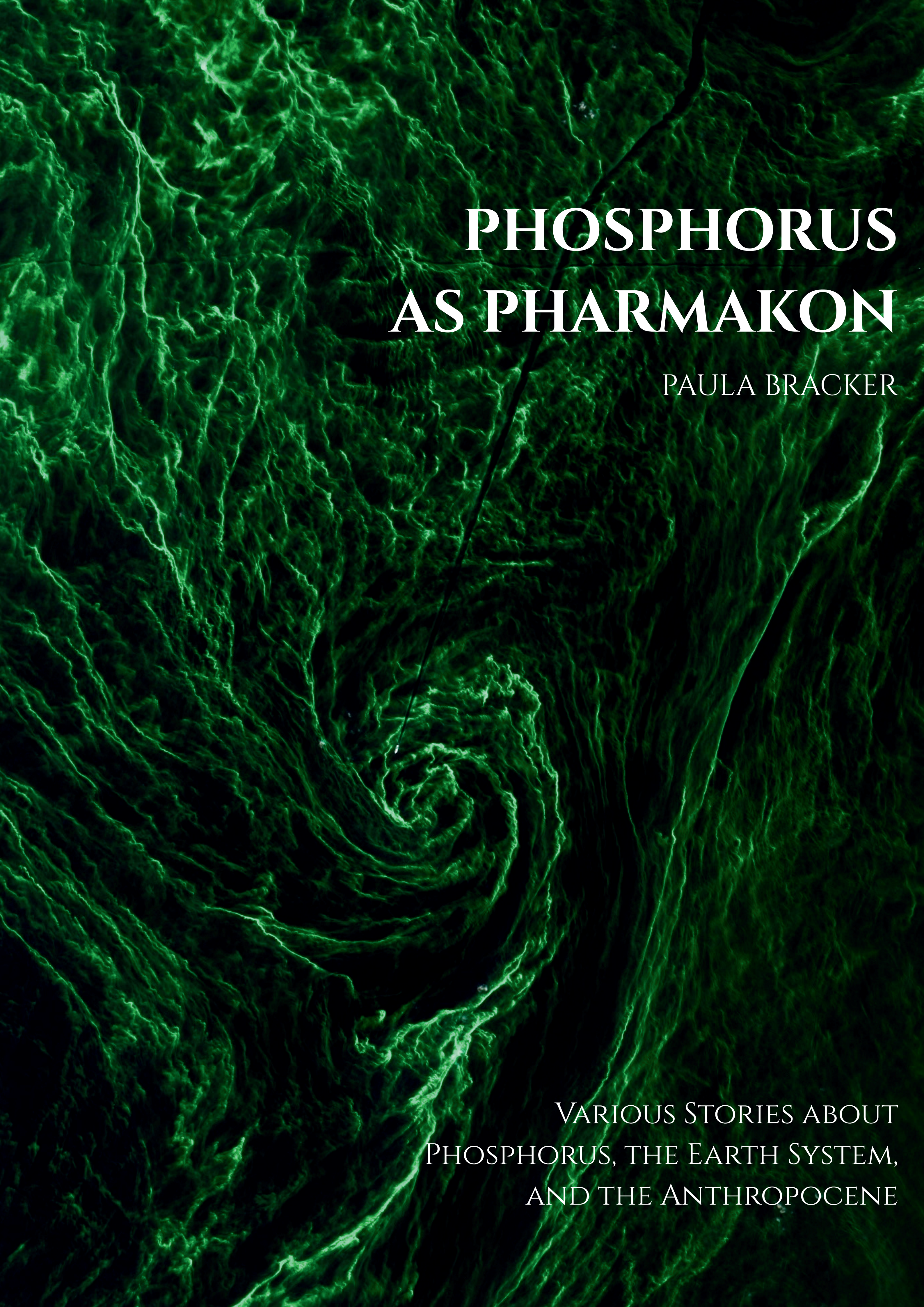

PHOSPHORUS AS PHARMAKON

PAULA BRACKER

Various Stories about Phosphorus, the Earth System, and the Anthropocene

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ABSTRACT

The human relationship with the chemical element phosphorus is ambivalent. Phosphorus is essential to all life on Earth, circulating through rocks, soil, crops, animals and every cell in our bodies. Yet it is also used in bombs, contributes to the pollution of aquatic ecosystems when overapplied, and is associated with extractivism and colonialism. This thesis examines the various pathways of phosphorus to understand its relevance within the Earth system, and to explore where, when, why, how and by whom it is misused. The metaphor of phosphorus as a *pharmakon* – a substance that can be both a remedy and a poison – provides a starting point from which to examine the history of human interference with the phosphorus cycle. Industrial agriculture and the modern extractivist mindset have turned phosphorus into a pharmakon that is still life-sustaining, yet often deadly. Case studies of Lake Erie and the Baltic Sea demonstrate that the overapplication of phosphorus causes toxic algae blooms and dead zones in water bodies. Morocco, the Western Sahara and Nauru have become sites of environmental and social injustice due to phosphate rock extraction. Phosphorus is employed as a tool for reflecting on the impacts of human activity on the planet and for imagining possibilities for transformation. Following phosphorus into the realm of soil illustrates how rhizosphere interactions naturally form efficient recycling systems of nutrients that maintain balance in ecosystems. Promoting these interactions and recycling phosphorus through the use of manure, compost and human excreta is key to sustainable phosphorus management. Agroecology and organic farming are two systemic approaches that require alternative social structures and policy action. These approaches promote careful and reciprocal relationships with phosphorus and nature, offering possibilities to *heal* its disrupted cycle and thereby contributing to environmental and human health.

TABLE OF CONTENTS

1. INTRODUCTION

The human relationship with the chemical element phosphorus is ambivalent. Due to its various crystalline structures and chemical reactivities, phosphorus has a multitude of characteristics, effects, and meanings depending on its usage. It is both life-sustaining and destructive; it is an essential nutrient, a scarce resource, a toxic pollutant and a recyclable material. Its linguistic origin is even ambiguous: In Greek mythology, *Phosphoros* is the personification of the *morning star*, the *bringer of light*; in Latin, the equivalent term for phosphorus is *Lucifer*, the Devil (Commelin 2003, 71). Since phosphorus is highly flammable and was the 13th chemical element discovered, people called it the *Devil's element* (Roberts 2019, 6).

Phosphorus circulates continuously through rocks, soils, plants, animals, manure, dead organic matter, rivers, lakes, and the ocean. It is one of the building blocks of deoxyribonucleic acid (DNA), strengthens our bones, and is essential for chemical reactions in our cells. Phosphorus, flowing through our bodies, physically connects us with the Earth system and makes evident how we are dependent on healthy ecosystems: There is no food and no agriculture without this essential element. Yet, humans have disrupted this cycle, and what sustains life on the one side now brings death on the other. Due to its high flammability, white phosphorus is used in incendiary weapons and nerve gas in contemporary warfare. Phosphate rock deposits – crucial for synthetic fertiliser production in industrial agriculture – are deeply entangled with histories and ongoing practices of colonialism, extractivism, and geopolitical conflicts. In addition, the overapplication of phosphorus in industrial agriculture leads to toxic algae blooms, which transform water bodies into *dead zones.* (Ashley, Cordell, and Mavinic 2011, 737–39) In the Anthropocene – the newly proposed geological epoch that is characterised by a significant human impact on ecosystems and the Earth's geology – phosphorus becomes "a means to narrate the complexities and failures of anthropogenic life" (Neale, Phan, and Addison 2019).

This research is an environmental humanities investigation of the element phosphorus and its pathways through the Earth system, combining a cultural studies approach with a human ecological perspective. Drawing on an analysis of literature from both cultural and natural sciences enables a cross-disciplinary examination of the complex connections and interactions between phosphorus, humans, and the environment. This work explores the element's ecological, historical, technological, and symbolic entanglements guided by the following questions: *What is the role of the chemical element phosphorus in the Earth system? What are its pathways? And how can the metaphor of phosphorus as pharmakon serve as a multifaceted approach to investigating humanity's impact on Earth in the context of the Anthropocene?*

Conversations with experts from BOKU University in Vienna, and from the agricultural sector, working with a compost, manure application technologies and in the field of agricultural science journalism, provided me with a more grounded understanding of the natural flows of phosphorus and the socio-technical contexts of its use. Phosphorus flowing through multiple systems enables us to imagine complex connections and dependencies at micro and macro levels. It further demonstrates how deeply humans are embedded in the biological, geochemical, and ecological cycles, which they often claim to control. By tracing when, where, how and why humans began to intervene in these natural cycles, phosphorus becomes a starting point for examining the emergence of modern conceptions of nature as separate and exploitable.

Employing a cultural studies approach, this work also investigates the epistemological and historical shifts in Western thought and modern sciences that contributed to the transformation of agricultural and food systems into industrialised ones. By considering phosphorus as a *pharmakon* – a substance that is both remedy and poison – this research reflects critically on how the element is used and misused in historical and contemporary systems of production and consumption. This ambivalent metaphor, after Jacques Derrida (1981) and Bernard Stiegler (2018), provides a narrative device for illustrating the interplay between healing and harm: Narrating the life-sustaining currents of phosphorus aims to create fascination for the element and illustrate how phosphorus permeates the Earth. Narrating how we are intervening in its currents and turning the element into a poison aims to illustrate how we are destroying ecosystems in the Anthropocene.

Although this thesis is dedicated to a single chemical element, all stories told remain anthropocentric and embedded in human epistemologies. The element becomes meaningful to us because of its entanglement with our bodies, our histories, and the ecological crisis we are part of. Phosphorus becomes a means to imagine how we are physically intertwined with the Earth and to rethink our relationship with nature. This work therefore finally asks how we can take care of phosphorus as pharmakon to *heal* its broken cycle and contribute to environmental and human health.

2. A PREFACE TO THE PHARMAKON

Pharmacology analyses the interactions between exogenous substances (drugs, *pharmaka*[1]) and organisms (biological systems) (Kurz 1990, 2). It is an experimental science and initially determines results without evaluation. However, conclusions can be drawn about the application to the ill organism for therapeutic purposes (pharmacology) or the detection,

[1] There is no equivalent word to *pharmakon* in the English language that exhibits the same dual meaning. Since this work refers specifically to this meaning, it uses the Greek term *pharmakon* and its plural form *pharmaka*.

treatment, and prevention of poisoning (toxicology) (Kurz 1990, 2). Whereas toxicology is concerned exclusively with the harmful effects of substances on an organism, pharmacology is an overall consideration of the effects of pharmaka. The word *pharmakon* derives from Greek, meaning *medicine*, *poison*, or *magical remedy* (Hunnius and Burger 1998). According to the *Hunnius Pharmaceutical Dictionary* (1998) the pharmakon is a substance (chemical element or compound) which causes beneficial or toxic effects after being absorbed by the body. Many pharmaka act as either remedy or poison depending on the dosage (Hunnius and Burger 1998). In Jacques Derrida's essay "Plato's Pharmacy" (1972) and Bernard Stiegler's *The Neganthropocene* (2018) the pharmakon is ambivalent in its essence and meaning, thereby destabilising the idea of binary oppositions.

Plato's Pharmacy

In his essay "Plato's Pharmacy", which is part of his book *Dissemination* (1972), Jacques Derrida (1981) dissects Plato's dialogue *The Phaedrus* and investigates *writing* and the *written word* as a pharmakon: "This pharmakon, this 'medicine', this philter, which acts as both remedy and poison, already introduces itself to the body of the discourse with all its ambivalence.“ (Derrida 1981, 70) It is beneficial and maleficent. Being indeterminate, the pharmakon contradicts and challenges every philosophical principle by transcending its limits as "nonidentity, nonessence, nonsubstance" (Derrida 1981, 70). Thereby, philosophy is sustained by endless contrarieties and an endless absence on which it is founded. Incorporating multiple meanings, the pharmakon becomes an example of polysemy, the property of a word or phrase having several meanings.

Derrida (1981, 103) further explains that Plato attempts to master and dominate the ambiguity of the pharmakon, in his case *writing*, based on "clear-cut oppositions: good and evil, inside and outside, true and false, essence and appearance". Closely linked to Plato's depiction of the written word, Derrida criticises his understanding of *logos* as a symbol of rational reason. In other words, our conception of the world based on human reason is to be defined in categories that arise in "the aftermath of decision" (Derrida 1981, 115) – they arise after one has decided for a category. At the same time, one needs to speak as well of the irrationality of living logos, which is defined by "spellbinding powers of enchantment, mesmerising fascination, and alchemical transformation, which make it kin to witchcraft and magic" (Derrida 1981, 115). The pharmakon thus opens a mysterious indeterminate space, which is – concerning the logos – a carrier of potentialities. The nature of logos, or the pharmakon, is obscure and ambiguous from the beginning, it incorporates contradictions and is not defined by only one counterpart. The living logos consequently is not merely rational, but irrational as well and defined by "magical 'pharmaceutical' forces" (Derrida 1981, 116).

Comprehending the pharmakon is an "act of domination and decision" (Derrida 1981, 117) by its master, the *pharmakeus*.

For Derrida, the pharmakon symbolises an interplay of opposites. It depends on the context and the master's decision if it will cure or harm. Applying Derrida's comprehension to a wider context, systems or entities contain ambivalent forces and are from the beginning both productive and disruptive. Their meaning for life and their behaviour then depends on how they are comprehended and used.

Pharmacology and the Neganthropocene

> "Halfway through the second decade of the twenty-first century, we, non-inhuman beings that we are, find ourselves trying to live within a state of emergency that is permanent, universal and unpredictable, and that seems bound to become unliveable. We all feel this urgency. But most of the time we deny it – except when we have no choice but to observe its immediate and disastrous effects upon our everyday existences, which tend thereby to find themselves reduced to subsistence, that is, to survival." (Stiegler 2018, 204)

In *The Neganthropocene* (2018) Bernard Stiegler reflects on the concept of the pharmakon in the context of the Anthropocene, which he considers an era of collapse, an era that has a "massively toxic character" (Stiegler 2018, 34). Stiegler comprehends the two-sidedness of the pharmakon in relation to two concepts deriving from thermodynamics: *entropy* and *negentropy* (Stiegler 2018, 42). For him toxic means entropic; and as he considers human activity on the planet as a serious geophysical factor, the Anthropocene is viewed as an epoch "in which entropy is produced on a massive scale" (Stiegler 2018, 51) by human beings. Human behaviour threatens every form of life on Earth and creates a state of emergency affecting the entire biosphere (Stiegler 2018, 204). As the Anthropocene consists of systemic entropy or chaos, Stiegler uses the term *Entropocene* and simultaneously calls for the constitution of the so-called *Neganthropocene*: "I argue that the Anthropocene is unlikeable, insolvent and unsustainable and that it is therefore an Entropocene, which is to say that it implies a turn, a turning point, a detour, *ein Kehre*, as *Ereignis*, turns into what we call the Neganthropocene." (Stiegler 2018, 103)

In the course of the industrialisation and the invention of new technologies, "the question of fire and its pharmacology" replaced a mythological cosmology (Stiegler 2018, 40). The Anthropocene epoch only becomes apparent from the moment the question of the cosmos is understood in terms of combustion: The pharmakon is domestic fire – "fire as that artifice par excellence delivered to mortals by Prometheus" (Stiegler 2018, 40). In this instance, Prometheus symbolises the ambivalence of knowledge and technology that he gave to humanity in the form of fire, enabling them to improve on the one hand, but having a destructive power on the other. Consequently, the author argues that the pharmakon is a condition of but also a threat to hominisation, the development of human beings. It can produce both entropy and negentropy. (Stiegler 2018, 53–54) In his work, Stiegler mainly refers to the usage of technology: Technics on the one hand can be an accelerator of entropy on every cosmic level; consequently, it leads to more disorder and randomness in a system. On the other hand, technics can give "rise to a new form of life" as "a new form of negentropy" (Stiegler 2018, 42). It preserves and creates meaningful, organised structures in society. (Stiegler 2018, 34–43)

According to Stiegler (2018, 45), it is the question of the Anthropocene how to exit this toxic era to enter the Neganthropocene "as a curative, careful epoch". Following the author, due to its ambivalence we must take care for the pharmakon, for shaping the conditions of human's existence on Earth (Stiegler 2018, 42). In this context, pharmacological knowledge might constitute and produce "a neganthropology in the service of the Neganthropocene" (Stiegler 2018, 59). *Noesis* as the human capability to think critically, to understand and to create is an essential part of the negentropic process "that is life in general" (Stiegler 2018, 77) and a precondition for a neganthropology. Stiegler argues that *care-fully* thinking and *thinking that cares* can go beyond the limits of the Anthropocene. For him, *thinking* means to take care, to act and to create. It means to take care of the pharmakon and thus to enter the Neganthropocene – an epoch of critical thinking and reflecting as well as of reconnecting and creating mindfully. (Stiegler 2018, 206, 215)

Derrida (1981 [1972]) and Stiegler (2018) consequently share the thought that the pharmakon is both good and bad at once and that it is the decision of the master, the *pharmakeus*, how to use it. The pharmakon is characterised by indeterminate forces and can produce entropy (toxicity) and negentropy (viability and renewal). While Derrida describes the comprehension of the pharmakon as an act of domination and decision, Stiegler speaks of taking care of the pharmakon to constitute negentropy, new life. To take care of the pharmakon means to enter the Neganthropocene which is not humancentric, but non-anthropocentric. It means to take care for every form of life on Earth through an environmentally sustainable pharmacology:

> "A new pharmakon carries new possibilities of psychic and collective individuation, and it thus requires 'therapeutic' prescriptions – in the form of magic, then religion, then politics – therapeutic prescriptions that constitute practices of care (sacrifice, ritual, worship, deliberation and debate), practices configured by the social systems in which attentional forms emerge." (Stiegler 2018, 34)

Phosphorus as Pharmakon

As a substance that naturally circulates through the Earth system and forms the basis of all life, one might ask how phosphorus can be toxic or harmful at all. Phosphorus becomes toxic in the Anthropocene since we are misusing the element. Following the pharmacological principle of dealing with all effects of pharmaka, Derrida's concept of the ambiguous pharmakon and Stiegler's assumptions about the Entropocene, the essence of the pharmakon is both: live-giving and healing as well as toxic and deadly. In the context of the Anthropocene, the concept of the pharmakon can be considered as a metaphor for phosphorus as a natural substance. Its potential toxicity has become more relevant as humans have begun to overuse or destructively use it. The chemical element phosphorus becomes an ambivalent pharmakon through its human uses, meanings, and effects.

Pharmacology analyses the interactions between pharmaka and organisms or biological systems. This work aims to promote an environmentally sustainable pharmacology after Stiegler. It follows and narrates various histories and pathways of phosphorus and analyses its interactions with various organisms and systems. *Phosphorus as pharmakon* together with the old pharmacological principle of Paracelsus, stating "the dosage makes the poison", serves as a metaphor to make evident how human beings are influencing the interactions between phosphorus, organisms and ecosystems. By diving into different disciplines and following the natural pathways of phosphorus, this project analyses where, when, how, why and by whom the element is misused. As we are abusing phosphorus as a pharmakon it becomes a toxic substance that is harmful towards environmental health, deeply entangled with human health. Consequently, we are engaged in self-destructive behaviours yet cannot comprehend the interconnections between these actions and their consequences.

As phosphorus is a limited resource on Earth, leading to political interdependencies and conflicts, it is more important than ever to question how we use the element in the context of the Anthropocene. Engelmann and McCormack (2018, 242) state that "[i]n many ways, […] the elemental is alluring because it both captures something tangible about the world and also remains excessive of human agency or intervention". Phosphorus carries fascinating and manifold stories that permeate all systems and forms of life. In this work, most of these stories are narrated against the backdrop of the Anthropocene, which invokes phosphorus' toxic side. Similar to Timothy Neale, Thao Phan and Courtney Addison's "Anthropogenic Table of Elements" (2019), this work uses phosphorus "as a means to narrate the complexities and failures of anthropogenic life" (Neale, Phan, and Addison 2019).

By tracing the element through the Earth system, this work aims to create awareness for phosphorus and the Anthropocene as an era of human impact. In relation to Stiegler's concept of the Neganthropocene, as an epoch of carefulness in opposition to the Anthropocene, this thesis assumes that we first need to understand our modern thinking patterns and impact before we can overcome the Anthropocene. We need to understand our present state of being human, encompassing how we intervene in the Earth system, and the toxic harmful behaviour patterns ingrained in the relations that constitute our existence in this world. Based on this understanding, we might then be able to promote transformations towards sustainable futures and perhaps paths into the Neganthropocene.

3. A GENEALOGY OF PHOSPHORUS

In September 2024, the German biologist and science journalist Kerstin Hoppenhaus published her book *Die Salze der Erde. Was drei chemische Elemente mit Kolonialismus, Klima und Welternährung zu tun haben*[2]. Next to phosphorus, Hoppenhaus (2024, 86) describes the importance of two other nutrients in the fertiliser trio: nitrogen and potassium. Nitrogen has also exceeded its planetary boundary[3], but in comparison to phosphorus, it is not a limited resource as it can be produced artificially: Through the invention of the Haber-Bosch process at the beginning of the 20th century, nitrogen can nowadays be extracted from the air and can be technically fixated, making it available to plants. This increased agricultural production and resulted in a population explosion. (Hoppenhaus 2024, 64) Synthetic nitrogen and industrial farming made it possible to foster the over-consumption of wealthy countries but led to a disproportionate increase in the use of fertilisers.

Unlike nitrogen, phosphorus and potassium cannot be produced synthetically. Both elements lie deep in rock, are difficult to extract, and are therefore limited (Hoppenhaus 2024, 66). Already back in 1974, Isaac Asimov described phosphorus as *life's bottleneck* (Asimov 1975, 166) and said that "[w]e may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation – but for phosphorus there is neither substitute nor replacement" (Asimov 1975, 170). Next to nitrogen and potassium, phosphorus is a nutrient, resource, pollutant and recyclable material.[4] The element therefore flows through different stages with different characteristics through the Earth system.

3.1 THE BASIS OF LIFE

Nutrient

Phosphorus is the basis for all life on Earth and essential to global food security (Roberts 2019, 8). It is a building substance of the DNA – as it connects its parts, the nucleotides – and of ribonucleic acid (RNA) (Ashley, Cordell, and Mavinic 2011, 738; Daneshgar et al. 2018, 2). It plays an essential role in the chemical "energy transfer through living cells as a component of adenosine triphosphate (ATP)" (Daneshgar et al. 2018, 2), by transferring phosphate groups "from energy-yielding to energy-requiring processes" (Ashley,

[2] English translation: *The salts of the Earth. What three chemical elements have to do with colonialism, climate and world nutrition.*
[3] *Planetary boundaries* are „the safe limits for human pressure" on the Earth system (Stockholm Resilience Center 2025).
[4] Kerstin Hoppenhaus devides her book *Die Salze der Erde* into these four parts.

Cordell, and Mavinic 2011, 738). When one or two phosphate groups split off, adenosine diphosphate (ADP) or adenosine monophosphate (AMP) is formed. This process releases energy, which is then used for other processes in the cell, e.g. for muscle contractions, the transmission of nerve impulses or the synthesis of new compounds (Hoppenhaus 2024, 286). In the form of phospholipids that "contain phosphorus in the form of phosphoric acid" (Ashley, Cordell, and Mavinic 2011, 738), it contributes to the formation of cell membranes. These phospholipids are also found "in the lipoproteins of blood plasma" (Ashley, Cordell, and Mavinic 2011, 738). Daneshgar et al. (2018, 2) explain that bones and teeth contain the most phosphorus in the body of a living being in the form of calcium phosphate salts – a human body contains approximately 650g of phosphorus. Within the biosphere, humans and animals acquire phosphorus through the consumption of plants or other animals. Plants, in turn, absorb phosphorus from the soil through their root systems (Ashley, Cordell, and Mavinic 2011, 738).

Resource

Phosphorus is a relatively rare element on Earth: It occurs in nature only in bounded form, mostly in the Earth's crust as phosphate rock, which is an essential resource for the fertiliser industry. Axel Anlauf (2024) explains that this finite resource has exceeded its planetary boundary and describes phosphate rock as "one of the most intensively mined substances on Earth". With a production of over 200 million tonnes per year, phosphate rock is mined ten times more than copper (Anlauf 2024). Meanwhile, around 22.6 million tonnes of phosphorus get lost per year by being washed into the sea through rivers – the global boundary is around eleven million tonnes per year (Richardson et al. 2023, 9). In 2014, phosphate rock was added to the European Union's list of critical raw materials (Europäische Kommission Brüssel 2014).

As part of the phosphorus cycle, phosphorus enters the soil naturally via apatite weathering (inorganic phosphate) or decomposed organic matter (organic phosphate). According to Daneshgar et al. (2018, 2) very little dissolved phosphate is directly available to plants in the soil, meaning that only a small amount of phosphates can be absorbed by the plants. Agriculture, therefore, actively increases the phosphorus concentration in the soil through fertilisation. Naturally, there is a balance between phosphate release from rock and erosion into the oceans: Parts of this released phosphate are again sedimented in the sea in the form of very persistent calcium and iron phosphates. Together with organic decomposition such as animal waste and decaying plants and animals on land and in the sea, the phosphorus cycle is completed. (Daneshgar et al. 2018, 2, 7–8) Industrial agriculture interrupts this cycle and has become dependent on limited deposits of phosphorus-rich minerals as apatite: 90%

of all mined phosphate rock is used to produce fertilisers, states Mosaic[5] (Mosaic Company 2025).

Figure 1. *Nauru: Aerial documentation of the phosphate mine*, John Gollings, n.d., © John Gollings

Paradoxically, crops in industrial agriculture cannot absorb all the phosphorus due to over-fertilisation of the soil. Through erosion of the ground, this not-absorbed phosphorus ends up in rivers, lakes and oceans, and leads to toxic algae blooms (Keatley et al. 2011, 1). Bodies of water turn into *dead zones,* and human beings living close to these waterways become health-endangered (Egan 2023, Introduction).

3.2 A WORLD OUT OF BALANCE?

Pollutant

In March 2023, the American environmental journalist and author Dan Egan published *The Devil's Element: Phosphorus and a World Out of Balance* reflecting on the negative impacts of phosphorus on Earth by starting with toxic algae blooms in bodies of water from the coasts of Florida to the Great Lakes of America. While negative consequences of over-

[5] Mosaic is one of the companies dominating the global phosphorus fertiliser market and profiting from its overuse.

fertilisation through industrial agriculture can already be noticed in different areas of the world, there is very little public awareness of phosphorus and its ambivalent role in the Earth system compared to CO_2 and nitrogen. Even in scientific research on nutrient management in soil, phosphorus has been much less discussed than nitrogen and carbon, states the soil scientist Christoph Weihrauch (2018, 1). He explains that phosphorus first attracted increasing scientific attention in the 1960s due to toxic algae blooms and eutrophication in lakes and coastal waters in the US and Canada (Weihrauch 2018, 2). The term *eutrophication* describes a process in water bodies in which algae and other plants grow excessively by "feeding on increased input of nutrients, which in turn causes a depletion of oxygen and reduction in animal life" (Anthropocene Working Group 2022b).

However, it took several years to realise that these environmental events were linked to the erosion of agricultural land, which contained high concentrations of phosphorus in the topsoil as a result of years of fertilisation. Weihrauch (2018, 2) speaks of a paradigm shift caused by these incidents that moved the scientific focus to a more intensive study of the reaction behaviour of nutrients in soil and phosphorus losses from soils to water bodies. Since the end of the 1990s, concerns about a possible *phosphorus crisis* have added another dimension to the scientific discourse, states the author. Experts have started to focus more on the sustainable use of nutrients in agriculture to preserve resources, and to work on developing alternative fertilisers that can replace raw materials containing phosphorus, which are becoming increasingly scarce. Nonetheless, following Weihrauch, there are still many unanswered questions in phosphorus research. (Weihrauch 2018, 1–2, 5)

Recyclable Material

The Viennese Municipal Department 48 (MA48), which is responsible for municipal waste management, and Wien Energie, Austria's largest energy supplier, have been working together for several years to recover phosphorus from Vienna's sewage sludge for use as fertiliser. The aim is to close the material cycle by returning recycled phosphorus to the soil. Through the process of incineration, 12.000 tonnes of sewage sludge ash can be produced per year, containing 1.500 tonnes of phosphorus (Zlamal 2022). However, as there are no legal regulations in Austria on how to recycle phosphorus from sewage sludge and how to reuse it as a fertiliser in agriculture, the ash is deposited unused in landfills for a long time (Zlamal 2022). In May 2024, Austria was – after Switzerland and Germany – the third country in Europe to introduce the recovery of phosphorus from sewage sludge as a legal requirement: From January 2033, 80% of the phosphorus contained in sewage sludge must be recovered from its incineration ash (Bundeskanzleramt der Republik Österreich 2024, 16). Already in 2016, Switzerland decided to recover phosphorus from sewage sludge ash and animal bone meal from January 2026 (Plattform SwissPhosphor and Bundesamt für Umwelt 2023).

Germany enacted the regulation one year later for January 2029 (Bundesministerium der Justiz Deutschland 2017, 3505).

To conclude: Over the past ten years, much has been happening in scientific research about phosphorus and some legislations in the political field have been introduced. Still, there is little or no public awareness of phosphorus and its importance in the Earth system and more regulations in the political and economic field are needed. This lack of knowledge about and attention to phosphorus constitutes the beginning of this research. The aim here is to raise awareness of the element and our connections to it among a wider audience, since it affects us all.

3.3 ALCHEMY, THE DEVIL, AND THE CHEMISTRY OF GHOSTS

An Alchemical Discovery

In 2019, on the 350th anniversary of the discovery of phosphorus, the International Plant Nutrition Institute (IPNI) dedicated the final special volume of their journal *Better Crops with Plant Food* to phosphorus. One of the authors, Terry Roberts, describes that phosphorus was discovered in 1669 by the German alchemist Henning Brand who was originally searching for the philosopher's stone, "a legendary alchemical substance capable of transmuting lower base metals into gold" (Roberts 2019, 6). To discover this stone, every alchemist was looking for, Brand experimented with the "distillation of human urine with pieces of silver" (Roberts 2019, 6) and produced something new, uncanny: A white waxy substance, casting "a bewitching glow" and smelling "faintly of garlic" (Egan 2023, Introduction) – a scenery one can observe in the painting *The Alchemist Discovering Phosphorus* by Joseph Wright of Derby, finalised in 1771. Brand named this substance *Kaltes Feuer*[6]; later, it was changed to *phosphorus*, meaning *light bearer* (Roberts 2019, 6).

[6] English translation: *Cold Fire.*

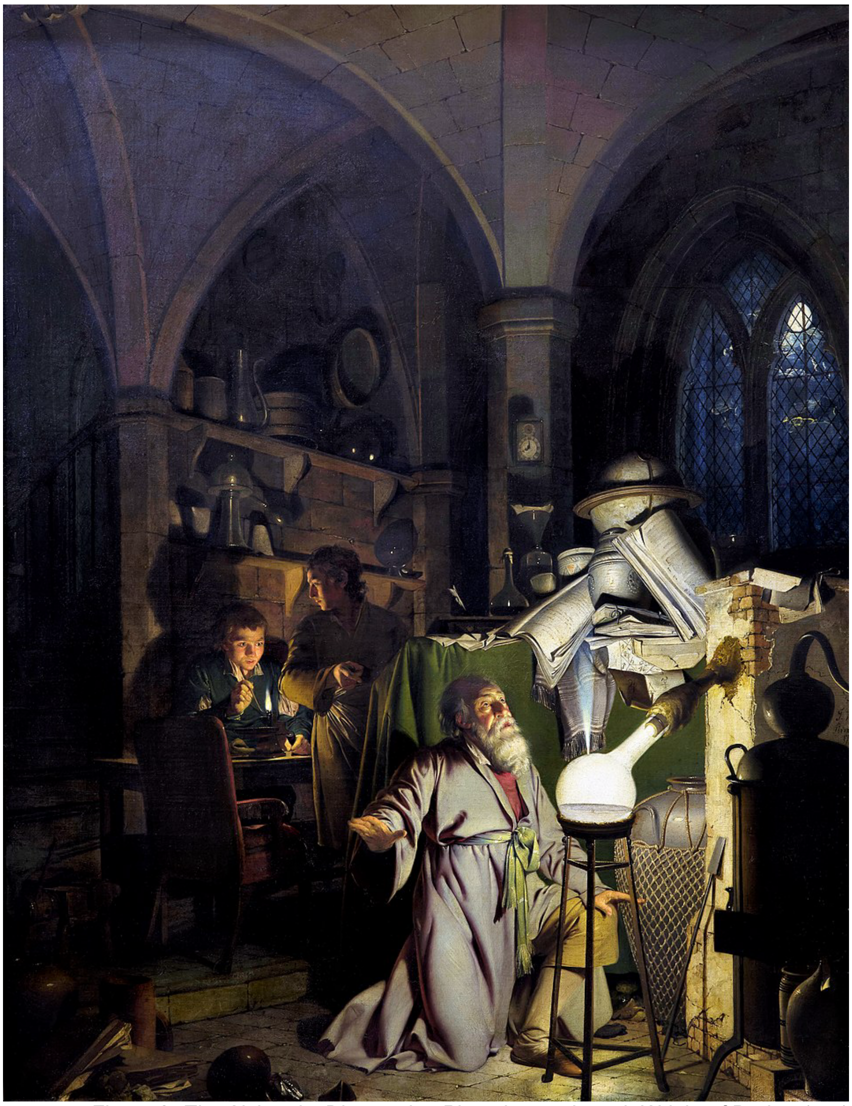

Figure 2. *The Alchemist Discovering Phosphorus*, Joseph Wright of Derby, 1771
Oil on canvas, 127x101,6cm, Derby Museum and Art Gallery, England, © WikiCommons

The term *phosphorus* derives from the Greek word for planet Venus, *Eosphoros* or *Phosphoros.* In Greek mythology, *Phosphoros* is the personification of the morning star, as it precedes the sunrise in the east in the predawn sky (Commelin 2003, 71). *Phosphoros* therefore is the *bringer of light*. In Latin, the equivalent term and personification of the morning star is *Lucifer*, the bringer of dawn: *luc*=*light* and *fer*=*bearer* (Commelin 2003, 71; Egan 2023, Introduction). In medieval Western Christian thought, *Lucifer* has become the personification of the evil, the Fallen Angel or the Devil – an idea originally deriving from the Hebrew Bible or the Old Testament:

> "The name 'Lucifer' was born through the association of the great prince of Isaiah 14, the morning star, Helel-Ben-Shahar, who falls from the heavens through his pride, with the cherub of Ezekiel 28, who was 'perfect in his ways from the day he was created until iniquity was found in him', and of both with Satan, prince of this world and obstructor of the kingdom of god." (Russell 1992, 12)

Jeffrey Burton Russell (1992, 97) explains that Lucifer or the Devil was created with the ability to choose between alternatives, and thus the ability to change from good to evil. This *changeability* was also built into human nature: a necessary consequence of free will to choose good or evil and to change the good *for* the evil. (Russell 1992, 96–97) Following Latin mythology and Western Christian thought concerning Lucifer, the essence of the term *phosphorus*, including various stories about its origin, is thus ambivalent just like the notion of the *pharmakon*. It incorporates the good and the evil and the ability to change from good to evil. In addition to its linguistic origin referring to the devil, in 1776, phosphorus was recognised „as the 13th element in the history of the discovery of elements“ (Roberts 2019, 6). Due to this evil number, its high flammability and its usage in military applications, phosphorus "became known as the 'Devil's element'" (Ashley, Cordell, and Mavinic 2011, 738).

The Devil's Element

There are four allotrope modifications of phosphorus characterised by different crystalline structures and chemical reactivities. Red and violet phosphorus is not metallic, not poisonous and does not glow in the dark. The former serves as an ignition agent in matchsticks produced in toxic fabrics harming the health of the factory workers. Black phosphorus is metallic, not poisonous, does not glow and has no important applications. In comparison to that, white phosphorus – the substance that was discovered by the alchemist Henning Brand – is very toxic, highly reactive, flammable and glows in the dark with a greenish light (Naturhistorisches Museum Wien 2024). Due to its toxicity, white phosphorus is used as an active ingredient in rat poison (Egan 2023, Introduction). Typically, white phosphorus is a waxy solid substance that appears yellowish or colourless, but when it is exposed to oxygen, this substance instantly ignites. Once white phosphorus is ignited, it is "very difficult to extinguish […] and sticks to surfaces like skin and clothing" , states the World Health Organization (WHO) (2024). Therefore, the WHO declares this substance as very harmful to humans in many ways: It causes "deep and severe burns, penetrating even through the bone" (World Health Organization 2024), and due to phosphoric acids and phosphine, produced when phosphorus burns, its irritating smoke is also harmful to the eyes and respiratory tract.

Because of these dreadful characteristics, white phosphorus was used for killing in both World Wars. There are some oral testimonials from the Second World War of a greenish glowing substance dripping into cellars near exploded bombs. Egan (2023, chap. 1) refers to the plan of British Prime Minister Winston Churchill and U.S. President Franklin Roosevelt in 1943, which "directed their military leaders to hold nothing back in the future aerial bombardment of German cities". Bombs packed with phosphorus have been dropped on the cities, where the phosphorus burned through buildings, bunkers and people (Egan 2023, chap. 1). Nowadays, when people search for orange nuggets of amber or fossilised sea creatures on the beaches of the Baltic Sea or nearby Elbe River, they still must watch out for elemental phosphorus nuggets remaining from old war bombs. Egan (2023, chap. 1) recounts one of many stories, in which a man accidentally picks up a phosphorus nugget from the water near Hamburg, mistaking it for amber. He puts it in his pocket and suddenly it starts to burn. The author explains that the man was saved, but had to stay in hospital for several months to recover from burns over a third of his body. (Egan 2023, chap. 1)

White phosphorus bombs are still used in conflicts and wars today: White phosphorus is "used for military purposes in grenades and artillery shells to produce illumination, to generate a smokescreen and as an incendiary" (World Health Organization 2024). According to the WHO (2024), a phosphorus bomb is "not a chemical weapon under the Chemical Weapon Convention (CWC)"; but "as an incendiary weapon directly against humans in a civilian setting", it "may violate Protocol III (on the use of incendiary weapons) of the Convention on Certain Conventional Weapons (CCCW)".

In October 2023, Human Rights Watch (2023) issued a statement in which Israel is suspected of using white phosphorus bombs in military operations in Gaza and Lebanon, putting civilians "at a risk of serious long-term injuries" (Human Rights Watch 2023) after reviewing evidence. Incendiary weapons inflict agonising burns, respiratory damage and organ failure. According to the organisation, the usage of white phosphorus in Gaza as one of the world's most densely populated areas violates international humanitarian law (Human Rights Watch 2023). Human Rights Watch has also documented "the Israeli military's use of white phosphorus in previous conflicts in Gaza, including in 2009" (Human Rights Watch 2023). In South Lebanon, Israeli aggression expresses itself in the usage of phosphorus bombs "in 30 villages and over 195 times" (Serhan, Pop-Arad, and Davila 2025).

Besides Israel, the US Army was charged in 2017 for using phosphorus bombs in Syria and Iraq, Russia is currently accused for using them in the war against Ukraine, and it is alleged that the Turkish army uses them in the conflict with Kurdish institutions (Deutscher Bundestag 2017; Frankfurter Allgemeine Zeitung 2023; Human Rights Watch 2017). Even if white phosphorus bombs are not strictly prohibited like chemical weapons, Israel, Russia and Turkey are currently accused of firing these incendiary bombs directly at populated civilian areas. Human Rights Watch (2017) states that "from 2000 to 2016, white phosphorus munitions were reportedly used in at least seven conflicts – Afghanistan, Gaza, Iraq, Lebanon, Somalia, Ukraine, and Yemen". In this context of military operations, phosphorus is clearly a means of expressing evil human behaviour, becoming the Devil's element.

The Chemistry of Ghosts

Contrary to this, phosphorus in the form of phosphates that contain the PO_4-group gives life. Plants need phosphorus to grow, and animals and humans need it to produce energy for physical processes. For the longest period in human history, the food supply depended on the amount of phosphorus available (Naturhistorisches Museum Wien 2024). When dead organic material from plants, animals or human bodies start to decompose as part of the phosphorus cycle, “[g]aseous forms of phosphorus, phosphine (PH_3) and diphosphine (P_2H_4)” (Kadlec 2020, 451) can be released together with methane. A mixture of methane and phosphine “emitted from marshes and bogs can auto-ignite, forming the flickering lights known as ‘Will-o’-the wisp’” (Kadlec 2020, 451). Graveyard ghosts, mysterious ghostly lights in swamps, and spontaneous human combustion are all mystical folklore, that can be controversially explained by chemical reactions involving phosphorus in decaying organic matter (Harkup 2017).

Phosphorus with the atomic number 15 in the periodic table occurs in nature and human usage in many different forms and compounds with various characteristics. However, the element appears almost exclusively in bounded form, usually as phosphate in apatite or phosphorite, typical phosphorus-containing minerals (Hoppenhaus 2024, 282). This work will primarily utilise the elemental’s name, irrespective of its physical state. The term *phosphorus* thus encompasses not only the element itself but also its compounds, including phosphates. Specific chemical compounds will only be named when they are particularly discussed or used by other authors, this work is referring to.

4 AGRICULTURE

The development of phosphorus as a fertiliser is deeply intertwined with the development of agricultural practices. Hereby, agriculture is two-sided as well: It provides life through food, fibre, other goods and employment. On the other hand, its industrialisation to feed a growing population is one origin of climate change, loss of biodiversity, resource and soil fertility loss, and water shortage – challenges that agricultural practices in turn must face themselves (International Assessment of Agricultural Knowledge, Science and Technology for Development 2009, 2). Therefore, phosphorus management is crucial in determining whether these problems worsen or improve. The way in which agriculture is practiced can decide whether phosphorus, used as a pharmakon, continues to destroy or heal the land on which we depend.

In their *Global Report*, the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) (2009, 2) states that sustainable agriculture needs to effectively manage “a range of interdependent physical and natural resources – land, water, energy, capital and so on”. The report highlights that, as agriculture is a significant contributor to many of today’s most pressing challenges we encounter today, it also has the potential to play a key role in solving them. The IAASTD requires a fundamental change in agricultural methods away from monoculture, agrochemicals and mineral fertilisers in addition to a change in food consumption, processing and trade. (International Assessment of Agricultural Knowledge, Science and Technology for Development 2009, 2)

4.1 AGRICULTURE AND THE GLOBAL FOOD SYSTEM

Something is wrong…

"Something is wrong with our agricultural and food system", stated Jules N. Pretty (2002, xi) already two decades ago in his book *Agri-Culture: Reconnecting People, Land, and Nature*. On the one hand, hundreds of millions of people are suffering from hunger, and on the other hand, further hundreds of millions are eating too much or the wrong food, producing tonnes of waste (EAT-Lancet Commission 2019, 12; Pretty 2002, xi).

Agriculture began about 10.000 years ago when population growth and the related overexploitation of natural resources forced the transition from hunter/gatherer to agriculture and livestock farming (Balgheim 2023, 5). Agriculture comprises "crop-, animal-, forestry- and fishery-based systems" (International Assessment of Agricultural Knowledge, Science and Technology for Development 2009, 2), and is consequently deeply interrelated with the global food system, and in general with the social, economic and ecological systems. When human beings started to cultivate land and destroy forests to gain more land for growing crops, they started to actively transform natural ecosystems.

Millenia later within the context of the industrialisation in the second half of the 19th century, new scientific knowledge about nutrients and fertilisers increased food yields in Europe and resulted in a strong population growth. Since then, increasing food production has been a significant reason for the destruction of ecosystems: The land used by agriculture to provide food for a selected part of the world population is the same land that is the basis for plant and animal organisms. Any land used by agriculture is at the expense of natural ecosystems and biodiversity (Heinrich-Böll-Stiftung 2024, 8–9).

> „Foods have a special significance and meaning, as do the fields, grasslands, forests, rivers and seas. Yet, over just the last two or three generations, we have developed hugely successful agricultural systems based on industrial principles. They certainly produce more food per hectare and per worker than ever before, but only look efficient if we ignore the harmful side effects – the loss of soils, the damage to biodiversity, the pollution of water, the harm to human health." (Pretty 2002, xii)

For centuries, phosphorus has been, next to nitrogen and potassium, the basis of industrial farming that made it possible to feed an ever-growing world population – or to cover the excessive consumption of wealthy countries. By increasing agricultural yields, we have begun to interrupt material cycles such as the phosphorus cycle. We have become dependent on external sources of energy and raw materials such as phosphate rock. And meanwhile, we produce tonnes of waste such as faeces from factory farming, our meat consumption is based on. An increase in the use of fertilisers and pesticides no longer results in a higher food production, but in soil erosion, water pollution, an increase in greenhouse gases and loss of biodiversity (Heinrich-Böll-Stiftung 2024, 8–9). Agricultural activities are linked to 30% of global emissions leading to climate change by e.g. land-use changes such as deforestation (International Assessment of Agricultural Knowledge, Science and Technology for Development 2009, 3, 11). Overdosing phosphorus aimed to satisfy human hunger but transformed it into a toxic pollutant destroying ecosystems.

One Health

In the *Food Planet Health Report* the EAT-Lancet Commission (2019, 5) calls for a radical transformation of the global food system and a transition to a *Planetary Health Diet*. The planetary boundaries of our food system are exceeded due to excessive consumption by wealthy countries, while many other populations continue to face significant undernutrition (EAT-Lancet Commission 2019, 12). In 2022, one person in ten of the world's population was facing hunger and 2.4 billion people were experiencing "moderate to severe food insecurity"[7] (United Nations. General Assembly Economic and Social Council 2024, 6).

The EAT-Lancet Commission (2019) states that food in the Anthropocene forms a complex connection between human and planetary health: "Food is the single strongest lever to optimize human health and environmental sustainability on Earth." (EAT-Lancet Commission 2019, 5) In *Der Kulinarische Kompass für eine gesunde Erde. Flächenbedarf und Klimaschutz*, WWF Germany (2021, 2) demonstrates as well that our food system is the biggest threat to nature and our health, and that the impact of our food consumption on Earth is often underestimated. From a global perspective, our food systems exceed the Earth's limits and at the same time harm human health (WWF Deutschland 2021, 2). In general, human, animal and environmental health are closely interlinked. *One Health* is an approach that focuses on these relationships and aims to balance and optimise "the health of humans, animals and ecosystems by integrating these fields, rather than keeping them separate" (World Health Organization 2023). The WHO (2023) states that human activities and stressed ecosystems make it possible for new diseases to emerge and spread. These stressing factors include "animal trade, agriculture, livestock farming, urbanization, extractive industries, climate

[7] The Food and Agriculture Organization of the United Nations (FAO) defines food insecurity by a person's lack "to access enough safe and nutritious food for normal growth and development and an active and healthy life" (FAO 2025). Following the FAO's *World Food and Agriculture Statistical Yearbook 2024*, the prevalence of undernourishment is the highest in Africa and kept increasing in 2023 to 20.4%, meaning that this percentage of Africa's population is unable to access enough food that is required to live a healthy life. Meanwhile, Asia is the country with the highest number of undernourished people (52%), given its large population base. On the other hand, more than one in four adults in America, Europe and Oceania were obese in 2022. (FAO 2024, 28–29)

change, habitat fragmentation and encroachment into wild areas" (World Health Organization 2023) – all factors which our food system is based on.

Complex Challenges

Our food system is based on agricultural land, and agriculture is dependent on nutrients and fertilisers such as phosphorus. Thus, our eating behaviour is explicitly influencing the global application of phosphorus and trade with phosphate rock. Multiple challenges come together: Promoting sustainable agriculture, with the sustainable use of phosphorus as a fertiliser, that can feed an ever-growing population (Sustainable Development Goal 2); and deeply related to that, a transformation of our food system towards one that is based on sustainability, resilience and equity (United Nations. General Assembly Economic and Social Council 2024, 6).

With their Planetary Health Diet, the EAT-Lancet Commission (2019) introduces a solution to these challenges by suggesting to implement a healthy diet for 10 billion people by 2050. With the concept of *planetary health,* the commission refers to a concept by the Rockefeller Foundation-Lancet Commission on planetary health in 2015, which explains it as "the health of human civilization and the state of natural systems on which it depends" (EAT-Lancet Commission 2019, 7). The Planetary Health Diet clarifies the critical role diets play in linking human health and environmental sustainability, which must be considered in relation to one another. The EAT-Lancet Commission demands a "combination of substantial shifts toward mostly plant-based dietary patterns, dramatic reductions in food losses and waste, and major improvements in food production practices" (EAT-Lancet Commission 2019, 10).

In order to achieve substantial shifts in the way we eat and use land, we need to substantially change the way we comprehend food, landscapes, and nature. Social constructs of the modern world transformed food and land into commodities, and agriculture began to be organised along linear factory lines. The development of phosphorus as a fertiliser and a toxic pharmakon is deeply intertwined with the evolution of industrial agriculture.

4.2 THE EVOLUTION OF AGRICULTURE AND THE CARTESIAN SPLIT

The Neolithic Revolution

Robert Mikkelsen (2019, 17) explains that, when humans transitioned from hunting/gathering to farming, crops were harvested and taken from the field resulting in depleted phosphorus levels in the soil. Farmers started to supplement phosphorus with animal manure or to "adopt shifting cultivation" (Mikkelsen 2019, 17). With the development of cities, nutrients migrated systematically from the fields to the city and civilisations started to address plant nutrient depletion next to increasing crop production differently. Some areas were burnt down and nutrients got re-introduced to the system with residual forest ash. In Egypt, farmers settled near flood plains and allowed the floodwaters to bring in nutrient-rich silt. (Mikkelsen 2019, 17)

Because it was difficult to burn and move regularly, and because alluvial land was limited, most farms relied on some form of recycling of organic material, such as crop waste or animal and human manure (Hoppenhaus 2024, 29; Mikkelsen 2019, 17). Settled agriculture consequently was highly dependent on the location chosen, and even small negative climatic events could no longer be simply avoided by nomadism. According to Balgheim (2023, 5), the transition to settlement in the context of the Neolithic Revolution was accompanied by a regulation of food crops and the storage of harvested crops. From 800 AD through the Middle Ages to the 18th century, agriculture developed from two-field farming to three-field farming. These were rotating systems in which one-third of farmland was always left fallow and used as pasture, which had a fertilising effect. Incorporating food and fodder crops as red clover and root crops into the rotating system further resulted in a significant improvement in soil fertility. This was additionally supplemented with manure and crop residues. (Balgheim 2023, 5) Consequently, the regulation of food crops as part of settled agriculture necessitated the regulation of phosphorus, which needed to be supplemented artificially in order to sustain plant life, as it had been removed from the soil during the previous harvest.

Bones and Bird Excrements

Next to recycled organic material, old *pounded* bones became of great interest as a source of phosphorus, explains Mikkelsen (2019, 17). The demand for bones grew quickly at the beginning of the 19th century and England was one of the countries that imported the most from Europe and the great battlefields during this time (Mikkelsen 2019, 17). Hoppenhaus (2024, 43) describes that meanwhile, in 1802, the German researcher and explorer Alexander von Humboldt reached the west coast of Peru and encountered a yellow-brownish substance mined from nearby bird islands that was supposed to have an excellent fertilising effect. According to Hoppenhaus, Humboldt took a sample, analysed it in Europe, and concluded in 1804, that this *guano* contained a lot of nitrogen and a particularly high amount of phosphorus. (Hoppenhaus 2024, 44)

Around twenty years later, in 1828, the chemist Carl Sprengel acknowledged for the first time that plants extract minerals from the soil and postulated with his mineral theory that plants live exclusively from inorganic minerals such as nitrates, sulfates, chlorides and phosphates that are stored in humus (Balgheim 2023, 6; Hoppenhaus 2024, 36). In 1840, Justus von Liebig introduced his work on *Agrikulturchemie* and first recognised the importance of nutrients in terms of their quantity and ratio to each other. His so-called *Gesetz des Minimums*[8] states that the yield is determined by the nutrient that is present in the smallest amount. Together with Carl Sprengel, he founded the principles of plant nutrition and fertilisation (Balgheim 2023, 6; Hoppenhaus 2024, 37–38). These new scientific findings in Western European agricultural sciences fuelled the search for new sources of phosphorus in order to sustain the ever-growing agricultural sector.

In 1841 – as a consequence of a trade agreement between a Peruvian merchant and French investors, the English trade house and the Peruvian government – 6.300 tonnes of guano were delivered to England on 23 ships (Hoppenhaus 2024, 45). Due to the new findings about mineral fertilisers, the Western European demand for guano increased rapidly and reached its peak in 1870: A total of 700.000 tonnes were exported from Peru, showing no respect for the birds and the people living there (Hoppenhaus 2024, 46). While the *Age of Guano* was just beginning, the British agricultural chemist John Benet Lawes was experimenting with bones and produced from 1843 on bone meal decomposed with sulfuric acid (Roberts 2019, 6). According to Roberts (2019, 6), this manufacture and selling of so-called *superphosphate of lime* "marked the beginning of the world's phosphate fertilizer industry".

Figure 3. *Guano Island Poor Man's Galapagos, off the shore of southern Peru, 2015,* © dbrgn/WikiCommons CC BY-SA 3.0

[8] English translation: *Law of the minimum.*

Following Mikkelsen (2019, 19), the phosphorus fertiliser industry entered the modern era when mineral deposits of phosphate rock (apatite) were discovered around the world: “e.g. [in] England, 1847; Norway, 1851; France, 1856; USA, 1867; Tunisia, 1897; Marocco, 1921; Russia, 1930” (Mikkelsen 2019, 19). Nowadays, phosphate rock is the most common origin for phosphorus fertilisers and will be further investigated in relation to extractivism in Chapter 5.1 “Rocks and Precious Phosphates”.

The Industrial Revolution and the Cartesian Split

The beginning of the modern fertiliser industry was one expression of the transition of Western European countries and the USA from agrarian to industrial societies in the context of the Industrial Revolution and Imperialism during the 19th century. The evolution of industrial farming and the transition of phosphorus into a toxic pharmakon consequently needs to be considered as deeply intertwined with historical shifts in Western thought during the rise of the modern colonial-capitalist era. To promote a different relationship with phosphorus and new paths towards sustainable agricultural practices, we need to understand the origins of human alienation from nature:

> „For all of our time, we have shaped nature, and it has shaped us, and we are an emergent property of this relationship. We cannot suddenly act as if we are separate. If we do so, we simply recreate the wasteland inside of ourselves.“ (Pretty 2002, 10–11)

The dualistic worldview and the distinction between body/mind, human/nature, self/other, and whole/part can be derived from the conceptions of René Descartes (1596-1650): *Dualism* includes the idea that body and mind are two separate and independently existing substances which causally interact with one another. Consciousness resides within the non-physical and non-spatial realm of the mind, in contrast to the physicality of the brain (Waldkirch 2000). During the European Enlightenment in the 17th century “faith in the capacity of the rational human mind to order and conquer all [emerged,] suggesting a superiority of mind over matter and of humans over ‘non-rational’ nature” (Adams and Mulligan 2003, 3). Within this turn of so-called *Cartesian Dualism* Western colonial authorities felt legitimised to exploit and plunder nature, and to occupy and shape the world of so-called *wild* and *uncivilised* indigenous peoples: “The Eurocentric colonial system was one of hegemony – a system of power relations in which interests of the dominant party were disguised as universal and mutual, but in which the colonizer prospered at the expense of the colonized.” (Adams and Mulligan 2003, 51) Within this *othering* and a shift towards purely materialistic sciences in Western society, all matter of the Earth had been declared dead, justifying its exploitation.

In the context of the European Enlightenment, Western societies transformed into emancipating societies colonising other peoples and nature. Modern societies began to alienate themselves from the so-called *natural world* and to determine the history of nature and other living beings. Since then and in the context of the Anthropocene, the history of the Earth has been subordinated to the history of humans. However, nature and the Earth – after almost 4.5 billion years of Earth history – will continue to exist, even without us.

The Western linear thinking against nature infiltrated the way we use the land in agriculture: "[W]e affect nature and land, and are affected by it." (Pretty 2002, 16) Phosphorus flowing through the human body illustrates that we are part of the natural world and the Earth system (Hoppenhaus 2024, 277). We shape nature, and it shapes us. We eat food and other organisms, that shape us, and whose existences are shaped by our consumption behaviour. Misusing phosphorus as a pharmakon, as a result of viewing nature as separate from us, changes its cycles to our own disadvantage.

For this reason, at the very least, we should transform our one-sided relationship with nature, in which we only take, into a reciprocal one, in which we care for nature, other societies and other living organisms. Michel Serres (1992, 10) asks for a *Natural Contract* in which we reconceptualise our relationship with the environment. He designates us human beings as *parasites* that are dominating and appropriating the Earth. It is in this context that the word *environment* is given its meaning: By placing ourselves in the centre of a system that is surrounding us – the Earth's system. According to Serres, to form and transform society and to create a world according to our ideas, we have left the pure state of nature, signing a *Social Contract* (Serres 1992, 8). Following on from the idea of human parasitism, Serres underlines that we must understand that we need the world to exist. The Earth existed a long time before human history even started, it can exist without us and will continue to exist when human beings disappear again (Serres 1992, 7). To save ourselves as part of the Earth system, Serres argues, we must add a Natural Contract to our exclusive Social Contract. This contract should contain symbiosis and reciprocity, meaning that both partners owe their lives to one another and care for each other as a global collective (Serres 1992, 14, 20).

The Need to Reconnect

With the Sustainable Development Goal 15, the United Nations call for a fundamental shift in humanity's relation to nature to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (United Nations Department of Economic and Social Affairs 2025). If we fundamentally change the way we view nature, we might also change the way we use phosphorus as a pharmakon in order to promote its healing properties towards ecosystems. One possibility to practice a reciprocal relationship with nature including a curative application of phosphorus is sustainable agriculture. By referring to the environmental historian Donald Worster (1993, 92), Pretty (2002, 55) argues that sustainable agriculture uses nature's goods the best while not damaging the environment; it can protect the land while using it: "Good farming makes people healthier, promotes a more just society, and preserves the Earth and its network of life." (Pretty 2002, 55) The author considers sustainable farming as a collective cultural practice in which communities exchange traditional knowledge about landscapes and nature, a practice that can "contribute to a range of public goods, such as clean water, wildlife, carbon sequestration in soils, flood protection and landscape quality" (Pretty 2002, 56).

Combining scientific knowledge with old or indigenous wisdom can provide new perspectives on the world and challenge our objectification of nature. In her book *Braiding Sweetgrass. Indigenous Wisdom, Scientific Knowledge and the Teachings of Plants* (2013), the Native American[9] botanist Robin Wall Kimmerer (2020, 31) intertwines "indigenous ways of knowing" with scientific knowledge and asks how we can make our relations with the world sacred again, in order to overcome social constructs of the modern world. The author argues that when "food has been wrenched from the earth, depleting the soil and poisoning our relatives in the name of higher yields, don't buy it" (Kimmerer 2020, 31). Establishing a relationship based on gratitude and reciprocity can enhance the evolutionary fitness of both plants and animals: "A species and a culture that treat the natural world with respect and reciprocity will surely pass on genes to ensuing generations with a higher frequency than the people who destroy it. The stories we choose to shape our behaviors have adaptive consequences." (Kimmerer 2020, 30) In her book, Kimmerer shares her observations on the interactions between plants, organisms and humans. She tells "old stories and new ones that can be medicine for our broken relationship with earth, a pharmacopoeia of healing stories that allow us to imagine a different relationship, in which people and land are good medicine for each other" (Kimmerer 2020, x). Following the pathways of phosphorus through the Earth system and understanding our ambivalent relationship with the element can help to comprehend the complexities of our relationship with the Earth. However, it also allows us to imagine a different relationship, where people and land can mutually benefit from each other – or following Kimmerer, where they can be *good medicine for each other.*

[9] Robin Wall Kimmerer is a member of the Citizen Potawatomi Nation, indigenous North American peoples.

4.3 PHOSPHORUS AS A PROXY FOR THE ANTHROPOCENE?

The Great Acceleration and the Green Revolution

After the Second World War the industrialisation of agriculture reached one of its climaxes with the Green Revolution in the 1960s. The aim was to get as much as possible out of the fields to fight world hunger (Vergauwen and De Smet 2017, R861). Modern methods of efficient agriculture and yield maximisation included large-scale monocultures, the chemicalisation of fertilisers and pesticides, only a few high-yielded varieties, more irrigation, genetically modified organisms and factory farming (Heinrich-Böll-Stiftung 2024, 10). During the Second World War, many workers moved from agriculture to industry, which also contributed to the ongoing rationalisation of the agricultural sector and the associated intensification of soil cultivation with more efficient large machinery (Balgheim 2023, 6). Norman E. Borlaug, an American agricultural scientist who was responsible for the genetic improvement of wheat in Mexico, is called the *Father of the Green Revolution*. In 1970 he was awarded the Global Nobel Prize for his "work to feed a hungry world" (Vergauwen and De Smet 2017, R861). Nowadays, almost every eaten wheat is dwarf wheat introduced by Borlaug that has "shorter stems and a much greater yield, making it cheaper and easier to grow than older varieties" (Vergauwen and De Smet 2017, R861).

While on the one side, global food production tripled in recent decades, the Green Revolution had negative consequences as well: The excessive use of fertilisers and pesticides led to eutrophication and the loss of biodiversity, an increase in greenhouse gases, a reduction in water supplies due to increased irrigation, to groundwater pollution, and soil salinisation and humus loss (Heinrich-Böll-Stiftung 2024, 10). Furthermore, small farms became uncompetitive and countries in the Global South were taken over by global investors through *land-grabbing*. Many of them invested in so-called *cash crops* such as soybean or sugarcane – crops that are only produced for the global market and not for the farmers and local communities themselves (Heinrich-Böll-Stiftung 2024, 22–27). Nowadays, the disproportionate increase in the use of fertilisers is no longer reflected in food production but rather has resulted in environmental pollution and dependencies on large corporate powers that supply the global market with cultivated genetically modified seeds and agrochemicals.

A Marker for the Anthropocene?

The Anthropocene Working Group (AWG), "an interdisciplinary research group dedicated to the investigation of the Anthropocene" (Max Planck Institute of Geoanthropology 2025), decided to define the beginning of this new geological epoch in 1950 with the *Great Acceleration*. In 2009 the AWG was founded by the Subcommission on Quaternary Stratigraphy which is part of the International Commission on Stratigraphy. Referring to the atmospheric chemist Paul Crutzen and the biologist Eugene Stoermer and their introduction of the term *Anthropocene* in 2000 as "a human-dominated […] geological epoch" (Crutzen 2002), the AWG dedicates their research to the search for a Global Stratotype Section and Point (GSSP or *Golden Spike*) for the beginning of the Anthropocene. For this purpose, twelve research groups consisting of social scientists, geologists, palaeontologists, oceanographers, climatologists and stratigraphers started to investigate different sites all over the world that might represent "the most suitable location for a GSSP for the Anthropocene" (Max Planck Institute of Geoanthropology 2025). Using the geological method of stratigraphy, they were looking for so-called *proxies* in the Earth's sediment layers that contain – like an archive – information about past geological epochs until today. Proxies can e.g. be ice cores, sediments or corals. They allow conclusions to be drawn about past living conditions and environmental changes and can provide information about the Earth and its transformation nowadays: Comparing sediment layers provides insight into the impact of humans on Earth, which is inscribed in its sediments.

The AWG consistently refers to the year 1950 and the global phenomenon of the Great Acceleration as a reference point for the Anthropocene: After the Second World War, the industry and economy developed rapidly. Standardised production processes were causing the production of consumer goods to explode and mark the beginning of mass consumerism (Defert 2024, sc. 37:03-37:45). The Green Revolution in agriculture also coincided with the Great Acceleration as a global event, leaving multiple traces on Earth. The sediment layers in the Earth's archive clearly show the effects of intensive agriculture, the industrial revolution and limitless growth. One expression of intensive agriculture is the broken global phosphorus cycle, a biogeochemical flow whose modification represents one of the nine planetary boundaries crossed:

> "Biogeochemical cycles concern the distinct pathways of chemical substances through the Earth's surface reservoirs, that make up a global flow across the biosphere, the hydrosphere, the atmosphere, the cryosphere, and the uppermost part of the lithosphere. Over the course of the last century, human activities have started to exert a tremendous influence on these chemical fluxes, such that they would now be more accurately called *anthrobiogeochemical* cycles." (Max Planck Institute for the History of Science 2022)

As regular and systematic fertilisation with phosphorus is an important requirement for intensive farming, high yields and economic success, lots of the nutrient is applied several times a year. However, most of the phosphorus does not remain in the soil or end up in the harvest; due to soil erosion, a lot of the overapplied phosphorus flows into rivers, lakes, and finally into the sea, explains Hoppenhaus (2024, 144). There, the nutrients serve as fertilisers too and cause various organisms to reproduce in large numbers and proliferate indefinetely.

Huge toxic algae blooms take the light from other organisms. The water turns opaque and seaweed and large algae can no longer thrive, depriving many marine organisms of breeding grounds and habitat. After their death, the new biomass sinks to the sea ground, where it is decomposed by microorganisms consuming lots of oxygen. The more plankton is flourishing the more sinks to the ground and the more oxygen is consumed by the decomposers. At some point, there is no oxygen left for other marine organisms that cannot change their habitat, and areas with oxygen deficiency turn into dead zones. (Hoppenhaus 2024, 145)

Agriculture and Eutrophication

Eutrophication is a global problem: The three largest dead zones are in the Baltic Sea (up to 84.000 km²), the Black Sea (up to 40.000 km²) and the Gulf of Mexico (up to 22.000 km²) (Umweltbundesamt 2024). In the USA, one of the largest lakes is highly eutrophic since the mid-twentieth century. High phosphorus, chlorophyll concentrations and finally toxic algae blooms that harm human health and aquatic ecosystems can be found in Lake Erie in Ohio at the border to Canada. In freshwater systems, cyanobacteria or blue-green algae cause these blooms (United States Environmental Protection Agency 2024). Through warmer water temperatures caused by climate change, these single-celled organisms reproduce indefinitely and produce a toxic substance which can kill dogs and cause poisoning in humans (Egan 2023, chap. 6). In the case of Lake Erie, the reduction of phosphorus is expected "to reduce the amount of cyanobacteria biomass in the lake to less than 9,600 metric tons (MT) in 9 years out of 10" (United States Environmental Protection Agency 2024).

In his book *The Devil's Element: Phosphorus and a World Out of Balance* (2023) Egan makes agriculture responsible for Lake Erie's pollution since the 1950s. He explains that the Maumee River basin leading to Lake Erie "is home to some three-million acres of laser-straight rows of corn and soybeans (along with lesser amounts of wheat, hay, and oats)" (Egan 2023, chap. 6) and many livestock farms. According to Egan, the pollution of Lake Erie resulted in bans on phosphorus detergents and in the Clean Water Act in 1972. This Act obligated cities and industries to dramatically reduce fertilisers and other pollution discharges into rivers, lakes and coastal waters, but mostly reprieved the agricultural sector. Farmers in the Maumee watershed reduced the amount of factory-made chemical nutrients applied to their fields in recent years due to government money and publicly funded programs. These programs encouraged farmers to plant cover crops "to soak up excess fertilizer and anchor phosphorus-saturated soils so they don't wash into the lake" (Egan 2023, chap. 6) or to build gates to slow down the phosphorus-contaminated rainwater flowing from the field into underground pipes. However, Egan says a big part of the problem is manure and farms transforming into industrial livestock farms:

„American agriculture today is often conducted on an industrial scale. Just like any factory, farms that can have more than ten thousand head of cattle produce a predictable daily load of pollution (manure) that is anything but diffuse. Farmers liquefy the stuff and pump it into pond-sized sewage lagoons that can hold millions of gallons. To keep those lagoons from overflowing, farmers must regularly spread their phosphorus-rich waste on farm fields—sometimes even if those fields do not need a nutrient boost." (Egan 2023, chap. 6)

Figure 4. *Lake Erie Toxic Algae Blooms*, Peter Essick, 2011, © Peter Essick, National Geographic

Through soil erosion and runoff of agricultural manure from land, those excessive phosphorus inputs show themselves in eutrophication in rivers, lakes and oceans. Withers and Haygarth (2007, 2) explain that depending on the soil of the agricultural land, soil phosphorus dissolves and begins to move solubilised or attached to colloids and particles during storm events. Hereby, phosphorus mobilisation is not only dependent on the soil type but also on climate conditions and farm management practices. Following the authors, the delivery of phosphorus then encompasses the transfer from land to water streams. It is consequently influenced by the proximity of agricultural land to the water or by retention barriers such as hedges, ramparts or wetlands. Withers and Haygarth state that land and areas with a high risk of phosphorus mobilisation and delivery are referred to as *critical source areas*. The particular role of agriculture in eutrophication lastly becomes evident in the impacts of washed-off phosphorus in aquatic ecosystems. (Withers and Haygarth 2007, 2) By interfering with the chemical phosphorus flux, industrial agriculture transformed it into an *anthrobiogeochemical* cycle that leaves its traces in the Earth's sediments. While one part of the overdosed phosphorus causes eutrophication in aquatic ecosystems another part is retained in sediment layers of the ocean ground (Song and Burgin 2017, 1484).

Traces in the Deep Sea

Aside from Lake Erie's algae blooms, two research groups from the AWG proposed two sites as potential GSSP for the Anthropocene in relation to the industrialisation of agriculture: The East Gotland Basin in the Baltic Sea and Beppu Bay in Japan are strongly determined by the runoff of agricultural fertilisers and influenced by an increased input of nitrogen and phosphorus into the sea. Both sites provide evidence that the structural shift towards industrial agriculture, involving the overapplication of phosphorus, is an example of human activity leaving traces in the Earth's geology.

Jérôme Kaiser, a sedimentologist and organic geochemist, and Juliana Ivar do Sol, a microplastics researcher, investigate the nutrient inputs in the Baltic Sea based on drilling cores from the seafloor of the Eastern Gotland Basin. The Baltic Sea is a semi-closed basin and a landlocked arm of the Atlantic Ocean, which is highly impacted by anthropogenic pressures (Kaiser et al. 2023, 26). It is the world's second-largest brackish sea, containing a mixture of seawater and freshwater and its surrounding land has a "long and rich human history" (Anthropocene Working Group 2022b). The researchers explain that human activities such as fishing, trading and high levels of nutrient runoff from the surrounding land have a significant impact on the sea's ecology: The Baltic Sea is one of the most eutrophic seas on the planet, with huge effects on marine ecosystems (Anthropocene Working Group 2022b). According to the AWG (2022b), these cultural, environmental and climatic changes can be traced in the seafloor sediment at depths of 249 meters in the Gotland Deep or 459 meters in the Landsort Deep. A forty-five-centimetre-long core stores these changes from around the 1840s to 2018 and shows a clear cut and transition to dark matter, which refers to the period from 1950 onwards: Since then, there have been high nutrient inputs into the Baltic Sea caused by the structural change of agriculture (Anthropocene Working Group 2022b; Defert 2024, sc. 12:06-12:48).

Figure 5. *Algae Bloom in East Gotland Basin in the Baltic Sea, Baltic Blooms*, ESA, 2019, © ESA, contains modified Copernicus Sentinel data (2019), processed by ESA

This structural change since the mid-twentieth century is also noticeable in Beppu Bay in Japan, another location proposed as GSSP for the Anthropocene. The bay is located on the northeast coast of one of the biggest islands in Japan: Kyūshū. Due to intensive urbanisation and industrialisation the quantity of pollutants and fertilisers entering the bay through rivers increased since the 1960s, explains the geologist and paleobiologist Michinowu Kuwae (Anthropocene Working Group 2022a). For Kuwae, Beppu Bay represents a microcosmos of the impact of human beings (Schwägerl 2023).

> "Increased supply of organic pollutants and nutrients, along with population concentration and agricultural land expansion to the coast, has led to marked marine ecosystem degradation, eutrophication, and hypoxia after 1960—patterns which are recorded in sedimentary sequences from microfossils, inorganic, and biogeochemical proxies." (Kuwae et al. 2023, 4)

According to Kuwae, increases in nitrogen and phosphorus from anthropogenic sources have led to the growth of dinoflagellates, a single-celled microalgae belonging to the most important group of phytoplankton (Schwägerl 2023). Hoppenrath and Saldarriage (2012) explain that these small calcifying microorganisms practice photosynthesis and bind large amounts of the carbon dioxide contained in the atmosphere. Consequently, dinoflagellates are key agents in the global carbon cycle and the basis of the oceanic food chain. This phytoplankton species reflects physical and chemical properties of the seawater and thus, deteriorating environmental conditions by forming calcareous cysts. When dinoflagellates die, only their cysts remain and sink to the ocean ground, where they preserve information about oceanographic conditions from the past and today. (Hoppenrath and Saldarriaga 2012) Kuwae assumes that in the future dinoflagellates can serve as leading fossils[10] for the Anthropocene: They thrive and proliferate when the living conditions for most other marine species are existentially threatening (Schwägerl 2023).

To conclude: Algae in surface waters or their dead biomass in sediment cores in the ground of the deep sea are strongly influenced by an increased input of phosphorus. This organic biomass can serve as a proxy for the Anthropocene, as its abundance marks the beginning of the Great Acceleration and Green Revolution – two events that symbolise the progressing Western separation from, and destruction of, nature. In this context, phosphorus itself is not a direct proxy for the Anthropocene, but the consequences of its overuse are stored in ocean sediments. Phosphorus as the pharmakon is not the evil element but becomes a toxic pollutant through its overdosage in industrial agriculture.

5 ROCKS, SOIL, AND SEWAGE SLUDGE

In agriculture, neither phosphorus, nitrogen, nor potassium can be permanently dispensed with when fertilising, explains Hoppenhaus (2024, 115). While most countries with highly industrialised agriculture can obtain at least parts of their nitrogen requirements from the air using the Haber-Bosch process and mine potassium domestically or obtain it from neighbouring countries, they are usually dependent on phosphorus imports, often over long distances. Following Hoppenhaus, this challenge does not only concern industrialised countries, but newly industrialised countries as well as Brazil and India. Although phosphorus is abundant on Earth, exploitable deposits are rare: More than 80% of the world's discovered phosphate resources are located in just six countries. Depending on global circumstances, phosphorus can therefore become scarce for geopolitical reasons, such as increasing prices due to global economic crises, pandemics, or wars. (Hoppenhaus 2024, 115–16)

Europe is reliant on a complex system of dependencies, neocolonialism and extractivism in other countries to get phosphorus as a fertiliser. At the same time, soils become infertile and human waste full of phosphorus gets lost in our sewerage systems. The following chapters will

[10] *Leading fossils* are fossils that can be used to determine the relative age of a surrounding rock or sediment layer (Martin, Bischof, and Eiblmaier 2000).

investigate geological, biological, chemical and socio-political systems that contain phosphorus as a valuable, but scarce resource. Hereby, we will follow phosphorus in its multiple forms through the phosphorus cycle to understand where we intervene and break the cycle and analyse how we can apply the element differently.

5.1 ROCKS AND PRECIOUS PHOSPHATES

The Phosphorus Cycle

Phosphorus flows through various phases of concentration and dilution in the phosphorus cycle (Hoppenhaus 2024, 115–16). Following Werner (1999, 344), this biogeochemical cycle is separated into an inorganic and organic cycle. The inorganic cycle is considered a superior cycle, starting with primary mineral weathering. Phosphate ions are mostly found in primary apatite minerals in sedimentary rocks (lithosphere). These rocks weather naturally as part of the rock cycle over millions of years, and the phosphate enters the overlying ground cover (pedosphere). Dissolved and particulate phosphorus is then carried by rivers into the oceans, where it is redeposited in sediments and might return to land after a long geological process called *up-lift*. This overarching inorganic flow integrates the organic, or biological cycles of terrestrial and aquatic ecosystems. (Werner 1999, 344) In the soil, phosphorus is present in different forms: “soluble, mineral, absorbed and organic” (Daneshgar et al. 2018, 2). Daneshgar et al. (2018, 2) explain that there is only a small amount of soluble phosphate anions (PO_4^{3-}) that is released in the process of soil formation and that is available for plants. Phosphates thus enter the biological cycle through plants, that are eaten by animals and humans. With the waste and dying of this organic biomass and its decomposition, organic phosphates either return to the soil or are taken up by detritivores, such as microorganisms that break it down into inorganic fractions. (Daneshgar et al. 2018, 2) In other words, they can be enriched in organic compounds or converted into more stable binding forms through reactions with soil components during a long mineralisation process. These phosphorus-containing compounds are washed off through seepage water and soil erosion and enter lakes or oceans through rivers. In these water bodies phosphorus is absorbed by marine organisms like phytoplankton (cf. Chapter 4.3), whose waste or bodies sink to the ocean ground and form new sedimentary layers (Daneshgar et al. 2018, 2; Werner 1999, 344).

Phosphorus has no stable gaseous form and is thus not available in the atmosphere, unlike nitrogen. Only a small amount of phosphorus is transported via dust, aerosols and rain. But mainly, phosphorus transfers between “rocks, water, soil, sediments and organisms” (Daneshgar et al. 2018, 8). According to Hoppenhaus (2024, 115), the rarity of degradable phosphate deposits originates in the phosphorus cycle: In some rocks in terrestrial ecosystems phosphorus occurs in high concentrations. Due to wind and weather and other forces of the atmosphere and biosphere, phosphorus is dissolved from rock, and travels slowly and in many detours through bacteria, fungi, plants, animals and microorganisms on land through the soil or in water through lakes, rivers and the sea. Along this way, as Hoppenhaus illustrates, it becomes increasingly diluted and more complicated, almost impossible, to extract in an economically profitable way. It is only when phosphorus accumulates again, when the currents are favourable and the chemistry is right, when the ground is sinking and sediments fossilise, and when the seafloor rises again over millions of years – that new deposits are formed from which phosphates can be extracted. (Hoppenhaus 2024, 115) These specific interactions under various physical and chemical conditions result in a small number of phosphate rock deposits. These unique processes make phosphorus a limited resource, distributed in only a few places in the world, but essential for every country's agricultural and food system. Globally, Europe is the region most dependent on phosphate imports (Daneshgar et al. 2018, 5).

Political Dependencies and Illegal Resource Exploitation

Anlauf (2024) states that today, phosphate rock is one of the most intensively mined substances on Earth. With the Great Acceleration starting in the 1950s and the Green Revolution, the application of agrochemical fertilisers increased globally, resulting in a dramatic increase in extracting phosphate rock. Due to advanced techniques, the United States dominated the phosphate industry in the 20th century "[d]espite having just one percent of global phosphate reserves" (Anlauf 2024). Based in the United States and Canada, the two companies Mosaic and Nutrien became major dominating forces in the global phosphate industry, determining prices and "leaving farmers, especially from the Global South, vulnerable to fluctuations" (Anlauf 2024). According to Anlauf, Mosaic still controls 13% of the global phosphate market, conducting its major operations in Peru, Brazil and Saudi Arabia. But since the 1990s, North American companies controlling the world market have been challenged by state-owned and -controlled companies from emerging economies. (Anlauf 2024) Nowadays, the biggest global phosphate rock reserves are found in Morocco and parts of occupied Western Sahara, where the state company OCP Group S.A., owned by the Moroccan government, controls one-third of global phosphate rock exports (Anlauf 2024; Daneshgar et al. 2018, 4).

Up to 2018, the Canadian company Nutrien has been "responsible for purchasing 50% of the rock exported from Western Sahara" (Western Sahara Resource Watch 2023). According to Anlauf (2024), due to geological factors and expensive environmental regulations, North America became dependent on other phosphate reserves from countries such as Morocco and occupied Western Sahara. In the USA, the toxic and slightly radio-active by-product of mining phosphate rock called *phosphogypsum* must be stored in huge piles, while in Morocco, this by-product containing uranium and radium can be just dumped into the sea

(Anlauf 2024). Not only is Nutrien environmentally harmful somewhere else, but the company was also importing phosphate rock that had been illegally mined in a territory that Morocco has been occupying since 1975. Up to today, Morocco exploits phosphate rock against international law in mines located in occupied Western Sahara, mostly sited in the city and mine of Bou Craa (Global Environmental Justice Atlas 2022). These illegal sources of phosphate rock represent "one of the Moroccan government's main sources of income" (Western Sahara Resource Watch 2024). Given that Nutrien is one of the world's leading fertiliser providers, it becomes clear that the global agricultural and food systems are based on exploitation and social and environmental injustice in the Western Sahara territory against the Saharawi people.

In June 2019, Nutrien (2019) stated on their website that they "no longer require imports of any offshore phosphate rock" and that they closed every phosphate facility relying on imported phosphate rock from OCP. They claim that their open facilities "are supplied by their own rock mines" (Nutrien 2019), which are "underground deposits formed by marine sediment" (Nutrien 2025). According to Mining Watch Canada (2019) and Western Sahara Resource Watch (WSWR) (2024, 26), Nutrien is still involved in phosphate rock exports from Western Sahara via the Chinese stock-exchange registered company Sinofert Holdings. 52,7% is controlled by the Chinese government-owned Sinochem group and 22% is owned by Nutrien (Mining Watch Canada 2019). Sinofert is one of the *companies under observation* by the WSRW (2024, 26).

In 2023, the main importers of illegally mined phosphate rock from Western Sahara were Innophos Holdings Inc., a US company exporting large quantities of phosphates to Mexico, Paradeep Phosphates Ltd. from India/Morocco, Ballance Agri-Nutrients Ltd. and Ravensdown from New Zealand and an unknown company from Japan (Western Sahara Resource Watch 2024, 10). In their report, WSRW (2024, 10) refers to the Council on Ethics for the Norwegian Government's Pension Fund Global, stating in 2015:

> "'Companies buying phosphate from Western Sahara are in reality supporting Morrocco's presence in the territory, since the phosphate is sold by the state-owned Moroccan company OCP and it must be assumed that the revenues generated by the operation largely flow to the Moroccan State. In its present form, OCP's extraction of phosphate resources in Western Sahara constitutes a serious violation of norms. This is due both to the fact that the wishes and interests of the local population are not being respected and to the fact that the operation is contributing to the continuance of the unresolved international legal situation, and thus Morocco's presence and resource exploitation in a territory over which it does not have legitimate sovereignty.'" (Western Sahara Resource Watch 2024, 10)

WSWR (2024, 2) calls on all involved companies to stop “all purchases and shipments of Western Sahara phosphates” until the conflict between Western Sahara and Morocco has been resolved. Not involved in any trades or shipments but in supporting and supplying the Moroccan mining company OCP are the German engineering company Siemens Energy, the US company Caterpillar, the Australian company Worley Ltd., and the German industrial conglomerate ThyssenKrupp (Western Sahara Resource Watch 2024, 13). Consequently, the former Spanish colony Western Sahara, listed as a United Nations Non-Self-Governing Territory since 1963 and occupied by the Moroccan state since 1975, is a key example of illegal phosphate exploitation, supported by companies and countries worldwide (Global Environmental Justice Atlas 2022).

Figure 6. *Bou Craa Phosphate Mine, Western Sahara*, NASA, 2018, © NASA

As Austria and Germany have no phosphate deposits within their own borders, both countries are completely dependent on imports from other countries. In their report from 2021, the Austrian Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2021, 26) explains that with an annual volume of around 6 million tonnes, the EU is the second largest importer of phosphate rock after India. The main sources of supply are Morocco, Russia and Algeria; most of the phosphate rock imported to Austria comes also from Morocco and occupied Western Sahara and is shipped via Slovenia. In addition, the EU imports 1.5 million tonnes of phosphoric acid from Israel, Morocco and Western Sahara, another form to import concentrated phosphorus (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021, 26–28). Therefore, the EU and Austria are deeply involved in international political dependencies and the overexploitation of phosphates in the occupied Western Sahara. The food we consume is based on inequalities and causes harm *somewhere else*. Here, one might refer to Rob Nixon's concept of *slow violence*, a "violence that occurs gradually and out of sight, a violence of delayed destruction that is dispersed across time and space, an attritional violence that is typically not viewed as violence at all" (Nixon 2011, 2). For Nixon, slow violence contains forms of structural violence and thus, imperceptible violence, being embodied by neoliberal and Western paradigms and agencies, that have consequences somewhere else, where it is not tangible for those being responsible (Nixon 2011, 11). In this context, phosphorus might again be regarded as a metaphorical proxy for human toxicity, represented in social and environmental injustice. Extracting the element to the extent required by industrial agriculture, becomes a form of slow violence.

New Deposits?!

After Morocco and the Western Sahara, China holds the second biggest global reserves and is one of the biggest global producers of phosphate rock (Daneshgar et al. 2018, 4). In 2019, China produced 110 million tonnes of phosphate rock – still potentially just ore[11] (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021, 24). But while China is extracting almost half of the world's phosphate rock, the country's focus lies on its domestic fertiliser market, protected by trade barriers (Anlauf 2024). So, most of the extracted phosphates stay in the country, and only parts get imported to Europe.

According to Daneshgar et al. (2018, 4) other deposits comparable to those in Morocco and Western Sahara have been found in the continental plates of the Atlantic and Pacific Oceans. Nevertheless, there are currently no economically profitable methods to extract phosphorus from the ocean ground. How phosphate rock production and consumption will develop in the future seems to be "one of the most controversial issues among researchers" (Daneshgar et al. 2018, 5). Global population is continuing to grow significantly and the "demand for phosphorus will increase due to the unavoidable need to produce more food" (Daneshgar et al. 2018, 5).

In 2018, based on evaluations of the Geological Survey of Norway (NGU), the British Norwegian mining company Norge Mining discovered over 70 billion tonnes of phosphate ore in south-west Norway close to the smalltown Eigersund (Jones 2023): "The prospective area enriched in apatite [with phosphate], ilmenite [with titanium] and magnetite [with

[11] When phosphate rock is extracted from the ground and contains a sufficiently high level of phosphorus, it is called *ore* (Daneshgar et al. 2018, 3). The ore is processed to increase its purity: From sedimentary phosphate ore, sand and clay is removed and the resulting product is called *phosphate rock* (Daneshgar et al. 2018, 3).

vanadium] covers at least 230 km^2 and is 7000 meters thick, and in a small area of just over 1 km^2, the three minerals make up 30-40 per cent of the rock." (Norge Mineraler 2019)

According to Norge Mining's founder and vice president, Michael Wurmser (2019), this discovery of EU-declared Critical Raw Materials could secure autonomy for the West. Next to fertilisers, phosphorus is also used in computer chips, lithium-ion phosphate batteries for electric vehicles and solar panels, and is thus important for green technologies (Jones 2023; Norge Mineraler 2023). On their website, Norge Mining (2023) commemorates Henning Brandt's discovery of phosphorus as "the key to life on Earth" and declares to use the element "to unlock the door to a greener future". After this news, the European media were reporting that the EU could finally stop importing phosphates from non-European countries, some in states of conflict, such as the Western Sahara. In 2023, the Deutsche Phosphor-Plattform (DDP) (2023) reacted to these assertions with a critical statement relativising the mining company's claims: The discovered 70 billion tonnes are not pure phosphate rock, but mineralised rock, i.e. ore; the P_2O_5 content of phosphate rock in the Norwegian deposits is around 0.1-3% according to the report of Norge Mining – this is far below the P_2O_5 content of currently operating mines; the deposits are located at depths of up to 4.500 meters, which require expensive, energy-intensive and technologically complex deep mining; in addition, the authorisation process for mining projects is usually 10-20 years (Deutsche Phosphor-Plattform e.V. 2023). The DDP states that despite all optimism, newly discovered phosphate ore deposits still are finite resources. The association thus supports the new phosphorus recovery obligation anchored in the amendment to the sewage sludge regulation, with which Germany wants to become less dependent on raw material imports and protect natural, finite resources. (Deutsche Phosphor-Plattform e.V. 2023)

Neither the discovery of new phosphate deposits nor the invention of new mining technologies will solve our toxic dependency upon phosphate rocks and in general, natural resources. We do not only misuse and overdose phosphorus as a pharmakon, leading to eutrophication; in order to get enough of the pharmakon, we also overexploit it based on an extractivist mindset.

Extractivism, Colonialism and Sites of Destruction

Following Durante, Kröger and LaFleur (2021, 20) extractivism characterises the modern era and describes the appropriation and domination of nature. The authors explain various definitions, all describing "actions that as practiced on the ground often result in irreversible transformations that radically change the target of extraction, such as the landscape and the environment and often also the socio-economic and ecological relations between populations and landscapes" (Durante, Kröger, and LaFleur 2021, 23). These violent operations transform landscapes so much that habitable spaces and territories are destroyed, and their inhabitants are strongly affected. In comparison to the word *extraction*, the concept of *extractivism* abstractly designates “a particular way of thinking and the properties and practices organised towards the goal of maximising benefit through extraction, which brings in its wake violence and destruction” (Durante, Kröger, and LaFleur 2021, 20). Durante, Kröger and LaFleur (2021, 24) explain that “modern extractivist practices” began or increased around 500 years ago and are deeply “entangled with European colonialism, the development of the modern world, and the Enlightenment and scientific revolution”. Even 5000 years ago, within the development of the great imperial empires, human extraction of resources has been destructive towards natural ecosystems. The authors refer to Carolyn Merchant’s book *Reinventing Eden. The Fate of Nature in Western Culture* (2013), considering Greek and Christian narratives as paving the path “for the modern colonial-capitalist era” (Durante, Kröger, and LaFleur 2021, 25) and modern concepts of dominating nature. Merchant argues that certain mindsets have displaced *sacredness-based* understandings of co-existence, reciprocity, nurturing and caring for the Earth (Durante, Kröger, and LaFleur 2021, 24–25). The extractivist mindset is therefore deeply entangled with the Cartesian ontology and has “paved the way for centuries of violence and destruction against indigenous communities and ecosystems” (Durante, Kröger, and LaFleur 2021, 25).

The islands Banaba and Nauru in the Pacific Ocean are such places, exploited and destroyed by colonialist powers since the late 19th century (Hoppenhaus 2024, 97). Hoppenhaus (2024, 97) describes that during imperialism, Germany occupied Nauru in 1888 without knowing that it had conquered an island of treasure. Banaba and Nauru were later discovered as sources of fertilisers, when islands with large seabird populations were targeted in the hunt for guano. In 1899, however, the Australian prospector Albert Ellis recognised the high phosphate content of rock samples from the islands. Both islands are so-called uplifted atolls on an extinct deep-sea volcano that rose together with the ground of the sea around 120 million years ago in the Cretaceous period. As the sea ground up-lifted over millions of years, the island mountains rose together with calcareous reefs and phosphate-rich sediments, forming new compounds and fossilising. (Hoppenhaus 2024, 98–99)

Hoppenhaus (2024, 102–6) further narrates that after his discovery, Albert Ellis returned to Banaba, negotiated with the locals and, after signing a cheap contract, 1500 tonnes of phosphate rock left the island that same year. A long history of Pacific colonial history took its beginning, including violent exploitation and expulsion of local communities and other living beings. In 1968, the Banaba people unsuccessfully demanded independence from the British colonies, who left the island almost uninhabitable. By 1979, the island’s phosphate deposits which had taken millions of years to form, were completely depleted, leaving a wasteland in the middle of the ocean. (Hoppenhaus 2024, 111–13)


Figure 7. *Nauru: Aerial documentation of the phosphate mine*, John Gollings, n.d., © John Gollings

Following Hoppenhaus (2024, 113), a similar fate awaited the neighbouring island of Nauru. After the First World War, Nauru became a British Mandate territory administrated by Australia. Great Britain, Australia and New Zealand oppressed the island and extracted tonnes of phosphates, especially after the Second World War when the demand for phosphate fertilisers increased and phosphate mining and farming were modernised with machinery. Nauru finally gained independence in 1968 and became one of the richest countries on Earth in terms of per capita income thanks to the trade with phosphate rocks. Nevertheless, by the 1990s, phosphate reserves gradually depleted and the prosperity it had generated collapsed, leaving an island whose natural resources and livelihoods had been largely destroyed. (Hoppenhaus 2024, 105–14)

The exploitation of the Guano Islands in front of Peru, the usage of bones from great battlefields, and the violent destruction of the islands Banaba and Nauru in the context of the agricultural evolution are all expressions of a Cartesian, extractivist ontology. This mindset is violent against nature and other societies until today, which becomes apparent in the occupied Western Sahara, and has infiltrated almost every human interaction with phosphorus. To understand how we can change our relationship with phosphorus so that it can once again become a life-giving substance, we must follow the element into the fascinating realm of soil and observe all its interactions, which we are dependent on.

5.2 SOIL AND DIVERSE INTERACTIONS

A Neglected Scarce Resource

In 2024, the Heinrich-Böll Foundation Germany, TMG – Think Tank for Sustainability and the German Federation for the Environment and Nature Conservation dedicated an entire issue to the subject of soil: The *Soil Atlas*. The board of the three institutions (2024, 6–7) argues that soils are the basis of our existence, yet they are rarely the focus of social and political debate. Fertile land is a limited resource, and as the population is continuously growing, on average, less fertile land is available per person. More soils are covered by traffic and settlement areas so that they can no longer absorb water or breathe, and biodiversity in the soil is declining. Industrial agriculture since the 1950s, including monocultures, one-sided fertilisation and the use of pesticides, also damages soil life and results in the loss of fertile soils and biodiversity (Heinrich-Böll-Stiftung 2024, 10). While soil organisms are being harmed and the climate crisis is accelerating, large corporations such as Nutrien and Mosaic are profiting from the overuse of fertilisers. In the seeds and pesticides industry, Syngenta Group, Bayer, Corteva and BASF dominate the global market. Through their lobbying, they exert a strong influence on policy and thus hinder the necessary change. (Heinrich-Böll-Stiftung 2024, 20–21)

According to the Soil Atlas (2024, 8) soils store water and the greenhouse gas carbon dioxide – even more than forests do. They are consequently essential to our survival, especially in the context of climatic transformations in the future. Besides the climate crisis, intensive agriculture is currently degrading soils to the point of desertification. When soils are compressed by heavy machinery, less water can infiltrate. During heavy rainfall, this can lead to localised floodings, that became more tangible as well in Austria and Germany over the past years. With the climate crisis, heavy rainfalls and flooding will become more common in the future. Healthy soils can at least mitigate the effects of these extreme weather events. Therefore, soil protection is needed immediately. Every single interference with the soil changes the structure and function of the natural soil-plant systems we are dependent on. (Heinrich-Böll-Stiftung 2024, 12–13) Agricultural practices and the application of phosphorus into the soil are influencing these systems: To what extent is the addition of phosphorus to the soil a critical factor in soil fertility? How can phosphorus be added to the soil sustainably?

Rhizosphere Interactions

Soil is no homogenous mass, but a network of particles, both mineral and organic, and pores filled with gases and water, in which a wide variety of substances can be dissolved, depending on the environment (Hoppenhaus 2024, 220). Soils are home to at least a quarter of all living organisms on Earth; and the interactions between plants and fungi, animals and microorganisms such as protozoa, bacteria and archaea have evolved over hundreds of millions of years (Heinrich-Böll-Stiftung 2024, 10).

Hereby, fungi are a particularly important part of the soil landscape. Their hyphae spread kilometres through the soil, collecting and decomposing nutrients and other substances (Hoppenhaus 2024, 221). Hoppenhaus (2024, 221) explains that fungi receive their energy not directly from the sun or the air, but from the decomposition of other dead organisms and from a cooperation with plants, called *Mykorrhiza* (deriving from the Greek words *mykes* = fungi; *rhiza* = root). Soil fungi attach themselves to the plants' fine root hairs. This enables them to access the sugars and other energy-rich carbon compounds, produced by the plants through photosynthesis and transported to their root systems. The plants, in turn, use the fungi's extensive network of hyphae to access water and nutrients they could never reach on their own: Some plants get up to 80% of their nitrogen and up to 100% of their phosphorus from the fungal filaments, the so-called *mycelium*. Until today, almost 80% of all terrestrial plant species live in close symbiosis with different Mycorrhizae-fungi. (Hoppenhaus 2024, 221–22; Wang and Shen 2019, 38)

But fungi do not only redistribute nutrients in the soil. They also ensure that certain nutrients are present in the soil in sufficient quantities, argues Hoppenhaus (2024, 225). For this purpose, they cooperate with one or multiple photosynthesis-practicing organisms. One of the best-known symbioses is lichens – a partnership between fungi and microscopic algae or bacteria. Often all three live together in a tiny, tightly knit ecosystem and form. Unlike mycorrhizae, they form a new entity with new characteristics: Lichens e.g. can survive on bare rock, which, depending on the type of rock, is an important nutrient and phosphorus depository in the Earth system. As part of the rock and phosphorus cycle, it takes millions of years until weathering brings the valuable substances back to the surface. Lichens, on the other hand, eat rock, according to Hoppenhaus. Their long hyphae penetrate every fissure and crevice in the rock, dissolving the hard rock with sharp acids and absorbing nutrients such as phosphorus. The author clarifies that lichens seem small and invisible, yet they cover 8% of the Earth's surface. They are not only growing on rocks but on the floor of forests and trees, in dry valleys of the Antarctic, in deserts and mountains, and on asphalt and concrete. Hoppenhaus states that lichens are a major contributor to weathering, and where they live and die they form the first layer of soil in which other organisms can take root. (Hoppenhaus 2024, 225–26)


Figure 8. *Lichen-covered tree, Tresco, Isles of Scilly, UK*, Michael Maggs, 2007, © MichaelMaggs/WikiCommons CC BY-SA 3.0

Hoppenhaus (2024, 226) summarises that the nutrient supply of soil life, and therefore of all of us – since almost all food has its origin in the soil – depends crucially on these old cooperations of mycorrhizae and lichens. Fungi and bacteria, together with plants, their roots and the myriads of other soil organisms, form one of the most complex food webs on the planet (Hoppenhaus 2024, 226). This web, defined by interactions between plants, soil and microorganisms that collectively control nutrient transformations and plant uptake, is called the *rhizosphere* or *root-soil interface* and is of great importance in the management of phosphorus-based fertilisers (Wang and Shen 2019, 36).

Wang and Shen (2019, 36) describe the rhizosphere as a wide, interactive dynamic zone that is defined and influenced by various physical, chemical, and biological processes. According to Hoppenhaus (2024, 226–27) the rhizosphere forms one of the most efficient recycling systems: Nutrients never get lost; they are passed from one organism to another through excretion, death and decomposition, and are reused until they leave the soil with the water into the sea. There they are again used by organisms that die, sink to the seafloor and decompose, returning the nutrients back to the ground. Biomass productivity of ecosystems is therefore highly dependent on these internal nutrient recycling systems. If ecosystems do not produce enough biomass, there will be significantly less life not only above ground but also in the soil. Less carbon dioxide can be absorbed from the atmosphere, and less humus in the soil can store water. Reduced productivity of ecosystems due to the wrong amount of phosphorus thus has far-reaching consequences. Hoppenhaus considers these natural recycling systems to be one of the core functions that maintain balance within the Earth system. (Hoppenhaus 2024, 226–27)

Testing Soils and Plants

Wang and Sheng (2019, 36) argue that understanding rhizosphere processes can "optimize plant root-soil-microbial interactions and achieve sustainable, positive effects" in phosphorus management as part of farming practices. Monocultures and the usage of mineral fertilisers and pesticides in industrialised agriculture damage and reduce diverse soil life, interrupting symbiotic interactions between plants, fungi and other microorganisms that are the basis of all botanic life and our food. In regards of a correct phosphorus application that sustains rhizosphere interactions and soil fertility, it is crucial to investigate the availability of phosphorus in the soil, which varies regionally, and to analyse the planted crops in relation to each other.

According to Kovar and Cantarella (2019, 13) soil tests provide an index of plant-available phosphorus in the soil and show how much phosphorus should be additionally applied. Meanwhile, plant tests allow conclusions to be drawn about the "P concentration in a specific part of the plant […] at a specific growth stage" correlating with the ultimate "growth or yield of the plant" (Kovar and Cantarella 2019, 13). This analysis helps to assess a phosphorus deficiency or sufficiency in the plant. Plant-available phosphorus soil tests in correlation with an analysis of the mechanisms of phosphorus uptake by plants are complex but crucial to define the amount of phosphorus fertiliser applied to the field. Otherwise, if only a fixed amount of phosphorus is applied to the field, crop yields can be below their potential, which impacts the economic return and results in unnecessary phosphorus application. (Kovar and Cantarella 2019, 13–15)

Phosphorus must further be applied "in the right place at the soil root interface" (Mezeli et al. 2019, 22). Hereby, site-specific soil and rhizosphere management practices are of great importance. Classic tillage tasks aim to loosen the soil to create an optimum seedbed for reliable germination of the crop plants and an ideal root zone for unhindered root growth (Uppenkamp 2023, 33). According to the Soil Atlas (2024, 40), an alternative to tillage with ploughs and heavy farm machinery is reduced tillage, which involves minimal or no soil disturbance at all. This strengthens the soil structure, protects against compaction and erosion, and increases the humus and carbon content of the soil (Heinrich-Böll-Stiftung 2024, 40).

Rhizosphere management strategies based on a good comprehension of rhizosphere interactions further "improve nutrient use efficiency and crop productivity in farming systems" (Wang and Shen 2019, 36). This means to manipulate different components of the rhizosphere ecosystem in order to enhance its processes and organism interactions, e.g. through an increased nutrient supply. Positive effects can be suppressed by applying too little or too much phosphorus, and are again closely related to the crop growth stage (Wang and Shen 2019, 36–37). One rhizosphere management strategy e.g. is to improve “the uptake of immobile nutrients” by using “mycorrhizal fungi and other beneficial microorganisms” like phosphorus-solubilising bacteria (Wang and Shen 2019, 37).

Other strategies to intensify root synergies are crop rotation and intercropping strategies, which intend to ensure an even humus balance and a fertile, healthy soil structure with high biological activity and productivity (Balgheim and Käufler 2023, 17). Crop rotations as they were already practised in the earlier days of agriculture enable integrated crop protection and promote biodiversity (Balgheim and Käufler 2023, 17). In contrast, monoculture systems as part of industrial agriculture cannot reach sustainable soil management through nutrient recycling (Crusciol et al. 2019, 43). Following the authors, “both the quantity and quality of crop residues in diversified cropping systems” (Crusciol et al. 2019, 43) are needed to promote effective nutrient recycling and an increase of organic matter in the soil. The concentration of phosphorus in the crop residue that is decomposed is a key factor for the mineralisation of phosphorus, which promotes microbial diversity and positively affects both phosphorus availability in the soil and crop growth. One example is palisade grass increasing the yield of soybean, white oat and maise; other phosphorus-mobilising species are chickpea and faba bean, intercropping wheat and maise. (Crusciol et al. 2019, 43–45) Cultivating legumes such as peas, field beans, lupins or soybeans also creates root symbioses with nitrogen-fixing bacteria, so that no additional nitrogen fertiliser is needed (Heinrich-Böll-Stiftung 2024, 41). Plants can store even more nitrogen in the soil than they need, benefiting subsequent crops and reducing the need for synthetic fertilisers[12] (Heinrich-Böll-Stiftung 2024, 41).

Sustainable Phosphorus Management

In summary, Peterson and Bruulsema (2019, 54–56) define the *4R Nutrient Stewardship* framework as a means of achieving sustainable phosphorus management. Phosphorus application practices “ensure that the right nutrient source is applied at the right rate, at the right time, and in the right place” (Peterson and Bruulsema 2019, 54). The term *right* aims to involve economic, social, and environmental interests such as “farm productivity, P use efficiency, improved water quality, or maintaining optimum soil test levels” (Peterson and Bruulsema 2019, 54). The right source is dependent on the nutrient content, the solubility and

[12] Once again, it becomes clear that successful yields depend not only on phosphorus but also on nitrogen and potassium. According to the law of the minimum, yield is determined by the nutrient present in the smallest amount. Sustainable agriculture must therefore adopt diverse and systemic approaches based on the interactions between plants, animals and soil in order to naturally promote a good nutrient supply. It is beyond the scope of this work to analyse the history and practices focusing on nitrogen and potassium. However, it should not be forgotten that both nutrients are also of great importance to agriculture and the food system. Both open up similarly large areas of research that are worthy of investigation.

its availability at the local scale. Selecting the right source then further involves considering "the rate, time and placement of the P application" (Peterson and Bruulsema 2019, 54). The right rate is in turn dependent on what the specific plant needs and on tests assessing the soil nutrient supply. Timewise, it is important to analyse if the soil is frozen and to consider the plant's needs in relation to the season and its nutrient uptake patterns. Finally, phosphorus fertilisers should be placed close to the roots, as this increases the phosphorus availability to the plant. Also, the seed placement is of great importance. The authors describe cropping systems as dynamic and highly dependent on geological, climatic and hydrologic local factors. Therefore, site-specific information is crucial to define 4R practices together with "agricultural scientists and stakeholders" that are aware of "local farm-based implementation to ensure that the practices are both efficient and economically feasible" (Peterson and Bruulsema 2019, 56). As a holistic approach, sustainable phosphorus management thus needs to investigate various site-specific factors and must develop accordingly to new resources and tools. (Peterson and Bruulsema 2019, 55–56)

Similar to the 4R Nutrient Stewardship approach, Flaten et al. (2019, 33–35) introduce so-called *nutrient management conservation practices (CPs).* These practices aim to treat environmental health like human health, by determining the right phosphorus dosage through the procedure of triage, diagnosis and treatment with a cure in order to reduce phosphorus runoff from agricultural land to surface waters. The authors argue that, similar to medical treatments in human health, the potential benefits, side effects and risks of prescribed substances must be thoroughly and *carefully* evaluated. This includes to holistically "consider the complexity of interactions between various agricultural nutrient, water, and soil management CPs, and their effect on water quality" (Flaten et al. 2019, 34). Nutrient management CPs further involve innovation and adaptation of the systems, facing geographic landscape changes, like varying soil circumstances in different seasons or consequences of climate change as heavy rainfall. For example, no fertiliser or manure should be applied on frozen or snow-covered soil. "Once a diagnosis is completed, the next step is to prescribe the right cure, making sure the 'cure' works for that local situation, then implement the treatment with care and precision." (Flaten et al. 2019, 34–35) When treating with the cure, long term, on-going care needs to be provided to improve environmental health. The authors hereby compare effective nutrient management strategies with healthy diets and regular physical activity, which contribute to long-term human well-being. To reduce phosphorus losses from agricultural land "a sustained effort over a long period" (Flaten et al. 2019, 35) is required to attain sustainable effects.

Flaten et al. (2019) consider phosphorus as a medicine that can harm and cure environmental health. Consequently, their approach can be related to the concept of the *pharmakon*, whose beneficial or harmful effects depend on an understanding of the substance and the specific organism or system to which it is applied. Phosphorus can be used to enhance rhizosphere interactions and crop productivity in sustainable farming systems instead of overapplying it to the soil. Rhizosphere and sustainable phosphorus management practices therefore offer possibilities to take care of phosphorus, enabling it to complete its life-sustaining cycle and heal entire ecosystems.[13]

A practical example of how to determine the right dosage and ensure a sustainable phosphorus management is a fertiliser app that helps farmers apply the right amount of nutrients to their fields. This so-called *Gülle.App* (2025) by the Austrian liquid manure tank producer Vakutec can be used to determine the amount of nutrients per hectare, depending on the type of manure, the manure tanker and its volume, the speed of the transport vehicle and the un/evenness of the terrain where the fertiliser is to be applied. In GPS mode, the amount of nutrients applied to the field can be even monitored live (Vakutec Gülletechnik GmbH 2025). The Gülle.App thus involves site-specificity, source type and rate, time and placement and can be considered as a tool for sustainable phosphorus management. An artificial intelligence-based assistant in the app further answers questions about previous tillage, when to apply the fertiliser based on weather conditions and crop needs and complies with current legal regulations. All in all, the app claims: *It's all in the dosage!*

5.3 MANURE, SLUDGE, AND PHOSPHORUS RECYCLING

Animal Manure

Phosphorus can be applied to the soil in the form of mineral or organic fertilisers. Mineral or synthetic phosphorus fertilisers are *inorganic* fertilisers, including phosphorus contained in salts extracted from e.g. phosphate rock (Hoppenhaus 2024, 287). They are usually manufactured industrially, modified from phosphate rock to ammonium phosphates or superphosphates and applied as granules, powders or liquids. *Organic* fertilisers contain nutrients mainly in the form of organic compounds such as plant parts or animal excrement. These include manure, slurry, digestate from biogas plants, compost or straw (Hoppenhaus 2024, 287). Guano and bone meal are organic fertilisers as well.

Synthetic phosphorus fertilisers deriving from extracted phosphate rocks are cheap and promise economic success in agriculture: "The development of the modern P fertilizer industry has provided farmers with easy and safe access to effective and affordable crop nutrients." (Mikkelsen 2019, 21) However, since phosphorus is a critical raw material and phosphate rock deposits are located only in a few and partly politically unstable or occupied regions in the

[13] Still, one should not forget that soil-improving strategies must be promoted systemically including political regulations and soil protection laws to keep soils healthy and preserve them for future generations (Heinrich-Böll-Stiftung 2024, 7).

world, phosphorus recovery and recycling play an important role in securing future supplies of the resource.

When additional phosphorus needs to be applied to the field, liquid livestock manure and compost are a meaningful alternative to mineral fertilisers. Leytem and Mutegi (2019, 26) argue that "[l]ivestock manures contain significant amounts of the primary nutrients [nitrogen, phosphorus, and potassium], secondary nutrients [such as calcium, magnesium, and sulphur], as well as a wide variety of micronutrients". Consequently, it is an excellent source of recycled nutrients for crop growth and can enhance soil health by supplementing organic carbon, "which can improve soil structure, water holding capacity, and water infiltration" (Leytem and Mutegi 2019, 26). Yet, manure phosphorus is not always used effectively in crop production. Following the authors, reasons for an ineffective attribution of manure phosphorus lie in various aspects: "[U]neven distribution of manure by grazing animals, incomplete collection and inappropriate storage of manure from housed animals, poor timing of manure application, high cost of transportation, and relatively low prices for mineral P fertilizer." (Leytem and Mutegi 2019, 26) As manure is very wet and bulky, it is difficult and expensive to transport and is usually spread close to the livestock farms where it is produced. The authors state that this results in the accumulation of phosphorus in soils around these farms, surpluses on arable land, reduced phosphorus use efficiency and increased phosphorus runoff into surface waters, which can lead to eutrophication. At the same time, there have been "structural shifts of livestock operations from small farms to larger-scale confined operations" (Leytem and Mutegi 2019, 26) in developed countries, resulting in the segregation of livestock and cropping systems and an uneven distribution of manure phosphorus.

According to Leytem and Mutegi (2019, 27), at a local scale, transferring and recycling manure phosphorus is compatible with reducing the use of phosphorus fertiliser, but "as farms grow in size, even local and within farm imbalances can occur due to high transportation costs of manure". At a regional scale, the recycling of manure phosphorus on croplands is also hindered due to high transportation costs. Often the areas with the highest amount of manure phosphorus are not located next to those having the highest phosphorus deficits, resulting in "hotspots of excess manure P" (Leytem and Mutegi 2019, 27). To meet the crop's demand for phosphorus, cheap synthetic fertiliser is used instead. At a global scale, Sub-Saharan Africa, Eastern Europe and South America represent regions experiencing extremes of high phosphorus deficits. (Leytem and Mutegi 2019, 27–28)

Leytem and Mutegi (2019, 28) consider livestock manure as a valuable global reservoir of reusable phosphorus, holding "the most conspicuous potential for mineral fertilizer substitution". Yet, efficient recycling of manure phosphorus is hindered by the difficulties of cost-intensive manure distribution. The authors argue that political regulations, economic subsidies and technical solutions are essential to facilitate the redistribution of livestock manure phosphorus from surplus to deficit areas. The effective recycling of manure-derived phosphorus across local, regional and global levels, is imperative for sustaining food security in the future. (Leytem and Mutegi 2019, 28)

Composting

Next to livestock manure, bio-based fertilisers deriving from sources such as composted organic waste, vermicompost or fermentation products, mulch and plant residues are becoming increasingly important in agriculture (Heinrich-Böll-Stiftung 2024, 41). They contain high levels of nitrogen, phosphorus and potassium available to plants and can provide the soil with important bacteria and fungi.[14] In the Soil Atlas (2024, 41) it is stated that there is an enormous potential for organic waste: The European Union generated around 86 million tonnes of biowaste in 2017.

One local composting plant is Wienerwaldkompost in Rappoltenkirchen nearby Vienna. The agricultural composting association was founded in 1992 by two farmers. Nowadays, the composting plant covers almost 11.000m² (Deckardt and Kienberger 2018). The two founders Stephan Deckardt and Bernhard Kienberger (2018) as well as the Umweltbundesamt Germany (2020) define composting, also known as *rotting*, as follows:

> "[…] Composting describes the part of the nutrient cycle in which organic material is broken down by soil organisms (heterotrophic) under the influence of atmospheric oxygen (aerobic). In addition to carbon dioxide, water-soluble minerals such as nitrates, ammonium salts, phosphates, potassium and magnesium compounds, which act as fertilizers, are emitted." (Umweltbundesamt 2020, 143)

Deckardt and Kienberger (2018) further explain that the term *compost* derives from Latin, meaning *the assembled*, and thus refers to the *collection site* or *compost hea*p, where organic materials and waste are deposited. The final product, the finished compost, is produced by the rotting process. Hereby, the source materials for the compost heap are critical to achieving a high-quality end compost. Before the active composting process can begin, these source materials must be mixed in a balanced manner. According to Deckardt and Kienberger it is important to ensure that the compost heap contains sufficient structural material, such as shrub cuttings and straw. These are mixed with smaller materials like waste from the organic waste bin. Here, Wienerwaldkompost processes biogenic waste from the district of Tulln and some

[14] In the *compost care sessions* of *Klasse für Alle*, „a program of continuing education, created by the University of Applied Arts Vienna" (Lumplecker 2025), people are learning, together with Sigrid Gerl from Kleine Stadtfarm and Andrea Lumplecker from Angewandte, how to create and take care of a compost heap in the garden of the main building of Angewandte. In April 2025, we have built a new raised vegetable bed and layered the dark, fresh compost soil full of nutrients, made from organic waste over the last six months, on top of foliage, branches and more organic waste. This was layered with universal soil, containing fewer nutrients, which forces the plants to grow their roots to access the nutrients in one of the lower layers. This again enhances soil health and maintains the natural balance of the nutrient cycle.

neighbouring municipalities. Furthermore, the compost heap must have the right water content – not too wet and not too dry. Microorganisms need oxygen to be able to transform organic matter. Therefore, the compost heap must be turned regularly: For the first weeks up to twice a week. This process aims to raise the temperature in the heap to almost 70 degrees Celsius. Then, unwanted weed seeds, slug eggs and pathogens die off. This process is called *sanitising*. Temperature, moisture and oxygen levels are constantly monitored throughout the process. After about 14 weeks, the compost is ready for screening. This is where the final impurities are removed. The compost is then stored for a further 4-8 weeks to *mature* and is then ready to be used as fertiliser. (Deckardt and Kienberger 2018)

Human Faeces and Complicated Regulations

As humans are part of the phosphorus cycle as well, their faeces have become an important source of phosphorus recovery in recent years. Human excrement as a phosphorus source is currently lost through advanced sewage systems in most industrialised countries; thus, humans are disrupting the natural recycling system of the element. To close its cycle, it is necessary to find ways not to lose phosphorus into wastewater and sewage sludge via the food chain (Kopp-Assenmacher 2025, 3–4).

In an effort to mitigate existing supply risks with phosphate rocks, Switzerland, Germany and Austria have been working to implement effective phosphorus recycling through municipal sewage sludge and animal by-products such as meat and bone meal for a few years. In May 2024, Austria was – after Switzerland and Germany – the third country in Europe to introduce the recovery of phosphorus from sewage sludge as a legal requirement: From January 2033, 80% of the phosphorus contained in sewage sludge must be recovered from its incineration ash (Bundeskanzleramt der Republik Österreich 2024, 16). Already in 2016, Switzerland decided to recover phosphorus from sewage sludge ash and animal bone meal from January 2026 (Plattform SwissPhosphor and Bundesamt für Umwelt 2023). Germany enacted the regulation one year later for January 2029 (Bundesministerium der Justiz Deutschland 2017, 3505). Yet, due to fertiliser regulations in each of the countries, human faeces from municipal sewage sludge can so far only be used for research purposes and not as fertilisers in agriculture. Reasons for this lie in the origin and composition of sewage sludges and the different technical processes for waste treatment and phosphorus recovery, states the lawyer Stefan Kopp-Assenmacher (2025, 4). The majority of waste used for phosphorus recovery derives from municipal wastewater treatment plants. This waste contains a high concentration of organic substances, as well as pollutants such as pathogens, medical residues and hormones. A much smaller proportion originates from industrial wastewater, which can contain a wide variety of contaminants and have a wide variety of compositions. Up to today, this complicates the process of defining and drafting the legal framework. (Kopp-

Assenmacher 2025, 4) Moreover, the regulation of phosphorus recyclates is subject to various legal frameworks, including those on waste, chemicals and products, complicating the transition from waste to product status (Projektträger Karlsruhe 2025).

The European Fertiliser Regulation provides clear criteria for the approval as fertiliser in agriculture, states Projektträger Karlsruhe (PTKA) of the Institute for Technology in Karlsruhe (2025): A recycled phosphorus product must fulfil certain quality standards and be regulated following the European Regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH). Further, a so-called *EU declaration of conformity* is needed to prove that the product fulfils the legal requirements of European directives. When a phosphorus recyclate receives status as a CE-marked product, meeting EU safety, health, and environmental requirements, it may be distributed as fertiliser throughout Europe. (Projektträger Karlsruhe 2025) In order to create a consistent legal framework on national and European levels, experts demand a more specified end-of-waste regulation for phosphorus recyclates (Projektträger Karlsruhe 2025). Following a set of rules and criteria, materials or substances can lose their waste status (European Commission Joint Research Centre 2023). Farmers and companies such as those in the chemical, pharmaceutical and food industries, must be able to rely on the safety and efficacy of recycled phosphorus. Furthermore, experts demand that national fertiliser regulations must be more aligned with the EU fertiliser regulation, to simplify procedures in this area (Projektträger Karlsruhe 2025).

Sewage Sludge Gold

In addition to the establishment of a more coherent legal framework, the development of a resource-efficient circular economy requires innovative, sustainable and economical solutions for phosphorus recycling. In Austria, the municipal department MA48 and Wien Energie are working together to recover the phosphorus contained in Vienna's sewage sludge (Zlamal 2022). The current draft of the Federal Waste Management Plan 2022 along with the Waste Incineration Regulation passed in 2024, finally allows for the implementation of the thermal treatment of municipal sewage sludge and the recovery of phosphorus from incineration ash, states Jürgen Czernohorszky, executive councillor for Climate and Environment in Vienna (Meyrath 2024). As part of Vienna's pioneering recycling project, a new drying plant for sewage sludge was officially opened near the *ebswien* sewage treatment plant in Simmering in November 2024 (Pramer 2024). Wien Energie (2025) describes that in a thermic procedure, sewage sludge as the final product of wastewater treatment, is first drained and dehydrated. Subsequently, the dried sewage sludge gets incinerated – a process in which pollutants are removed. The final product is sewage sludge ash, from which phosphorus can be extracted. (Wien Energie GmbH 2025)

Due to the non-existent legal framework on the recycling of phosphorus, this final step of phosphorus recycling from the ash cannot yet be completed; only about ten percent of the ash can be used directly in the industry, the rest is deposited in landfills (Pramer 2024). With a phosphorus recovery plant – which is planned to be built in a few years – new and cheaper technologies and a more specific legal framework, the Viennese and Lower Austrian demand for phosphorus in food production could be covered (Wien Energie GmbH 2025).

Figure 9. *Recycling of sewage sludge at the waste incineration plant in Simmering, Vienna*, Wien Energie GmbH, 2025, © Wien Energie GmbH

With these new measures of Wien Energie, the City of Vienna considers itself a pioneer in phosphorus recovery from sewage sludge ash, explains Czernohorszky (Zlamal 2022). In the summer of 2022, Vienna also hosted the European Sustainable Phosphorus Platform

Conference, where MA48 and Wien Energie together with Borealis Agrolinz Melamine GmbH[15] presented their future plans in the field of phosphorus recovery (Zlamal 2022). Nevertheless, it remains unclear how these plans will be implemented and what possible negative consequences they might entail. It is certain that these plants and technologies are very expensive and still quite energy intensive. So far, the cost of recycled phosphorus is three to five times higher than that of imported phosphate rock (Pramer 2024).

Composting Contaminated Human Faeces?

In the past, human excrement was already traditionally used as so-called *night soil* in China and Japan until the 20th century, explains Hoppenhaus (2024, 30–31). In Europe, too, nutrient-rich wastewater was applied to so-called *sewage fields* in the periphery of cities, used for agricultural purposes. However, by the early 20th century, the soil was no longer able to absorb the increasing amounts of wastewater and yields began to decline. Later, when wastewater was collected and treated in centralised sewage sludge treatment plants, the processed sludge was still used as fertiliser – for at least as long as the pollutant concentrations allowed it to do so. Even today, sewage sludge is still used as a fertiliser in some rural areas, but it gets usually incinerated. (Hoppenhaus 2024, 244–45)

In the final report of the Umweltbundesamt Austria on a circular economy in the waste sector, Friesl-Hanl et al. (2022) focus on the possibilities of sewage sludge compost as an alternative to energy-intensive sewage sludge ash. Sewage sludge compost is produced when organic biowaste is composted together with sewage sludge. In this context, organic pollutants as e.g. Bisphenol A[16], in sewage sludge play an important role, as they can be found in the soil after the application of sewage sludge compost. Furthermore, soil contamination with heavy metals is of significant concern. (Friesl-Hanl et al. 2022, 6)

Based on an extensive study of the particular pollutants in sewage sludge compost and their input into agricultural soils, Friesl-Hanl et al. (2022, 91) conclude that the application of sewage sludge compost results in a "significant transfer of pollutants, including POPs [persistent organic pollutants], to soils". To mitigate the accumulation of pollutants in sewage sludge, the authors of the report emphasise that first of all, it is important to prevent inputs into the wastewater system. Possible measures include "bans on the production or use of certain substances, […] guidelines in the field of waste water treatment and sewage plants (e.g. forced degradation, filtering), and changes in behaviour, for example regarding the use of chemicals and detergents" (Friesl-Hanl et al. 2022, 92). Moreover, there is a need to develop specific treatment technologies to reduce persistent organic pollutants and endocrine-disrupting

[15] Borealis Agrolinz Melamine GmbH and LINZER AGRO TRADE GmbH have a leading role in the plant nutrient market in Central Europe (Borealis AG 2025).
[16] Bisphenol A is a source material for the synthesis of and as an additive in plastic materials. It has hormone-altering, nerve-damaging and carcinogenic effects, and can cause food intolerances (Menard et al. 2014).

substances, that can disrupt the hormonal system of animals and humans, as well as microplastics present in wastewater, sewage sludge and sewage sludge compost. These so-called persistent organic pollutants are highly toxic and threaten human and environmental health. (Friesl-Hanl et al. 2022, 87–92)

This increased health risk from pathogens, heavy metals, microplastics and drug residues depicts the main reason for banning human faeces so far as fertiliser in comparison to animal manures.[17] In addition, human excrements are considered unclean or unhygienic in many cultures. Therefore, the project *nurec4org* promoted by the Deutsche Bundesstiftung Umwelt, aims to participatively define acceptance criteria for phosphorus recyclates in organic agriculture. These criteria include legal framework conditions, utilisation efficiency and impact, product quality and absence of harmful substances, resource/energy consumptions and emissions, price and costs, as well as transparency (Kraus, Zamzow, and Hoffmann 2019). In general, the project aims to provide farmers and consumers with more knowledge to simplify phosphorus struvite authorisations required in the EU regulation on organic products, and regional approaches to regional cycles (Kraus, Zamzow, and Hoffmann 2019).

In November 2024, a research team from Humboldt University Berlin (HU) provided new data, based on a three-year series of tests with human faeces fertilisers, for adjusting the national fertiliser regulation (Holzamer 2025). Maise plants were fertilised using compost derived from human excrement and a liquid fertiliser produced from human urine (Boness and Kautz 2025). The source material originated from dry toilets[18] which “were heated in a container for seven days and then composted to kill pathogens” (Boness and Kautz 2025). The researchers Boness, Kautz and Hoffmann-Bahnsen (2024) state that, the compost derived from human faeces proved to be an efficient source of phosphorus. The application of this compost resulted in a significant increase in the concentration of soluble phosphorus in the soil, as well as ielevated phosphorus levels in the plants. Yet, in this case as well, the next step of research is the investigation and evaluation of possible soil contamination and climate impacts of this new fertiliser. (Boness and Kautz 2025; Boness, Kautz, and Hoffmann-Bahnsen 2024)

Ongoing Research

As new technologies and guidelines are urgently needed in order to process human faeces into usable *clean* fertilisers, many research projects are currently being funded in

[17] Animal manure also contains pathogens or drug residues e.g. from livestock farming but is subject to strict requirements.
[18] In Vienna’s public space, composting toilets from öKlo can be found in many parks and squares. The Austrian company öKlo sells and rents composting toilets in Austria and Germany. Barbara Forstner (2022) from öKlo explains that human faeces can be used for heating, electricity generation, and to produce building materials or biogas. Together with BOKU University Vienna they have been able to prove that it is safe to reuse human faeces for composting with modern technology. However, the Austrian compost and fertiliser regulations have so far prohibited the use of humus from dry separation toilets in agriculture. Following the law, the application of human excrement is not yet permitted for commercial use while on the other hand, animal manure can legally be spread on agricultural land as fertiliser. (Forstner 2022)

Germany, Austria and the EU. In this context, the Bundesministerium für Bildung und Forschung Germany (BMBF) has e.g. started the measure *Regional Phosphor-Recycling* (RePhoR) in 2018, as part of the BMBF-strategy *Forschung für Nachhaltigkeit* (FONA). The aim is to develop innovative, economical and sustainable solutions for phosphorus recycling. To accomplish these objectives, BMBF (2023) has funded seven collaborative projects since 2020. Some of them are researching various phosphorus recovery processes from wastewater, sewage sludge or sewage sludge ash, implemented in industrial-scale settings. Several other projects are investigating more holistic approaches to the question of how to reintroduce recycled phosphorus into the nutrient cycle through agriculture or as a raw material in industry. (Bundesministerium für Bildung und Forschung 2023)

Another joint research project funded by BMBF Germany is *SUSKULT*, coordinated by the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT: 15 partner institutions from research and practice develop an innovative food production system based on a cultivation method called *hydroponics*. Plants grow and thrive indoors without soil but using mineral solutions (Fraunhofer UMSICHT 2025). Following the project description, this system enables precise control of water usage and nutrient supply to crops (Fraunhofer UMSICHT 2025). The necessary resources – carbon dioxide, phosphorus, potassium and nitrogen – as well as heat and water are derived from a sewage sludge treatment plant (Fraunhofer UMSICHT 2025).

Human faeces are full of phosphorus but currently get lost due to their contamination with pathogens or drug residues. Wastewater treatment plants or drying plants for sewage sludge, such as the one in Simmering, are therefore long-term investments. However, critics of the new recycling programme point out that some of the recovery processes are very energy-intensive, especially the transport and production of necessary chemicals (Hoppenhaus 2024, 246). In the long-term, it is thus considered to change the whole sanitation system from a mixing system to a separating one. According to Hoppenhaus (2024, 246–47), the recovery of nutrients from human faeces then is supposed to be more efficient and technically more feasible.

At present, there is a significant number of funded research projects underway that are investigating solutions and new technologies to reintroduce phosphorus back into the cycle. Ongoing research therefore promises many different possibilities in the form of new technologies for phosphorus recycling aiming to ensure humanity's independence from finite phosphate rock deposits. Consequently, phosphorus recycling becomes a technological response to the finite nature of natural resources. These technologies enable us to close the broken cycle, yet they do not prevent us from applying too much of the element somewhere else.

Despite the widely acknowledged and harmful consequences of nutrient surpluses, worldwide, the trade and application of phosphate rock in mineral fertilisers has even increased (Hoppenhaus 2024, 247). Sustainable nutrient management is hence not merely a scientific and technical challenge, but also a social and political one, states Hoppenhaus (2024, 248). Without individual decisions by every farmer and every consumer, but also without a renewed economic, legal and political framework, a fundamental change in the agricultural and food systems cannot be achieved (Hoppenhaus 2024, 248–49).

6 HOW TO TAKE CARE OF THE PHARMAKON

Following all these various stories about phosphorus and its pathways through rocks, soil, microorganisms, plants, animals, human beings, water bodies and the ocean ground shows how ecosystems have developed over millions of years and functioned without human beings. By investigating when, where, how, and why humans started to cross and intervene in these pathways, the chemical element phosphorus becomes a manifold example of how humans treat nature as a separate object one could exploit and destroy. Phosphorus carries various fascinating stories about life on Earth but also becomes “a means to narrate the complexities and failures of anthropogenic life” (Neale, Phan, and Addison 2019).

As phosphorus is a pharmakon, it incorporates transformative potential and also has healing and life-giving characteristics. Changing the way we use the element can change our impact on Earth. This work therefore finally asks how to take care of phosphorus as a pharmakon to close its cycle through the Earth system and ensure planetary health.

Transforming Thinking Patterns

As illustrated in Chapter 4.2 “The Evolution of Agriculture and the Cartesian Split”, it is our Western modernist thinking that separates us from nature. Following Durante, Kröger and LaFleur (2021, 24–25), this mindset paved the path for the modern colonial-capitalist era and concepts of dominating nature. This Cartesian ontology has displaced *sacredness-based* understandings of co-existence, reciprocity, nurturing and caring for the Earth (Durante, Kröger, and LaFleur 2021, 24–25). In this context, the misuse of phosphorus as a pharmakon in intensive agriculture is also understood as a consequence of societies’ transformation into modern and industrialised ones. In order to create a Natural Contract after Serres, based on symbiosis, reciprocity and care, we need to understand that we are inextricably interconnected with nature. Findings in the field of biological research have demonstrated many times that it is almost impossible to observe humans and nature separately – no human being can exist in isolation from its living environment (Hoppenhaus 2024, 264). The stories about phosphorus flowing through our bodies make this even more evident, almost tangible.

Pretty (2002, 55) argues that good farming can protect the land, even when using it. Following the author, sustainable farming aims to integrate natural processes such as nutrient cycling, soil regeneration and natural pest control (Pretty 2002, 56). The Committee on Twenty-First Century Systems Agriculture (2010, 1) defines agricultural sustainability by various goals including the satisfaction of human "food, feed, and fibre needs", as well as its contribution to biofuel needs; an enhancement of environmental health and the resource base; sustaining the economic viability of agriculture; and enhancing the quality of the life for farmers, farm workers and society as a whole. Following the committee, a transformation towards sustainable farming systems is increasingly influenced by "external forces, including science, knowledge, skills, markets, public policies, and their own values, resources, and land tenure arrangements" (Committee on Twenty-First Century Systems Agriculture 2010, 2).

Fiala and Freyer (2016, 80) explain that *organic farming* is a form of sustainable agriculture with its own set of rules and a catalogue of practices and approved materials described in binding guidelines. Organic farming has its roots in two historical social movements of the 1920s – a period marked by the rise of industrialised economies and agriculture, which contributed to an increasing alienation of society from nature. Both movements had different worldviews. The first was *biodynamic agriculture*, based on the anthroposophy of the Austrian Rudolf Steiner and outlined in his 1924 agricultural lectures. Secondly, there were *organic-biological farming associations*, based on the works of the Swiss biologist and pedagogue Maria Müller, the agricultural scientist and politician Hans Müller and the German microbiologist Hans-Peter Rusch. The agricultural system known as *natural farming* also has its origin in the 1920s. In principle, these agricultural movements opposed the developments of an industrialising economy and society by emphasising the connections between soil, plants, animals and humans, the need to increase soil fertility, the avoidance of mineral fertilisers and pesticides, and animal welfare. Moreover, they addressed nutritional aspects and the need for social, political and lifestyle changes. Fiala and Freyer further describe how, from the 1960s onwards, the organic farming movement re-emerged as a protest movement against industrial excesses, and as a counter-proposal to the Green Revolution. (Fiala and Freyer 2016, 81)

According to Fiala and Freyer (2016, 81), organic farming is based on worldviews in which phenomena are not isolated from their environment but are understood in their holistic nature by emphasising the hierarchical and horizontal interdependencies with the environment. Consequently, and from an ontological point of view, organic farming is holistic and follows a systemic approach that counteracts a Cartesian, extractivist mindset. The objectives and principles of organic farming are defined by law in the EU Organic Farming Regulation 2018 (Bundesministerium für Ernährung und Landwirtschaft 2024). It promotes network thinking, intercropping systems, closed nutrient cycles, low dependencies on external sources of energy and raw materials, diversity in livestock breeds and crop varieties, and adaption to local conditions by e.g. climate change. It focuses on small-scale mixed cropping and promotes a species-rich landscape. While organic farming represents a certificated framework of practices, *agroecology* is an overarching concept for sustainable agriculture that considers ecological, economic, political and socio-cultural dimensions (Heinrich-Böll-Stiftung 2024, 38–39).

Applying the Agroecological Approach

> „Agroecology is the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic, and social. It's transdisciplinary in that it values all forms of knowledge and experience in food system change. It's participatory in that it requires the involvement of all stakeholders from the farm to the table and everyone in between. It is action-oriented because it confronts the economic and political power structures of the current industrial food system with alternative social structures and policy action. The approach is grounded in ecological thinking where a holistic, systems-level understanding of food system sustainability is required." (Gliessman 2018, 599)

The systemic approach of agroecology aims to fundamentally transform agriculture and the food system. Hereby, it combines conventional agronomic research, focusing on production technologies and productivity, with the scientific study of ecology concerning the spatio-temporal interactions between organisms and their environment (Herzog and Pfiffner 2016, 613). Therefore, agroecology is characterised by its emphasis on organisms within an ecosystem, their relations to one another and organisms in other ecosystems and habitats. This requires thinking beyond the boundaries of the individual fields, including considerations of the farm as a whole and its surrounding landscape (Herzog and Pfiffner 2016, 613). Given the current climate crisis, the ongoing extinction of species and the increasing number of hungry and malnourished people worldwide, agroecology as a systemic approach becomes of great importance as an alternative to energy- and resource-intensive industrial agriculture (Heinrich-Böll-Stiftung 2024, 38).

In order to be sustainable and productive at once, the agroecological practices require an in-depth understanding of agricultural systems and the interactions between plants, animals, and soil. Based on that, they aim to optimise the interactions between crops, livestock, other organisms and environmental factors to ensure stable yields of high-quality food (Heinrich-Böll-Stiftung 2024, 38; Herzog and Pfiffner 2016, 615). As a science, practice and social movement, its objective is to achieve independence from external resources, such as synthetic fertilisers, and instead, to prioritise the cultivation of diverse crops, promote humus formation, and adopt a circular economy model that utilises manure and compost as organic fertilisers (Gliessman 2018, 600; Heinrich-Böll-Stiftung 2024, 38). The Heinrich-Böll Foundation (2024, 38) explains that this strengthens the agroecosystem's resilience to extreme weather, such as heavy rainfall, crop diseases and price instabilities.

In relation to phosphorus, no external sources, such as phosphate rock, should be used to produce mineral fertilisers. Instead, animal manure and compost from organic biowaste are to be used, and crop rotation and intercropping strategies should be promoted to ensure humus formation, rhizosphere interactions and a fertile soil structure. As outlined in Chapter 5.3, human faeces are also to be considered a potential source of phosphorus in the future.

Besides ecological and social considerations, the agroecological approach confronts economic and political power structures as well. The Heinrich-Böll Foundation (2024, 39) distinguishes between different dimensions of agroecological aspects: In the economic dimension, fair marketing methods are to be promoted, in which all those who produce and consume cooperate. Local markets are strengthened, and village communities shall become autonomous by gaining independence from large corporations. Political regulations intend to ensure that local communities control their land and the seeds they plant. By that, decentralised systems are to be established, and legal protection of participation is to be promoted. From an ecological standpoint, the focus lies on the adaptation to the climate crisis by promoting biodiversity, soil protection and fertility. In the socio-cultural dimension, the objective is to widely promote the adoption of a healthy and sustainable diet, as well as to facilitate the exchange of knowledge between farmers. In this context it is important to recognise the value of traditional farming knowledge and to provide enhanced support and empowerment to indigenous peoples and women. (Heinrich-Böll-Stiftung 2024, 39)

Can Sustainable Farming Feed the World?

Agroecology aims to fundamentally change our food systems. From the socio-cultural perspective, it is a healthy and sustainable diet that can provide change. But, as introduced in Chapter 4.1, the current food system is still one of excess and global injustice: On the one hand, too much is eaten and thrown away, while on the other, people are left to starve. The excessive side of over-consumption is based on industrial agriculture, on phosphate mining and neocolonialism, and might be responsible for more land and resource conflicts in the future. Pretty summarises it accurately: „Our daily consumption of food fundamentally affects the landscapes, communities and environments from which it originates.“ (Pretty 2002, xii)

The agroecological approach clearly demonstrates that a transformation in agriculture and the food system must be initiated by various stakeholders. Our eating and waste behaviour, the absence of sufficient legal regulations for phosphorus recycling and soil protection, as well as economic and political dependencies on a few global players controlling scarce resources, currently harm environmental and human health.

Nevertheless, if change is initiated at all these levels of action, can sustainable agriculture feed the world? Muller et al. (2017, 2) state that “by 2050, agricultural output will have to further increase by 50% to feed the projected global population of over 9 billion”. According to the authors, providing enough food while reducing the environmental impacts of intensive agriculture is only possible when food systems are well-designed. Issues related to livestock feed composition, reductions in animal populations, and the consumption of animal-based products, as well as the minimisation of food waste, must be addressed. Therefore, organic agriculture can only succeed when being “based on a comprehensive food systems perspective” (Muller et al. 2017, 6). Changing food consumption patterns, especially by reducing food waste, is crucial to promoting a sustainable agriculture, reducing the usage of resources and mitigating environmental impacts. (Muller et al. 2017, 6) Here again, it becomes evident that a more plant-based diet can help change the way we use land, protecting the climate and environment (Heinrich-Böll-Stiftung 2024, 42). The Planetary Health Diet by the EAT-Lancet Commission (2019) is an example of how a nutritional programme can benefit human health while being in balance with nature.

Findings of the *Farming Systems Trial* (2022), a research programme comparing conventional with organic farming systems conducted by Rodale Institute for more than 40 years, show that “organic farming systems match or outperform conventional production in yield while providing a range of agronomic, economic, and environmental benefits for farmers, consumers, and society“ (Rodale Institute 2025). The survey compared three agricultural systems: a conventional system using synthetic fertilisers; an organic cash grain system relying solely on leguminous cover crops and crop rotation for fertility and pest management; and an organic system utilising composted livestock manure as its primary nutrient source. The data collected shows that organic manure-based systems increase soil health, capture more carbon, result in higher microbial biomass, accelerate water infiltration under long-term organic management, and produce equal or more yields depending on the corn. Finally, the researchers of Rodale Institute (2025) state that „[a]n analysis of the cumulative labor, costs, returns, and risk for the three systems shows that the organic manure system is the most profitable for farmers“. This trial demonstrates that a sustainable farming approach that focuses on closing nutrient cycles by applying animal manure to the land not only preserves biodiversity and environmental, animal and human health, but is also profitable for farmers.

Moreover, the findings of a study conducted by Ricciardi et al. (2021) indicate that the majority of global farms are small farms, which are a focal point of sustainable agriculture. The authors argue that, on average, smaller-scale farms produce higher yields and support a greater biodiversity in crops and non-crops at the farm level and across surrounding landscapes, compared to larger farms. Consequently, supporting smaller farms is important for the preservation of biodiversity and manageable socio-economic structures. (Ricciardi et al. 2021)

Planetary Care

Taking care of the pharmakon means caring for the world we are part of and establishing a symbiotic relationship with our co-environment. This co-environment, or *Mitwelt*[19] is the foundation of our existence, a co-existence with other species. Hoppenhaus (2024, 270) says that a fundamental transformation will not only depend on new scientific insights, knowledge or technologies but very much on the so-called *soft skills* – social skills that have enabled us to live in complex societies throughout evolution. According to the author, the basis of our social skills is empathy, the ability to relate to and connect with others (Hoppenhaus 2024, 270–71).

Stories about phosphorus illustrate how we are physically embedded in and entangled with the planetary. They demonstrate how we influence and how we are influenced. Narrating the life-sustaining currents of phosphorus aims to create fascination for the element. Narrating how we are intervening in its currents and turning the element into a poison aims to show how we are currently destroying ecosystems. Decisions on how we want to take care of phosphorus as the pharmakon in order to care for the planetary will determine how life on Earth continues (Hoppenhaus 2024, 275). The agroecological approach including organic farming, offers a promising possibility for practicing symbiotic and reciprocal relationships with nature. Agroecology connects the ecological, socio-cultural, economic and political spheres. Change is required on every level of action, but collective cooperations and support can already facilitate fundamental transformations.

7 CONCLUSION

Pharmacology analyses the interactions between pharmaka and organisms or biological systems. In order to create an environmentally sustainable pharmacology after Stiegler, this work tried to analyse the interactions between phosphorus as a pharmakon and organisms or biological systems: The application of phosphorus influences soil fertility, rhizosphere interactions and the growing of plants. Through an overdosage of phosphorus in the soil, plants cannot take up all the phosphorus, and through soil erosion and land runoff, phosphorus causes eutrophication. In bodies of water, it nourishes algae and cyanobacteria that form into huge toxic algae blooms covering all aquatic life below and taking the light and oxygen of other

[19] The term *co-environment* refers to the German word *Mitwelt* and aims to overcome dualism and anthropocentrism and to emphasise the relational co-existence of humans, other species and nature. The term is often used by the German political economist, social and environmental scientist and transformation researcher Maja Göpel.

organisms, which they need to live. Bodies of water turn into dead zones, and human beings living close to these waterways become health endangered. As the dosage makes the poison, it is crucial to apply phosphorus correctly from the right source, at the right rate, at the right time, and at the right place, to prevent it from land runoff. The wrong dosage harms other organisms, biological systems, and finally, environmental health. The pathways of phosphorus through the planetary illustrate a cyclical system that is of vital importance to all living beings. However, due to human interactions with the system, it is currently out of balance.

The misuse of phosphorus as a pharmakon is closely linked to historical shifts in Western human thought, modern sciences, and agriculture. This metaphor therefore was employed as a tool for reflecting on the Western human impact on the Earth system in the context of the Anthropocene. Combining a cultural scientific and human ecological approach provided a systemic analysis of the interactions between phosphorus, humans, and the environment. Intensive agriculture, over-fertilisation, interruption of the phosphorus cycle, eutrophication, extractivism and exploitation of people and nature, colonialism, and white phosphorus bombs are all examples of our mistreatment of the chemical element phosphorus. Our interactions with the element transform it into a toxic substance, harming the environment. In large quantities and in the wrong place phosphorus brings death. But phosphorus as a pharmakon can still create life. If we learn to step back, adapt to its natural circular flows, and understand how we are dependent on these flows, phosphorus as a pharmakon might become a healing entity again. Although this work is dedicated to a single chemical element, all its content remains anthropocentric. All stories begin with phosphorus but end with the human. They aim to raise awareness of what it means to be human and to reflect on our very specific relationship with phosphorus, which permeates our lives.

Taking care of the pharmakon after Stiegler means recognising the ambivalence of phosphorus as pharmakon by considering its positive and negative impacts on the environment and society. This includes practices of critical thinking, reflecting, understanding, as well as reconnecting and creating mindfully. In relation to Stiegler's concept of the Neganthropocene, as a careful epoch in opposition to the Anthropocene, this work assumes that we first need to critically reflect on and understand our behavioural patterns and impact in the Anthropocene before we can again leave this era. We need to understand our present state of being human, encompassing how we intervene in natural systems, and the toxic harmful behaviour patterns ingrained in the relations that constitute our existence in this world. Based on this understanding, we might then be able to care for the planetary and promote fundamental transformations towards sustainable futures.

Phosphorus is the running thread through all the previously told stories about systems that we have thrown out of balance. Phosphorus flowing through multiple systems allows us to imagine all these complex connections and dependencies, it allows us to imagine how we are part of these flows and systems and how we are currently transforming them so much that nothing can adapt fast enough. Agroecology and organic farming provide systemic answers to all these complex challenges told before. However, what becomes evident: these concepts and practices require a fundamental shift in our thinking and understanding of the world, as well as systemic changes at multiple levels that go far beyond the impact of phosphorus.

8 AN EPILOGUE TO A TRIPTYCH

All the research conducted for this written master's thesis culminated in an artistic work: a three-part triptych bearing the same title, *Phosphorus as Pharmakon*. The visual language of every panel of wood are alchemical cosmograms that aim to show dynamic networks of relationships, temporalities and spatial entanglements on a two-dimensional surface. My drawings are based on cosmograms created around 1500/1600 – a time preceding the Industrial Revolution, the Enlightenment and the rise of modernity. These old compositions reflect a worldview in which microcosm and macrocosm are interwoven and opposites coincide.

Alchemy and pharmacology both comprehend substances as effective and powerful depending on the context, processing, dosage and the relationship to the body. These two sciences and practices offer attempts to engage with the material and metaphorical complexity of phosphorus, its effects and possible transformations. In the form of the triptych, alchemical cosmograms become a visual and conceptual method to narrate the ambivalence of phosphorus in the context of the Anthropocene.

The triptych's wings symbolically open the dualism of good and bad through which Western society – including myself – tends to think and act. They reveal historical shifts in agriculture and Western human thought and imagine possibilities for future transformation. The central panel holds the tension between these opposing forces and aims to unify both sides. As a whole, the triptych embodies the ambivalence of phosphorus as a pharmakon and reflects on our complex relationship with this chemical element. It leaves open the question whether – and how – each of us will choose to take care of phosphorus in order to sustain environmental and human health.

The entire project – encompassing the written thesis and the artistic work – was presented on June 18, 2025. The triptych was exhibited during the Angewandte Festival 2025 in Vienna, from June 25 to 28.

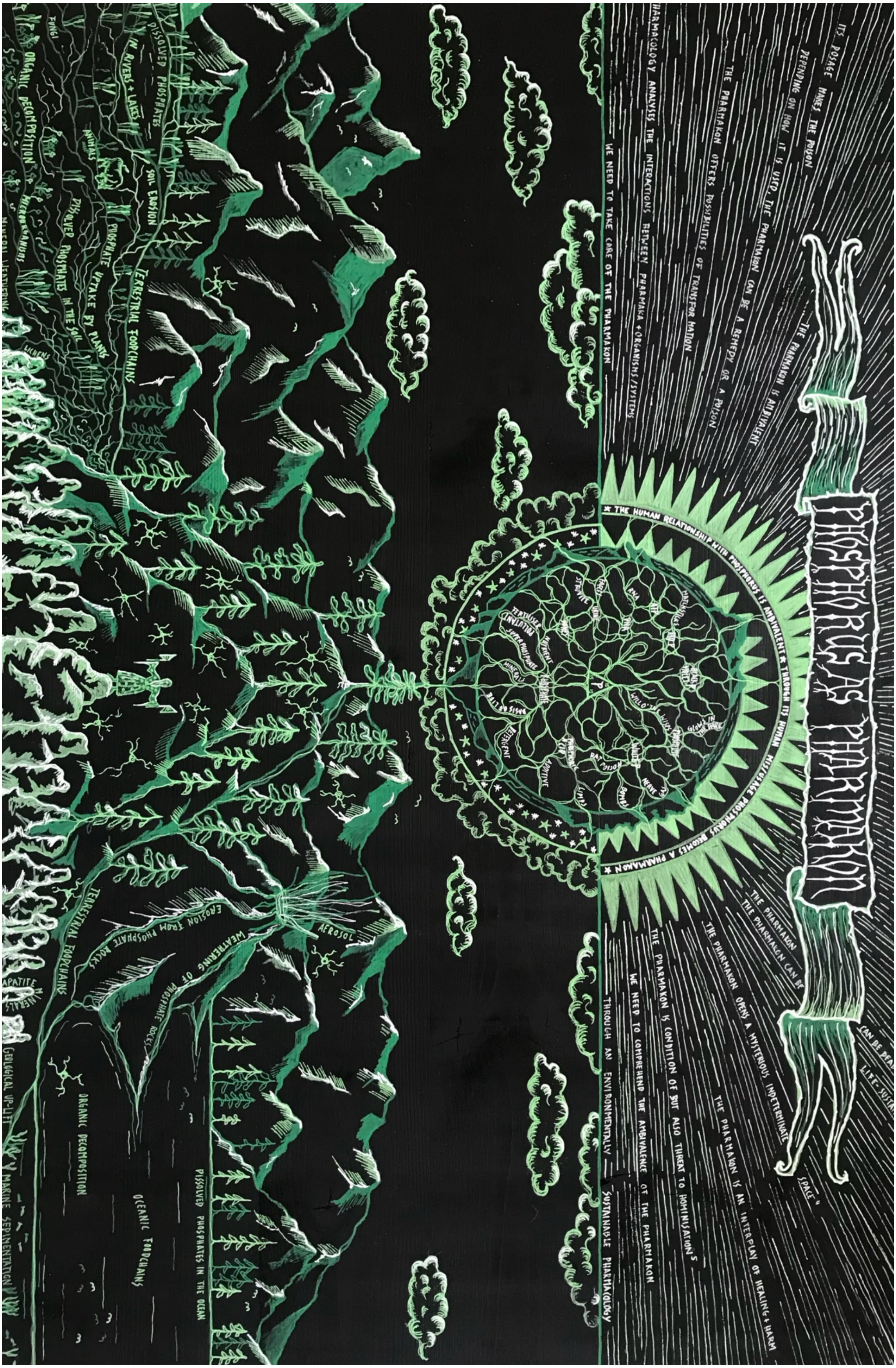

Figure 10. *Phosphorus as Pharmakon*, Paula Bracker, 2025,
Triptych (central panel), Acyclic pens on wood, 94x62cm, © Paula Bracker

Figure 11. *Phosphorus as Pharmakon*, Paula Bracker, 2025,
Triptych (left panel), Acyclic pens on wood, 46x64cm, © Paula Bracker

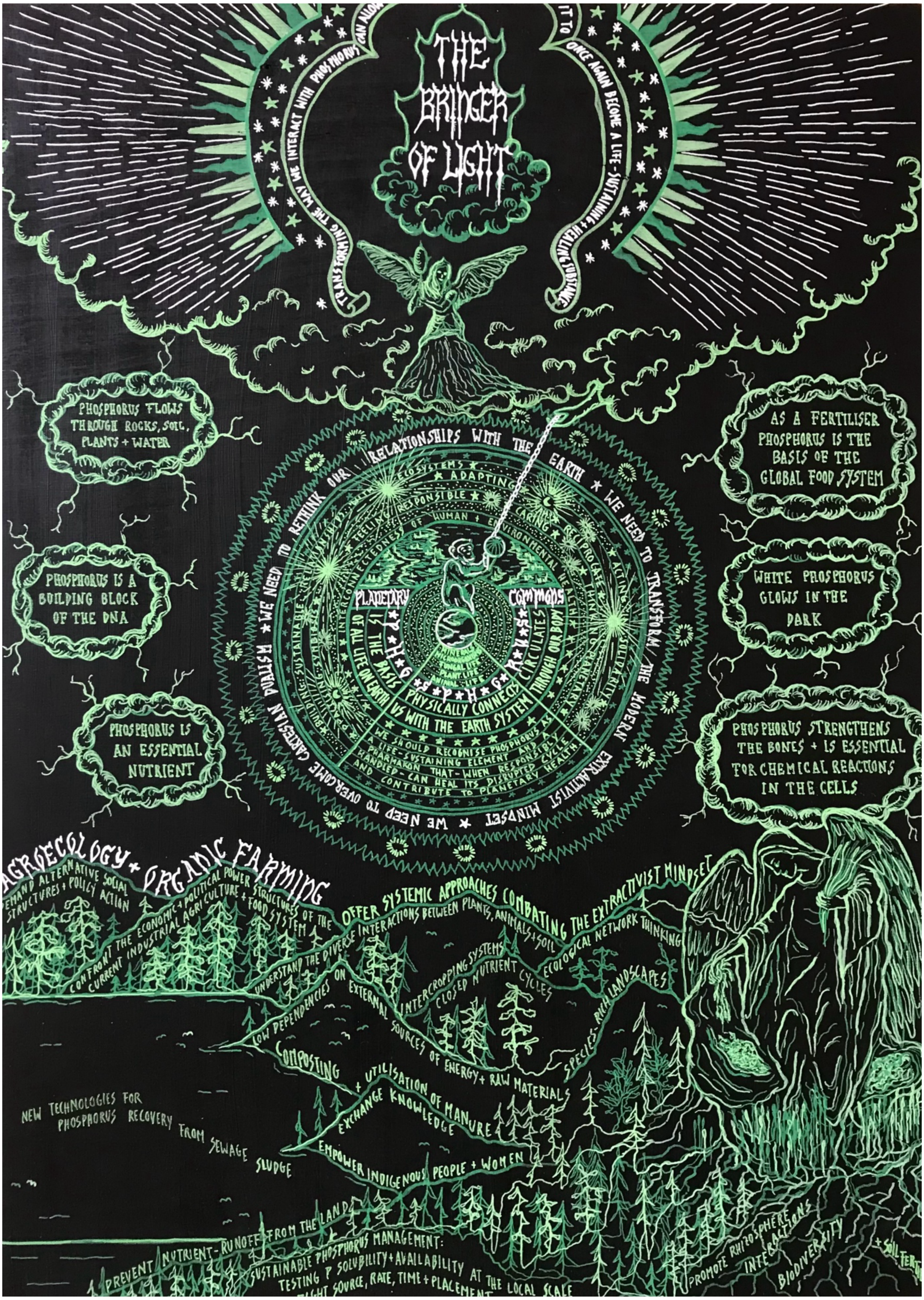

Figure 12. *Phosphorus as Pharmakon*, Paula Bracker, 2025,
Triptych (right panel), Acyclic pens on wood, 46x64cm, © Paula Bracker

9 LIST OF FIGURES

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