Life, Death, Wheat, and War

Stories of Nitrogen

By Anja Røyne
Original title: *Livet, døden, krig og korn. Historier om nitrogen*
English sample translated from the Norwegian by Olivia Lasky

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Foreword

Are humans nature?

You might think that's a stupid question. Of course humans are a part of nature. We can't live without breathing, eating, and drinking, and we have lives that start and end just like everything else living on this planet.

You might think that's a stupid question because we humans are so much more than plants and animals. We aren't at the mercy of our surroundings. We conquer the weather with clothes and roofs above our heads. We conquer distances with cars, planes, and the internet. Humans cultivate food and operate mines, and we can both pollute and purify, tear down and build up.

I've always been interested in the relationship we humans have with the physical world — the origins of everything we use, how mining metals and minerals affects nature (and, by extension, us), and what we can do to ensure our consumption does not place unnecessary strain on living things. In my first book, I tried to find answers about whether we could ever run out of the resources we humans depend on. This is a genuine concern for metals, even though the biggest issues might be in the distant future. But one of the conclusions I came to in the book *The Elements We Live By* was that we will never run out of nitrogen; it's everywhere in the air around us. You can breathe a sigh of relief now — we have a lot of problems, but nitrogen isn't one of them.

Speaking of breathing, each breath we exhale contains as much nitrogen gas as each breath we inhale, since the nitrogen in the air is completely useless to us. It's useless to plants, too, even though they depend on nitrogen to grow. In order to cultivate the food we need, humans have to supply soil with enough of the *reactive* nitrogen forms — of which there is precious little in the air, but which we've been producing in factories and using as artificial fertilizer for over a century. As long as factories have access to sufficient energy, this fertilizer source will never run out.

After *The Elements We Live By* was published, it didn't take long for me to start noticing how nitrogen can be the source of various problems. I was part of a research project that aimed to get bacteria to produce a climate-friendly form of concrete. First, we supplied the bacteria with urea, a nitrogen-containing compound. This then discharged ammonia, another nitrogen-containing compound, in the next round. It turned out that there are strict international regulations against ammonia emissions, which Norway already has trouble complying with. This was news to many of us on the project.

But that wasn't at all. In 2020, a nitrogen fertilizer warehouse exploded in Beirut, Lebanon, resulting in disaster for both the city and the country. The Oslo Fjord at home in Norway is practically being suffocated by nitrogen. Ammonia will apparently be the next climate-friendly fuel for the shipping industry. High gas prices resulting from war in Europe have led to soaring fertilizer prices and widespread concern for farmers the world over. The more I saw, the more clearly I understood how nitrogen connects everything in the world. Food and war, life and death.

Thanks to our inexhaustible supply of nitrogen fertilizer, the volume of reactive nitrogen cycling through ecosystems is now more than twice what it was before the rise of ammonia factories. This affects every one of the world's ecosystems, no matter how remote they might be. That makes life easier for some species and harder for others, threatening biodiversity — one of the most vital cards nature has to play in the face of a changing climate.

Breathe out, then take a deep breath in again. We might already have enough problems on our plate, but we can handle opening our eyes to one more. The story of nitrogen isn't just about pollution and decreasing biodiversity; it's also about possibilities. And how both humans and life itself have found solutions to seemingly insurmountable problems. It's about how everything is connected, from the smallest bacteria in the ground beneath our feet to the ozone layer that surrounds the planet, from life's humble beginnings to humans' emancipation from the fossil fuels threatening the future of life on Earth.

Cast of Characters

Nitrogen can perform many different roles, each with its own personality. Here are the most important ones you'll find in this book:

Nitrogen gas, N_2 (dinitrogen). A gas that constitutes 78% of the air we breathe. A lazy sort with more than enough on its plate; it takes a lot to convince it to contribute to chemical reactions, which is why it's perfectly harmless for us under normal circumstances. Boils at -196° Celsius, and is therefore used in liquid form when something should be kept extra cold.

Ammonia, NH_3. A toxic, corrosive gas with a sharp odor. An energy-rich molecule that can be combusted or take part in chemical and biological processes. Produced from nitrogen gas in factories and by nitrogen-fixing bacteria in nature, as well as through the bacterial decomposition of organic matter.

Ammonium, NH_4^+, A positively charged ion[1] that is formed when ammonia is dissolved in water. This type of nitrogen is most useful for plants. An ingredient in amino acids, which in turn are the building blocks of proteins.

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[1] An ion is an atom or molecule that has a deficit (positive charge) or surplus (negative charge) of electrons.

Nitric oxide, NO. A toxic gas without any smell or color. A temperamental type that reacts easily. Produced from oxygen and nitrogen in the air when large amounts of energy are supplied, for example, during lightning strikes or combustion.

Nitrogen dioxide, NO_2. A toxic, reddish-brown gas with a strong odor. Contributes to the color of industrial and traffic-related air pollution. Produced when nitric oxide reacts with oxygen in the air.

Nitrite, NO_2^-. A negatively charged ion that is toxic to plants and animals. Forms when nitrogen dioxide reacts with water to produce *nitrous acid* (HNO_2), which then dissolves in water to yield NO_2^-.

Nitrate, NO_3^- (nitrogen trioxide). Also called *salpeter*. Forms when nitrogen dioxide reacts with water and produces *nitric acid* (HNO_3), which then dissolves in water to yield NO_{3-}. Found in salts such as *sodium nitrate* ($NaNO_3$) and *calcium nitrate* ($Ca(NO_3)_2$). Plants absorb nitrate and convert it to ammonium, and then into amino acids.

Laughing gas, N_2O (nitrous oxide). The wild card of the nitrogen family. A gas that contributes to the greenhouse effect and depletes the ozone layer. Relieves pain and produces a feeling of euphoria when inhaled, but long-term exposure can result in nerve damage.

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Breathing Nitrogen

In this chapter, we'll examine the air and get to know the different members of the nitrogen family.

AIR AND BODY

Breathe in.

It happens automatically. Without breathing, you can’t live. The oxygen in the air you inhale into your lungs flows through the thin walls of your pulmonary alveoli, deep down into your chest, and is transported via the bloodstream to every living cell in your body. Each breath you take lets you live a little longer.

Breathe out.

Now you’re getting rid of the waste, exhaust, and emissions from all of the tiny power plants inside your cells. The food you’ve eaten has been converted into energy, the oxygen you inhaled has jiggled the carbon atoms free, and now a pair of oxygen atoms attaches to the carbon and carries it back out to the air. You’re done with it. The carbon dioxide you exhale into the air is ready to be absorbed by plants and become new, energy-rich food.

But only a small portion of air contributes to this essential cycle. Most of the air we inhale just stays in our lungs before it disappears again with our exhalations. This is the case for four-fifths of air — completely useless nitrogen gas.

And here’s where the story could have ended, but it doesn’t. You don’t get anything out of the nitrogen you inhale, but you also can’t exhale *without* nitrogen. Without nitrogen, you actually wouldn’t even exist.

Think of your body as a machine. It’s made of a variety of different components, each with its own special function. A skeleton that keeps your body upright. Membranes that surround each individual cell and ensure that we don’t just end up as soup. Electrical signals that stream through your nerve cells. Muscles that contract and stretch, and let us move through our days. In all of these processes, nitrogen is one of the most important ingredients.

We get oxygen by breathing and water by drinking, but nitrogen is something we have to get through food. The nitrogen gas in the air is of no use to us because it consists of molecules in which pairs of nitrogen atoms are bound together so tightly that they are almost impossible to pull apart. In our food, we find nitrogen chemically bonded to other elements, and these are the building blocks we need to make cells, muscles, and nails. Fortunately, we have the rest of life on Earth to help us. Some have taken on the task of transforming useless nitrogen gas into reactive nitrogen — the very building blocks of life itself.

WHEN THE EARTH AWOKE

The planet we live on formed about 4.5 billion years ago. At the beginning, it was dead. That doesn't mean it was cold or stagnant; the Earth's earliest history is full of meteorite impacts and melted stone, evaporating seas, volcanoes, and ice. But what we think of as "life" — organisms that take advantage of the opportunities their surroundings give them to both propagate and develop — wasn't there from the start.

No one knows how life came to be. Scientists can't look for fossil molecules or single cells because these are too fragile to stand the test of time. But what scientists *can* do is study the chemical composition of the oldest rocks on Earth, conduct experiments, and use large data models to investigate how life may have arisen. One thing is clear: everything we recognize today as "life" has a kind of machinery in which nitrogen bonded with carbon, oxygen, and hydrogen forms the most essential building blocks. Some of the most common of these are called *amino acids*, which are what proteins are made of. Life without amino acids might have been able to exist, but it would have been something completely different from what we are and what we see around us in our world today.

But how was it possible to create the very first amino acids?

Even at the time when the very first life emerged — perhaps around 3.7 billion years ago — nitrogen in the atmosphere existed in the form of useless nitrogen gas. Something must have torn the nitrogen atoms apart for life to arise. And there is a dramatic, powerful process up there in the sky that can do just that. It most certainly occurred before life awoke on Earth, and it still takes place today: thunderstorms.

When lightning flashes across the sky, it releases so much energy that nitrogen molecules in the air are torn to pieces. Then, lonely, frustrated nitrogen atoms find their way to oxygen atoms and end up as *nitrogen oxides* — molecules comprised of nitrogen and oxygen — which are cooperative enough to enter into reactions with other materials so that they, given the right conditions, eventually end up as amino acids.

It's important to note that there was no oxygen gas in this early atmosphere. The oxygen we depend on when we breathe didn't become part of the air until it was created by life itself as a byproduct of photosynthesis. The first photosynthesis processes started with cyanobacteria in the ocean about three billion years ago. Still, it took several hundred million years before they produced enough oxygen for it to accumulate in the air. It wasn't until around 2.2 billion years ago that we had an oxygen-rich atmosphere that started to resemble the one we have today. Yet even though there was no oxygen gas in the earliest atmosphere, experiments have shown that nitrogen oxides can form from lightning strikes even in an atmosphere composed of nitrogen gas and carbon dioxide — both of which were abundant in the air before life began to alter the atmosphere's composition. This means that when the first tentative attempts at life emerged, there were already small amounts of reactive nitrogen in the ocean: nitrogen compounds originating from lightning and thunder.

Life may also have started with nitrogen that came from the depths, not from above. Hydrothermal vents are areas deep in the ocean where geological processes beneath the seabed cause hot water to rise through the solid rock, leaching chemical compounds. Conditions there can become so extreme that nitrogen is released from minerals and combines with hydrogen to form ammonia. However, there was little nitrogen in the minerals under the sea before life became abundant on Earth and dead plants and animals sinking to the seafloor could turn into nitrogen-rich bedrock. This source, therefore, couldn't have been all that substantial. The amount of nitrogen generated by lightning must have also been quite limited. For life truly to gain a foothold, it needed to extract its own nitrogen.

It's almost impossible to imagine how this could have happened, but there is no doubt about the fact that it did indeed occur. Around 3.2 billion years ago, single-celled organisms developed a chemical machinery that enabled them to break the strong bonds in nitrogen molecules and use nitrogen together with hydrogen from water to produce ammonia. Today, we call this process *nitrogen fixation*, and it is essential to all life.

Nitrogen-fixing organisms use tools called *enzymes* — proteins that catalyze chemical reactions. The enzymes themselves don't take part in the reactions but remain unchanged, meaning they can be used again and again. Chemists call such substances *catalysts*; enzymes are catalysts that living organisms produce inside their cells to carry out the chemical reactions necessary for life itself.

Most nitrogen fixers today use enzymes that contain tiny amounts of the metal molybdenum, and chemical traces in ancient rocks lead researchers to believe that this particular variant of the process has been in use ever since biological nitrogen fixation began. This must have posed yet another challenge for early life, since there was little molybdenum to be found in the oxygen-poor primordial ocean. It would take several hundred million years before photosynthesis started to fill the oceans with oxygen and make more molybdenum available. Then, life could build up more of the nitrogen-fixing enzymes, which in turn produced more reactive nitrogen, more life, more photosynthesis, and more oxygen in a self-reinforcing spiral.

It’s impossible to separate the evolution of the Earth from the evolution of life. Life has always changed the conditions on Earth, sometimes dramatically, and then evolved further to adapt to those changes. An endless dance, forever spinning forward.

“CHOKING GAS” AND MEPHITIC AIR

Today, we know that air is composed largely of nitrogen and that extracting this nitrogen from the air and incorporating it into living organisms requires considerable effort. But for most of human history, these processes were completely unknown. It wasn’t until the late eighteenth century that scientists of the time finally developed the tools they needed to investigate what air is made of, and began to understand that it consists of different gases that both influence and are influenced by essential processes such as combustion and respiration.

“It may perhaps appear surprising,” wrote Daniel Rutherford in 1772, “that, though no animal can live without atmospheric air, yet this same air, after it has been breathed, becomes so deadly, that it destroys life more quickly than almost any other poison.” The Scotsman was part of a European community of active naturalists, or “natural philosophers,” as they called themselves at the time. Today, we would call them physicists, chemists, or biologists, but this was before the various natural sciences had branched off into separate disciplines. When eighteenth-century natural philosophers researched air, they often placed mice and other animals or insects in sealed containers until they died. Rutherford conducted several such experiments as part of his medical studies at the University of Edinburgh, and it was through this work that he became known as the discoverer of nitrogen.

We are all, as Rutherford wrote, completely dependent on air. Without breathing, humans and other animals will die. But there’s something strange about air; what we exhale becomes terribly toxic. And fire has a corresponding effect. Allow a flame to burn in an airtight container until it goes out, and the air inside will become as toxic as exhaled air. Rutherford called this corrupted air “mephitic,” and another term commonly used at the time was “fixed air.”

We now know that what Rutherford referred to as mephitic air — air that is exhaled and eventually becomes suffocating — was carbon dioxide. The life-giving oxygen in the air we inhale combines with carbon from the food we've eaten through processes inside each of our cells that release the energy we need to live. The poor mice that were trapped inside airtight boxes, breathing the same air over and over again, would inevitably convert so much of the oxygen in the air into carbon dioxide that they eventually lost consciousness and died.

Rutherford, however, didn't know more than the fact that air was possible to breathe at first, before gradually ceasing to be so. Was this due to a transformation or replacement of all of the air, or only parts of it? Rutherford investigated this by trapping air that had become mephitic inside a glass vessel whose bottom opening was submerged in a container of water mixed with lye. The carbon dioxide dissolved in the alkaline liquid, reducing the gas inside the vessel, which Rutherford could observe because the water surface level was drawn upward into the glass. But no matter how much he tried, he couldn't remove more than about 20 percent of the air in this way. The air that remained in the glass therefore had to be a different substance from the deadly gas in exhalations, even though it was just as effective at extinguishing flames and killing small animals.

Today, we know this suffocating gas — which comprises four-fifths of the atmosphere we breathe in daily — as nitrogen. Nitrogen gas was actually known as *kvelstoff* (suffocating substance) in Norwegian until the 1960s and is still called *kväve* (suffocate) in Swedish. It is incredibly effective at causing suffocation — so effective, in fact, that inhalation of pure nitrogen gas was introduced as a method of execution in the United States in 2024.

Fortunately, most of us never encounter nitrogen gas in a form pure enough to be lethal. But in situations where nitrogen appears in liquid form — because we need something extremely cold — it is important to be cautious.

LIQUID AIR

The lecturer stuck his left hand into the container of liquid nitrogen and left it there while he continued talking about other things. Those of us sitting in the auditorium eventually started getting a little worried. It couldn't possibly be safe to leave your hand in there for such a long time, could it?

Suddenly, it was as though the lecturer realized the same thing, and he pulled his hand out with a dramatic cry. He put his left hand on the lectern, grabbed a hammer with the other, and started smashing away at the cold hand. Fingers flew! Pieces of rubber glove filled with orange bits of finger rained down on the students. Audible gasps could be heard from the audience.

With a mischievous grin, the lecturer pulled off the glove's remnants, revealing his unharmed hand. The orange fragments that had landed on our desks were pieces of carefully carved carrots that he had hidden in the glove beforehand. This was an art he had perfected over many years as a lecturer for this introductory physics course. If I hadn’t already decided to study physics, I might have changed my major that very day. Later, I myself have done tricks with liquid nitrogen for new and enthusiastic students.

We normally find nitrogen as a gas in the air around us. If the temperature drops all the way down to -195.8 degrees Celsius (nitrogen’s boiling point), the nitrogen in the air starts to condense like dew on a cold windowpane. And once nitrogen has become liquid, it takes time for the liquid to turn back into gas. In the meantime, the cold liquid can be used to shock-freeze food or to freeze fertilized embryos that can later become living children.

It might seem surprising that it’s possible to make air *that* cold — but it’s not a matter of simply putting it in a freezer because liquid nitrogen is colder than any household freezer. The solution lies in the relationship between temperature and pressure. Have you ever noticed that gas coming out of a spray can feels cold, even though the can hasn’t been in the fridge? Or that your finger gets cold when you hold the valve down to let air out of a bike tire? That’s because a gas will always drop in temperature if it expands quickly. Liquid nitrogen is produced by compressing air at high pressure, cooling this compressed air, and then letting it get even colder by releasing it through a valve so the pressure falls. When the temperature drops low enough, the nitrogen condenses, while the oxygen in the air — which has an even lower boiling point — remains in gaseous form.

At the university where I work, we get liquid nitrogen from a manufacturer who extracts it from the air through such a process. When the liquid nitrogen is deposited into enormous tanks in the backyard, you can see thick clouds of fog forming as water droplets condense in the air due to the sudden cold.

Since nitrogen comes from the air, I’ve never been particularly anxious when I’ve used it at work, either in liquid form or as a pure gas for experiments. The only thing I want to avoid is freezing any of my own body parts — or someone's in the audience! I've been told that it's a bad idea to take a large container of liquid nitrogen into an elevator; you need to be careful about ventilation. After all, we need oxygen to breathe, and there might be too little if the elevator stalls and slowly starts filling with evaporated nitrogen. Sometimes things can actually go very, very wrong.

THE ACCIDENT AT THE CHICKEN FACTORY

January 28th, 2021. For the third day in a row, the workers on line 4 at the chicken factory in the American city of Gainesville, Georgia, noticed that the chicken coming out of the freezer room on the conveyor belt was only partially frozen. The line supervisor decided to send the workers on a break while technical staff came in to investigate what might be wrong.

When the workers returned from their 20-minute break, the line supervisor was nowhere to be seen, and white fog was coming from the freezer room. This kind of fog wasn't uncommon, so at first, they simply waited. But after an hour had passed and the supervisor still hadn't come back, one of the workers decided to look for him. She knew that he had gone to check out the problem in the freezer room, so she crawled through the opening in the wall where the conveyor belt came out. The floor in the freezer room was lower than the one in the packing department, and when she looked down through a thick white cloud, she could just make out one of the technical workers lying motionless on the floor in front of the conveyor belt.

None of the workers had been trained on the potential dangers of the freezing system, and the safety signs in English and Spanish that were supposed to hang on the doors were hidden inside the machine's control panel. It must have been difficult for any of the workers to know what was happening or what to do. After crawling back to the others, the worker went to find the supervisor of another line in the factory to tell him what she had seen.

When the supervisor from line 1 learned about the situation in the freezer room, he sent the workers on lines 1 and 4 out of the building and instructed the other line supervisors to do the same. The head of production logistics heard about the incident and went to the room next to the freezer room, where he found the line 4 supervisor lying lifeless on the floor. He tried to get him out, but began to feel ill himself and made his way to the changing room nearby, where he lost consciousness shortly thereafter.

The head of maintenance arrived around the same time. He found one of the workers from line 4 unconscious on the changing room floor and bent over to move her, but nearly fainted himself before managing to get out of the building. Fortunately, he knew enough about the system to realize that the cause of his unconscious colleagues' conditions was a leak of liquid nitrogen from the freezer. With the help of two other workers, he was able to shut the valve on the large nitrogen tank at the front of the building.

When the rescue workers reached the freezer room (wearing breathing equipment), they measured the floor temperature at -73 degrees Celsius. Two lifeless maintenance workers and the line 4 supervisor were brought out and declared dead at the scene. In total, six employees died that day.

Investigations afterward showed that the accident had been caused when a pipe that was supposed to measure the level of liquid nitrogen in the freezer was bent, most likely in the morning when workers were trying to figure out what was wrong with the freezer. When the pipe was bent, it began indicating the nitrogen level was too low, resulting in liquid nitrogen continuously flowing into and over the edge of the freezer, where it evaporated. Nitrogen in gaseous form takes up about 700 times more space than when it is liquid, and the cold gas is heavier than the surrounding air, making it sink and push away the oxygen-containing air in the room. In a poorly ventilated room without oxygen deficiency monitors, this can be deadly.

Nitrogen itself isn't dangerous. We breathe it in and out with every single breath without it doing anything except taking up space in our lungs. The problem is that we need the oxygen in the air around us, and our bodies have adapted to the normal oxygen content of about 20 percent. Even a small reduction can affect the body. At 16 percent oxygen, the pulse increases, breathing quickens, and thinking slows. At 14 percent, any movement will make you feel extremely tired, and your coordination and judgment will worsen noticeably. At 12.5 percent, in addition to being unpredictable and uncoordinated, you will feel so nauseous that you vomit, and you risk permanent damage to the heart.

With less than 10 percent oxygen in the air, you will lose consciousness after only a couple of breaths. This is what killed the workers at the chicken factory. When the excessive amounts of liquid nitrogen in the freezer room evaporated and became gas, the nitrogen gas pushed away all the oxygen-containing air, leaving behind an atmosphere that was odorless, colorless, and deadly.

DECOMPRESSION SICKNESS AND DONALD DUCK VOICES

Even though the nitrogen in the air usually doesn’t present a problem for us humans, the situation is entirely different when we inhale air under extremely high pressure — for example, when diving to great depths. When a diver descends in the water, the pressure of the water increases on their body, compressing it. The pressure in the fluid in their body and in the gas in their lungs and airways increases accordingly. This also applies to the air the diver inhales through the regulator on their oxygen tank.

Water pressure increases by one atmosphere for every additional ten meters of depth, which means that the pressure ten meters underwater is twice as much as at the surface and three times as great at twenty meters. The greater the pressure, the denser the gas. This means that when our lungs fill with air at a depth of ten meters, the air contains twice as many gas molecules as we’re used to. At a depth of thirty meters, there are four times as many air molecules in our lungs.

The problem for divers is that higher pressure increases the number of air molecules that come into contact with blood and other bodily fluids, which in turn causes more gas to dissolve in the fluid. Think about sparkling water: it’s produced under pressure and contains a lot of carbon dioxide, yet you can't see bubbles in the bottle when it’s sitting on the shelf in the store. It is only when you open the bottle, allowing the pressure to drop, that the water can no longer hold the gas. The gas then separates and forms bubbles. If a diver ascends too quickly from the depths so that the pressure in their blood drops rapidly, the nitrogen in their blood can turn into bubbles that block blood vessels and cause severe injury. This is what we know as decompression sickness or “the bends”.

It doesn’t take more than ten meters of depth before the nitrogen dissolved in bodily fluids can produce symptoms of what is called *nitrogen narcosis*. The phenomenon was first described in 1826 by a French doctor who was lowered to a depth of twenty meters in a diving bell. He reported experiencing a feeling similar to the intoxication caused by alcohol. During the next century, more and more reports of abnormal behavior among divers at great depths appeared. The medical mechanism behind this is still unknown, but one theory is that the high pressure causes nitrogen to interfere with important proteins on the surface of the body’s cells. Since it’s dangerous to behave unpredictably while diving, divers who go deeper than about thirty meters must use a gas that’s different from ordinary air. The most common solution is to use a gas mixture in which some of the nitrogen is replaced with helium, which can be breathed almost problem-free until much greater depths. Because helium is lighter than the other gases in normal air, sound waves travel faster – making divers sound like Donald Duck when they speak! Still, it’s better to sound a little goofy than to lose control of yourself underwater.