amplify or counteract climate change more or less offset each other," says Zaehle.

Conversely, there is another harmful impact that nitrous oxide has on the atmosphere, in addition to its greenhouse effect, that is not counteracted by an opposing effect from other nitrogen compounds: the gas also gnaws away at the ozone layer in the stratosphere, which protects us from harmful UV radiation. It reaches these high altitudes because it is extremely inert in the lower atmosphere. In the stratosphere, shortwave radiation from the sun splits the nitrous oxide molecules, and the degradation products attack the ozone.

Livestock sector as the largest source of nitrous oxide

Considering the many harmful effects of reactive nitrogen, it stands to reason that nations must take countermeasures. However, too little has been done to date – especially when it comes to overfertilization. After all, fertilizer is cheap, as is the disposal of slurry in fields. Moreover, farmers are under pressure to produce cheaply, and policymakers rarely make bold interventions because they do not want to deprive farmers of their livelihoods by imposing strict requirements. It is true that the amount of

GRAPHIC: GCO AFTER SÖNKE ZAEHLE

reactive nitrogen released in Europe has declined over the last forty years, mainly thanks to EU regulations, but it is growing in Asia, Africa, South America, and even in the US, not least because meat consumption is rising in countries like China. This means that an increasing quantity of artificial fertilizers are being used for feed production, and increasing quantities of manure are being disposed of. "The livestock sector is the biggest source of nitrous oxide," Zaehle says. Aquaculture, which now produces about half of the fish consumed worldwide, also impacts the nitrogen cycle. Not only is it the fastest-growing sector within food production, but it is also the fastest-growing emitter of nitrous oxide. Aquaponics, a process that uses the excrement from fish farming as a nutrient for plants, is one way of counteracting this.

EU action against the German government

Even declining figures in Europe are no reason to sit back and relax. Take Germany, for example: according to the German Federal Statistical Office, the use of nitrogen fertilizers fell from 1.85 million metric tons to 1.27 million metric tons between 2000/2001 and 2020/2021. But that is not enough. According to the German Advisory Council on the Environment (SRU), nearly half of Germany's natural and seminatural terrestrial ecosystems were overfertilized in 2009. And nitrate concentrations in groundwater still exceed the limit of 50 milligrams per liter set by the EU's Nitrates Directive at around 17 percent of monitoring sites. The European Commission therefore filed a lawsuit in 2016, and the European Court of Justice ruled in its favor two years later. The German government subsequently tightened the fertilizer ordinance in 2021, as a result of which farmers in nitrate-polluted areas must reduce their use of fertilizer by at least 20 percent and will have to comply with longer embargos in the fall and winter. Yet the upper limit for the amount of nitrogen fertilizer is still 80 kilograms per hectare per year.

"That is clearly too much for many locations," says Sönke Zaehle. To give an idea of the amount, he cites another figure: a natural ecosystem, such as a forest, converts an average of about 120 kilograms of nitrogen per hectare per year. By comparison, an additional 80 kilograms is a lot. Nevertheless, the president of the German Farmers' Association, Joachim Rukwied, decried the "technically flawed regulation that prohibits fertilization according to need in nitrate-sensitive areas." The constant piling on of legal requirements, he said, ignores the capability of farms. Sönke Zaehle likewise sees problems with implementation, but for him and his colleagues the current efforts do not go far enough. He therefore welcomes a resolution by the UN Environment Programme to reduce the nitrogen surplus by half by 2030.

An increase in organic farming could help here, since this involves no artificial fertilizers and the application of slurry is only permitted in a strictly regulated manner. While this does mean that the nitrogen is used more efficiently in the closed cycle, it can lead to lower yields than those achieved by conventional farming. Many conventional farmers are now also trying to avoid overfertilization by measuring the nitrogen content of the soil and adjusting the amount of fertilizer accordingly. Meanwhile, we can all help to ensure that less nitrogen is put into circulation. After all, overfertilization in agriculture is also a consequence of our diet. We can help to reduce it by throwing away less food, using organic products, or eating less meat. This would mean less use of artificial fertilizer and less slurry.

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GLOSSARY

REACTIVE NITROGEN
is the name given to inorganic and organic nitrogen compounds that plants and microorganisms can use, unlike the elemental form.

NITROGEN CYCLE
denotes the cycle of the element through the different parts of the Earth system: the atmosphere, hydrosphere, geosphere, and biosphere.

Nitrogen recycling: in aquaponics, plants are fertilized with the excrement of fish, so the large amounts of nitrogen produced in a fish farm do not contribute to the overfertilization of bodies of water.

PHOTO: SHUTTERSTOCK/TANAKORNSAR