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Remineralizing soils?
The agricultural usage of silicate rock powders in the context of One Health

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Philipp Swoboda

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Referent: Prof. Dr. Martin Hamer

Korreferent: Prof. Dr. Thomas F. Döring

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Abstract

The concept of soil health describes the capacity of soil to fulfill essential functions and ecosystem services. Healthy soils are inextricably linked to sustainable agriculture and are crucial for the interconnected health of plants, animals, humans, and their environment ("One Health"). However, soil health is threatened through unprecedented rates of soil degradation. A major form of soil degradation is nutrient depletion, which has been seriously underestimated for potassium (K) and several micronutrients. One way to replenish K and micronutrients are multi-nutrient silicate rock powders (SRPs). Their agronomic suitability has long been questioned due to slow weathering rates, although recent studies found significant soil health improvements and challenge past objections which insufficiently addressed the factorial complexity of the weathering process. Furthermore, environmental co-benefits might arise through their mixture with livestock slurry, which could reduce the slurry's ammonia (NH_3) emissions and improve its biophysicochemical properties. However, neither SRPs effects on soil health, nor the biophysicochemical effects of mixing SRPs with livestock slurry have hitherto been comprehensively analyzed. The overall aim of this dissertation is thus to review the agricultural usage of SRPs in the context of One Health. The first part of this thesis starts with an elaboration of the health concept in general and then explores the interlinkages between soil health and One Health. Subsequently, the potentials and oftentimes bypassed problems of operationalizing soil health will be outlined, and feasible ways for its future usage are proposed. In the second part of the thesis, it is reviewed how and under which circumstances SRPs can ameliorate soil health. This is done by presenting a new framework with the most relevant factors for the usage of SRPs through which several contradictory outcomes of prior studies can be explained. A subsequent analysis of 48 crop trials reveals the potential of SRPs as K and multi-nutrient soil amendment for tropical soils, whereas the benefits for temperate soils are inconclusive. The review revealed various co-benefits that could substantially increase SRPs overall agronomic efficiency. The last part of the thesis reports about the effects of mixing two rock powders with cattle slurry. SRPs significantly increased the slurry´s CH_4 emission rates, whereas the effects on NH_3, CO_2, and N_2O emission rates were mostly insignificant. The rock powders increased the nutrient content of the slurry and altered its microbiology. In conclusion, the concept of soil health must be operationalized in more specific, practical, and context-dependent ways. Particularly in humid tropical environments, SRPs could advance low-cost soil health ameliorations, and its usage could have additional co-benefits regarding One Health. Mixing SRPs with organic materials like livestock slurry could overcome the major obstacle of their low solubility, although the effects on NH_3 and greenhouse gas emissions must be further evaluated.

Zusammenfassung

Das Konzept der Bodengesundheit beschreibt die Fähigkeit des Bodens, essentielle Funktionen und Ökosystemdienstleistungen zu erbringen. Gesunde Böden sind sowohl für eine nachhaltige Landwirtschaft als auch für das Zusammenspiel von Pflanzen-, Tier-, Mensch- und Umweltgesundheit („One Health“) von entscheidender Bedeutung. Jedoch ist die Gesundheit der Böden vielerorts durch Degradation stark gefährdet, besonders durch die stark unterschätzte Nährstoffverarmung an Kalium (K) und Mikronährstoffen. Eine Möglichkeit zur K und Mikronährstoffversorgung sind silikatische Gesteinsmehle (SGM). Aufgrund von langsamen Verwitterungsraten wurde jedoch an ihrer agronomischen Effizienz bis zuletzt gezweifelt. Frühere Studien haben allerdings die faktorielle Komplexität des Verwitterungsprozesses nicht ausreichend berücksichtigt, und neue Studien berichten über signifikante Verbesserungen der Bodengesundheit. SGM könnten zudem weitere Umweltnutzen mit sich bringen, da ihre Mischung mit Gülle deren Ammoniak (NH_3) Emissionen reduzieren und deren biophysikalisch-chemischen Eigenschaften verbessern könnnte. Es wurden jedoch bisher weder die Auswirkungen SGM auf die Bodengesundheit noch auf Gülle umfassend analysiert. Das übergeordnete Ziel dieser Dissertation ist es daher, die landwirtschaftliche Nutzung von SGM im Kontext von One Health zu analysieren. Der erste Teil dieser Arbeit beginnt mit einer Erläuterung des Gesundheitsbegriffs im Allgemeinen, und beschreibt die Zusammenhänge zwischen Bodengesundheit und One Health. Danach werden die Potentiale und Probleme hinsichtlich der Operationalisierung von Bodengesundheit diskutiert, und es werden Vorschläge für ihre zukünftige Nutzung gemacht. Im zweiten Teil der Arbeit wird die Eignung von SGM zur Verbesserung der Bodengesundheit untersucht. Dazu wurde ein Framework mit den wichtigsten Faktoren erstellt, durch den viele widersprüchliche Ergebnisse früherer Studien erklärt werden können. Eine anschließende Analyse von 48 Pflanzenversuchen zeigt das Potenzial von SGM als K und Mikronährstoff-Bodenverbesserer für tropische Böden auf, während der Nutzen für Böden in gemäßigten Zonen nicht eindeutig ist. Es werden verschiedene Nebeneffekte identifiziert, welche die agronomische Gesamteffizienz von SGM erheblich steigern können. Der letzte Teil der Arbeit berichtet über die Auswirkungen der Mischung von zwei Gesteinsmehlen mit Rindergülle. Die SGM erhöhten die CH_4 Emissionsraten der Gülle signifikant, während die Emissionsraten von NH_3, CO_2, und N_2O weitestgehend insignifikant beeinflusst wurden. Die SGM setzten Nährstoffe in der Gülle frei und veränderten dessen Mikrobiologie. Zusammenfassend lässt sich sagen, dass das Konzept der Bodengesundheit spezifischer, praxisnäher, und kontextabhängiger operationalisiert werden muss. SGM könnten die Bodengesundheit insbesondere in den humiden Tropen verbessern, und ihre Verwendung könnte zusätzliche Vorteile für One Health mit sich bringen. Das Mischen von SGM mit organischen Materialien wie Gülle könnte das Haupthindernis ihrer geringen Löslichkeit überwinden, obwohl die Auswirkungen auf NH_3- und Treibhausgas-Emissionen weiter untersucht werden müssen.

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Abbreviations

As	Arsenic
B	Boron
Ca	Calcium
Cd	Cadmium
CEC	Cation exchange capacity
CH_4	Methane
Cl	Chlorine
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
EC	European Commission
EHEC	Enterohemorrhagic E. coli
ES	Ecosystem Services
EU	European Union
FAO	Food and Agricultural Organization
Fe	Iron
Hg	Mercury
I	Iodine
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
P	Phosphorus
Pb	Lead
PSNRU	Plant, Soil and Nutrition Research Unit
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
Ni	Nickel
NH_3	Ammonia
N_2O	Nitrous oxide
S	Sulfur
Se	Selenium
SOC	Soil organic carbon
SDGs	Sustainable development goals
SRP	Silicate rock powder
USDA	United States Department of Agriculture
WHO	World Health Organization
Zn	Zinc

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Achievements

The following papers and manuscripts emerged from this thesis and have been accepted/submitted for publication:

Swoboda, Philipp; Döring, Thomas F.; Hamer, Martin (2020a) Remineralizing soils? The agricultural usage of silicate rock powders. A review. *Science of the Total Environment.* https://doi.org/10.1016/j.scitotenv.2021.150976

Swoboda, Philipp; Döring, Thomas F.; Hamer, Martin; Trimborn, Manfred (2020b) Effects of rock powder additions to cattle slurry on ammonia and greenhouse gas emissions, physicochemical and microbiological properties. *Journal of Environmental Chemical Engineering* (revised manuscript submitted JECE-D-21-07966).

Vicca, Sara; Goll, Daniel; Janssens, Ivan; Hartmann, Jens; Hagens, Mathilde; Neubeck, Anna; Penuelas, Josep; Poblador, Silvia; Rijnders, Jet; Sardans, Jordi; Struyf, Eric; **Swoboda, Philipp**; Van Groenigen, Jan Willem; Vienne, Arthur; Verbruggen, Erik (2020) Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? *Global Change Biology* (paper accepted with major revisions GCB-21-1554.R1).

Anna Brückner, Juliana Minetto Gellert Paris, Dennis Schmiege, **Philipp Swoboda** (2020) Urban transformation and the need for One Health. Recommendations for Ruhr Metropolis. *ZEF Policy Brief* No. 1, online version: https://www.zef.de/fileadmin/webfil es/downloads/projects/onehealth/PolicyBriefs/One_Health_Policy_Brief_No_1_english.pdf

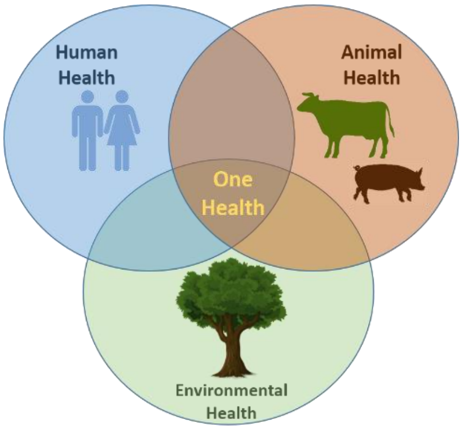
Furthermore, I presented part of my research at the following events:

Annual Meeting of the Soil Science Society of Switzerland and the German Soil Science Society. Bern, Schweiz, 24/08/2019 – 29/08/2019. Oral presentation: "Turning Rocks to Bread? A review of rock dusts as soil health amendment"

Symposium on One Health and Urban Transformation. Bonn, Germany, 3/11/2020. Poster presentation: "The agricultural usage of rock powders in the context of Soil Health"

1 General Introduction

The recently established One Health concept emphasizes the intrinsic interconnectedness of animal, human and environmental health (Figure 1), and aims to improve it in inter- and transdisciplinary ways (Box 1) (Zinsstag, 2015; Destoumieux-Garzón *et al.*, 2018). In the last years, One Health has gained considerable attention, since the limitations of single disciplined approaches towards tackling complex health challenges have become ever more obvious, such as recent zoonotic outbreaks like Ebola, Zika, and COVID-19 (Humboldt-Dachroeden *et al.*, 2020; Destoumieux-Garzón *et al.*, 2018), or increasing rates of antibiotic resistance and food-borne diseases have shown (Garcia *et al.*, 2020; Xu *et al.*, 2020). One Health therefore seeks to promote and improve cooperation between medical doctors, veterinarians and environmental scientists (Zinsstag, 2015; Atlas and Maloy, 2014).



Box 1: One Health definition

"One Health is a collaborative, multisectoral, and trans-disciplinary approach - working at local, regional, national, and global levels - to achieve optimal health and well-being outcomes recognizing the interconnections between people, animals, plants and their shared environment." One Health commission (2021).

Figure 1: The One Health nexus, interconnecting animal, human, and environmental health. Author´s graphic.

However, One Health initiatives have a strong focus on the human and animal domain, while the environmental domain is currently underrepresented (Garcia *et al.*, 2020). The importance of environmental health is recognized, but the involvement is often framed by the predominant zoonotic or vector-borne diseases focus of current One Health undertakings (Musoke *et al.*, 2016). Similarly, the involvement of soils, as central part of environmental health, is widely lacking in the recently established One Health literature (Humboldt-Dachroeden *et al.*, 2020; Pepper and Brooks, 2021; Flandroy *et al.*, 2018).

Contrary to this, the importance of soils on human health has been raised since ancient times. Biblical accounts depicted Moses (circa 1400 BC) as understanding that fertile soil was essential for the well-being of people, whereas Hippocrates (400BC) included the properties of the local ground as one of the things to consider for a proper medical evaluation (Brevik and Sauer, 2015). In the late 1700s, American farmers had recognized the distinct influence of soils on human health, recorded in *Letters from an American Farmer*: “Men are like plants; the goodness and flavor of the fruit proceeds from the peculiar soil and exposition in which they grow” (Crèvecoeur, 1904). In the 1800s, the recognition about the link between agriculture, soil, and an enduring society began to spread, while one of the first scientifically underpinned links of soils to human health was discovered by Robert Koch in 1870, who found that the cause of the deadly animal and human disease anthrax was a soil-born pathogen (*bacillus anthracis*) (Pepper *et al.*, 2009). In the beginning 1900s, the idea that soils influence human health gained traction (Brevik and Sauer, 2015). This was underpinned Robert McCarrision´s Studies in Deficiency Disease, outlining that the soil influences the vitamin content of food crops grown in it, and thereby influences human health (McCarrison, 1921). The US Department of Agriculture (USDA) increasingly invested into research at the interface of agriculture and human nutrition and founded the Plant, Soil and Nutrition Research Unit (PSNRU) (Kellogg, 1938). From the 1940s, the importance of soils was forwarded by early pioneers of organic farming, such as Lady Eve Balfour with her seminal work *The Living Soil* (1943), which is one of the earliest accounts that conclude that the “vitality” of the soil is essential for the quality of the food, and hence the health of the people. This was followed by other seminal works like J. I. Rodale´s (1945) *Pay Dirt: Farming and Gardening with composts*, Sir Albert Howard´s *The Soil and Health: A study of Organic Agriculture* (1947), and Andre Voisin´s *Soil, Grass, and Cancer* (1959). From the 1970s onwards, there was a broadening realization that soils fulfill more needs for human societies than merely producing food and fiber (Baveye *et al.*, 2016), which forwarded the understanding of various soil functions and ecosystem services[1]. These functions comprise biomass production, nutrient cycling, water storage, carbon sequestration, biodiversity preservation, and pollutant purification (Blum, 2005; Weil and Brady, 2017).

In the early 2000s, the increasing recognition of the importance and multifunctionality of soils forwarded the concept of soil health, often described as “the continued capacity of soils to function as vital living ecosystems that sustain humans, animals, and plants” (Moebius-Clune *et al.*, 2016; Bünemann *et al.*, 2018; Lehmann *et al.*, 2020). The capacity of a soil to fulfill these functions depends upon its biophysicochemical properties, as well as on the soil management. A major aim of soil health management is to harmonize the outcome of these functions, particularly because the negative environmental consequences associated with a focus on the productivity function of soils have become increasingly obvious in the last decades (Tilman *et al.*, 2011; Godfray and Garnett, 2014). One Health approaches similarly deal with adverse trade-offs of the intensification and expansion of agriculture (McMahon *et al.*, 2015), although soils have only recently been suggested as key element for dealing with One Health challenges like antibiotic resistance transmission and the cycling of beneficial or

[1] oftentimes used interchangeably and not clearly delineated, see discussion by Baveye *et al.* (2016).

pathogenic microorganisms (van Bruggen *et al.*, 2019; Hirt, 2020). Overall, a better integration between soil health and One Health is argued to forward research synergies, clarify the interconnectedness between the health spheres, and facilitate cross-disciplinary communication (Keith *et al.*, 2016; van Bruggen *et al.*, 2019).

Importantly, however, there is a partly by-passed critique and debate regarding some aspects of the soil health concept. Primarily, these concerns are about challenges to define soil health and finding universal quantitative assessments that encompasses all functions (Powlson, 2020; Baveye, 2021b). These challenges are above all related to the ambiguity of the health concept per se, for which definitions and unified operationalization approaches constitute an enduring problem (Nielsen, 1999; Lackey, 2007; Huber *et al.*, 2011; Vieweger and Döring, 2015). Particularly for soil health, the challenges relate to high degrees of soil heterogeneity, the site-specific nature of soil management, and ecosystem services and functions that oftentimes have conflicting or competing needs (Lehmann *et al.*, 2020).

Nevertheless, there is widespread and increasing interest in soil health, reflected in an exponentially increasing number of publications in the last decade (Janzen *et al.*, 2021), major EU projects about "Soil Health and Food", and the inclusion of soil health in efforts to achieve the sustainable development goals (SDGs) (Keesstra *et al.*, 2016; European Commission, 2020; Lal *et al.*, 2021). Furthermore, soils have up until recently been widely ignored by societies, with the public at large tending towards perceiving soils merely as "dirt" (Brevik *et al.*, 2020). However, the last years have shown an increased awareness and unprecedented usage of soil health by professional organizations, public institutions, and the popular press (Brevik *et al.*, 2020; Dick, 2018). These developments are not only underpinned by an increased awareness about the multifunctional importance of soils *per se* (Dick, 2018; Janzen *et al.*, 2021), but also by the fact that soil health is considerably threatened and the condition of soils in many regions of the world is alarming (FAO, 2015).

Soil health can be impaired by various forms of biophysicochemical deteriorations, described as soil degradation (Lal, 2015; Gomiero, 2016; Hossain *et al.*, 2020). More than 30% of all agricultural land has been affected by some degree of soil degradation (Scherr, 1999; FAO, 2015), and degradation continues at unprecedented rates with about 10 million ha of arable soils being rendered unproductive each year (IPBES, 2018; Hossain *et al.*, 2020). Soil degradation occurs via natural and anthropogenic factors and negatively affects various soil properties essential for soil health, such as the depletion of soil organic carbon (SOC), loss in biodiversity, acidification, compaction, and salinization (FAO, 2015; Lal, 2015). Among the most widespread forms of soil degradation is soil nutrient depletion (Jones *et al.*, 2013; FAO, 2015; Hossain *et al.*, 2020), which is characterized by a continuous stripping of soil nutrients without adequate replacement (Lal, 2015; Gomiero, 2016).

Despite a common focus on N and P (Vitousek *et al.*, 2009; Bouwman *et al.*, 2017), it has been suggested that global soil nutrient depletion rates are of greatest concern for K (Sheldrick *et al.,* 2002; Sheldrick and Lingard, 2004; Tan *et al.*, 2005; Mueller *et al.*, 2012) and that K inputs would need to at least double to replace the amounts removed from crops (Manning, 2015). Besides K, global nutrient mining is equally alarming for micronutrients like B, Fe, Cu and Zn (White and Zasoski, 1999; Jones *et al.*, 2013). The extent micronutrient deficiencies has been seriously underestimated, (White *et al.*, 1999; Jones *et al.*, 2013), which has severe consequences for human and animal health (Jones *et al.*, 2013; Spears, 2000).

Overall, the situation is particularly severe in the tropics, the center of global food insecurity and future population growth (Roser *et al.*, 2013; FAO, 2017), where more than 40% of the soils are nutrient depleted oxisols and ultisols (Sanchez, 2019). In these soils, prolonged periods of rock weathering have largely depleted the geogenic nutrient base of the soils (Chesworth *et al.*, 1983; Fyfe, 1989; Leonardos *et al.*, 1987; van Straaten, 2006). Replenishing the nutrient base of tropical soils is however challenging since soluble fertilizers are oftentimes not affordable, accessible, and do not replenish micronutrient deficiencies (van Straaten, 2006; Jones *et al.*, 2013). Therefore, finding sustainable ways to replenish the macro- and micronutrient stocks of soils is, especially in the tropics, of crucial importance.

In this context, finely ground silicate rocks have been proposed as alternative fertilizer and soil amendment (Fyfe *et al.*, 1987; Leonardos *et al.*, 1987; Harley and Gilkes, 2000). Many silicate rocks contain several macro- and micronutrients essential for plant growth, and could thus be used as a low-cost multi-nutrient fertilizer (Harley and Gilkes, 2000; van Straaten, 2006). However, despite their longstanding usage dating back to ancient times (Leonardos *et al.*, 1987; Winiwarter and Blum, 2008) and a well-established market in the organic farming sector (Manning, 2010; Abbott and Manning, 2015), the overall scope of their effects is unclear and findings are contradictory (Harley and Gilkes, 2000; van Straaten, 2006; Zhang *et al.*, 2018). The major reason for this is that the weathering of the rock particles and thus the release of nutrients is typically a slow process and dependent upon a complex interplay of various factors like rock and soil type, particle size and the trial duration (Harley and Gilkes, 2000; Zhang *et al.*, 2018).
Yet, besides Manning´s (2010) review of SRPs as alternative K source, there is hitherto no review of SRPs that comprehensively evaluates the most important weathering factors or SRPs overall effects on soil health. Furthermore, there is emerging evidence about pertinent co-benefits for environmental health like carbon sequestration via “enhanced weathering” (Hartmann *et al.*, 2013; Beerling *et al.*, 2020) or silicon induced biotic and abiotic stress resistance in plants (Epstein, 2009; Haynes, 2014).

Potential co-benefits with important One Health implications might also occur through mixing silicate rock powders with livestock manure, which is practiced since many decades by farmers in Austria, Germany, and the Netherlands (Snoek and Wülfrath, 1983; Kistner-Othmer, 1989; Shah *et al.*, 2018). There are various aims and claims by farmers and rock powder providers about the effects of mixing SRPs with livestock manure[2,3,4]. A momentous claim is that SRPs can reduce ammonia (NH_3) emissions from livestock manure. Livestock management is the major contributor (75%) of the EU´s total NH_3 emissions in 2017 (EC, 2019b), resulting in various negative consequences for environmental health like atmospheric deposition of nitrogen (N), eutrophication of ecosystems, soil acidification and fine particulate air pollution (Amon *et al.*, 2006; Sonneveld *et al.*, 2008; Schneidemesser *et al.*, 2016). However, there is contradictory evidence about NH_3 reductions of solid livestock manure with SRPs (Kistner-Othmer, 1989; Shah *et al.*, 2012), and no study was found that analyzed the effects on liquid manure (slurry), which is the predominant form of manure arising in Europe (Cherrier *et al.*, 2014).

Mixing SRP with organic materials like manure could furthermore increase rock weathering (van Straaten, 2007; Kleiv and Thornhill, 2007; Basak *et al.*, 2020) and influence the microbiology of the slurry (Ndegwa *et al.*, 2008), yet again, no single peer-reviewed study was found that analyzed these potential effects for cattle slurry and rock powders.

Overall, the theoretical possibility that mixing SRPs with livestock slurry can reduce NH_3 emissions, increase nutrient release, and influence the slurry´s microbiology warrants a comprehensive examination, since this would constitute a simple agronomic technique easily applicable for various farm scales and across various regions. This is particularly relevant since a major problem of many existing emission abatement techniques is that they are big-scale mechanistic interventions, which are oftentimes not affordable and feasible for small-scale farmers (Sajeev *et al.*, 2018).

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2 https://www.biolit-natur.com/de/biolit-story.html
3 https://www.actimin.nl/
4 https://www.schicker-mineral.de/landwirtschaft

1.1 Objectives, research questions, and thesis framework

The overall aim of this dissertation is to review the agricultural usage of silicate rock powders (SRPs) in the context of One Health (Figure 2). The first objective is to provide a broader frame for the thesis and outline how soil health is connected to plant, animal, and human health. Subsequently, challenges and the often by-passed critique regarding the assessment and operationalization of soil health will be discussed, to answer the research question:

a) What are the potentials and limitations of the soil health concept?

Thereafter, the second objective is to present the most important factors for the usage of SRPs and answer the following research question:

b) How and under which circumstances can silicate rock powders improve yields and ameliorate soil health?

Then, the aim is to review potential co-benefits as well as agronomic and environmental aspects of SRPs and identify the most pertinent knowledge gaps for future research.

The third objective is to investigate various claims regarding the longstanding yet hitherto scientifically unexamined practice of mixing SRPs with livestock slurry. Based on an experiment with cattle slurry and two rock powders the following research question is answered:

c) What are the effects of mixing silicate rock powders with livestock slurry on NH_3, CO_2, CH_4, and N_2O emissions, physicochemical and microbiological properties?

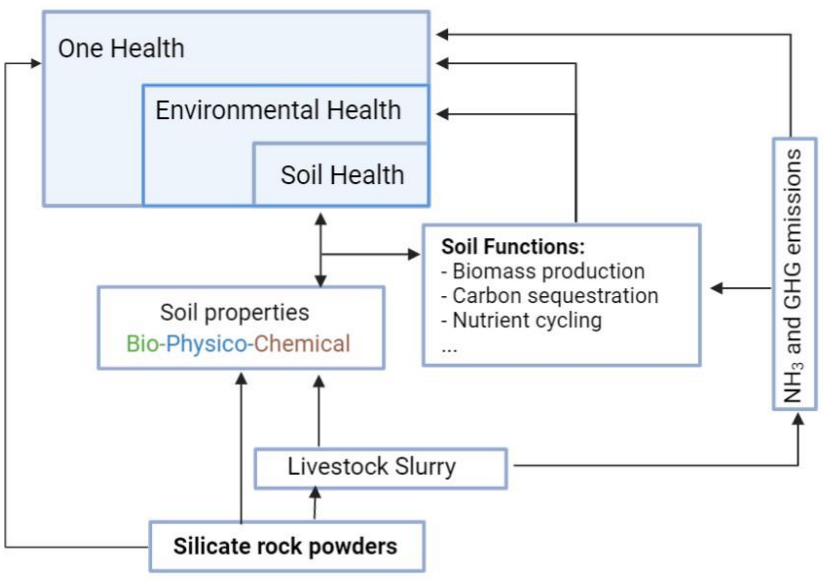

Figure 2: Conceptual framework of the thesis.

1.2 Structure of the dissertation

The remainder of this dissertation is grouped into three chapters and a general conclusion. The chapters correspond to the three major objectives**.**

Chapter 2 starts with an elaboration of the health concept in general with a subsequent focus on soil health. Then, exemplary interactions between soil health and the other health domains are presented. Thereafter, the potentials and problems of the soil health concept are outlined, and the practical difficulties of operationalizing it are discussed.

Chapter 3 first provides the agronomic and environmental background that justifies the usage of silicate rock powders as soil amendment. This is followed by presenting the most important factors for the usage of silicate rock powders. According to these factors, 48 silicate rock powder trials are reviewed. Thereafter, agronomic and environmental aspects as well as recommendations for future research are discussed.

Chapter 4 investigates the mixture of silicate rock powders with livestock slurry. It first summarizes various goals and problems of livestock slurry treatments in general, and then presents the findings of mixing silicate rock powders and livestock slurry. Subsequently, the agronomically and environmentally conflicting results are discussed.

Chapter 5 provides a synoptic conclusion of the main findings, and an outlook for the usage of silicate rock powders in agriculture from a One Health perspective.

2 Soil Health and One Health – important linkages and operational crossroads

"*Soil science is the foundation of protective medicine*" (Voisin, 1959)

2.1 Introduction

A major driving force influencing the health of animals, humans, and the environment is agriculture (Hawkes and Ruel, 2006; Garcia *et al.*, 2020). In the last 50 years, agriculture has steadily increased crop yields and thereby contributed to human health by reducing hunger, improved life expectancies, falling infant and child mortality rates, and reductions in global poverty (Willett *et al.*, 2019; Steffen *et al.*, 2015). Increased yields mainly resulted from greater inputs of fertilizers, pesticides and irrigation, new crop cultivars, mechanization, and other technologies of the 'Green Revolution' (Foley *et al.*, 2005; Tilman *et al.*, 2011). However, despite substantial increases in global food production, the negative consequences of modern conventional agriculture are increasingly being observed. Increased reliance on non-renewable resources, reduced biodiversity, water contamination, soil degradation, high-density livestock keeping, and the usage of pesticides and other agrochemicals associated with conventional farming systems all threaten the health of soils, plants, animals, humans, and ecosystems (IAASTD, 2009; Foley *et al.*, 2005; Tilman *et al.*, 2011; Rockström *et al.*, 2009).

In contrast to modern conventional farming, one core principle of organic farming is the pursuit to sustain the health of soils, ecosystems, and people (Döring *et al.*, 2015; IFOAM, 2008). This principle is encapsulated in the conception that 'the health of soil, plant, animal and man is one and indivisible', a key statement in one of the founding documents of the organic agricultural movement, Lady Eve Balfour'*s The Living Soil* (1948). As the title indicates, a central point is the importance of soil as the basis for healthy plants, animals, and humans. Other pioneers of organic farming like Sir Albert Howard (1947) and Jerome Irving Rodale (1945) equally investigated the links between soil and human health, whereas André Voisin stressed that medicine had largely ignored influence of soils on human health, and that soil science should be the foundation of protective medicine (Voisin, 1959). In the 1940s and 50s, one of the fundamental notions of organic farming was thus to sustain and feed the soil, which contrasted with conventional strategies to fertilize the plants with soluble fertilizers (Heckman, 2006). However, in the last decades the importance of soil sustaining practices also gained increased momentum outside the organic farming sector, since soil degradation continues at unprecedented rates (Stavi *et al.*, 2016; Lal, 2008; Pretty *et al.*, 2010; FAO, 2015) and insights accumulate about how soils are linked to plant health (Hirt, 2020), animal (Kemper *et al.*, 2017), and human health (Brevik and Burgess, 2015).

In this context, the relevance of soils for "One Health" has recently been outlined by some authors (Keith *et al.*, 2016; van Bruggen *et al.*, 2019). However, these conceptual linkages are still at an early stage and most studies focus on the influence of soils on human health (Abrahams, 2002; Brevik and

Burgess, 2015; Hough, 2007; Oliver and Gregory, 2015; Pepper, 2013; Nieder *et al.*, 2018). Furthermore, these linkages predominantly focus on nutrition and toxic agents (Brevik *et al.*, 2020), whereas some emergent topics encompass antibiotics (Cycoń *et al.*, 2019) or microorganisms (van Bruggen *et al.*, 2019). Other studies describe direct and indirect human health effects related to soil functions and ecosystem services like biomass production and climate regulation (Lehmann *et al.*, 2020). Reeve *et al*. (2016) e.g. reviewed the links between soil physical, biological, and chemical properties and plant health. However, this is a less feasible approach when animal or human health is concerned, since effects of soil physical properties on animal or human health would mostly be indirect, e.g. how bulk density affects the growth of plants, which are subsequently consumed by humans and animals. Generally, the approaches and categories that link soils with the other health spheres are methodologically inconsistent and fragmentary (Keith *et al.*, 2016; Ohno and Hettiarachchi, 2018; van Bruggen *et al.*, 2019).
These conceptual inconsistencies further complicate the operationalization of soil health, which is a main focus of ongoing critique (Powlson, 2020; Baveye, 2021b). Concerns regarding the operationalization mostly relate to difficulties in measuring soil health, which is typically approached by assessing various soil biophysicochemical properties. The number of suggested indicators steadily increased in the last years and likely further grows in the coming years (Baveye, 2021b; Lehmann *et al.*, 2020). However, no consensus has been reached about which indicators to select and how many would be pertinent (Seaton *et al.*, 2020). Ultimately, these difficulties in agreeing upon soil health indicators relate to the ambiguity of the health concept per se, for which quantifications constitute an ongoing problem in other domains as human or ecosystem health as well (Nielsen, 1999; Lackey, 2007; Huber *et al.*, 2011; Vieweger and Döring, 2015; Baveye, 2021b).

Therefore, the purpose of this chapter is to first outline difficulties in defining and approaching ‘health’ in general, and then to synthesize the scattered linkages between soil health and the health of animals, humans, and the environment (focusing on plants). Thereafter, the soil health concept will be reviewed with a focus on the often by-passed concerns regarding its operationalization, to answer the question: What are the potentials and problems of the soil health concept? Based on these findings, it will be discussed what are feasible ways to operationalize soil health.

2.2 Approaching health

The pursuit to improve the interconnected health of plants, soils, animals, humans, and their environment is increasing. This is mirrored by a steadily growing number of publications in the fields of holistic health concepts like Global Health, One Health, and Planetary Health (Humboldt-Dachroeden *et al.*, 2020; MacNeill *et al.*, 2021; Park *et al.*, 2021). Similarly, the number of studies that link soils to the other health domains, particularly human health, has equally increased in the last decade (Brevik *et al.*, 2020; Janzen *et al.*, 2021). However, what is rarely addressed yet crucial for any deeper discussion of health is the obvious question: What is health?

This question has been answered in various ways, with one basic commonality across all domains: there is no generally agreed-upon definition for health, neither for One Health, nor for soil, animal, plant, human or ecosystem health (Jadad and O'Grady, 2008; OIE, 2011; Vieweger and Döring, 2015; Huber *et al.*, 2011; Zinsstag, 2015). The concept of health is so complex that it is impossible to give a definition which is holistic and nonrestrictive, yet concise enough to be operationalized (Vieweger and Döring, 2015). There have been various philosophical approaches aiming to resolve the issue of defining health. These debates have occurred mostly for human health, although the major approaches and ideas could be, despite fundamental differences between the domains, used to equally approach health in the other domains (Döring *et al.*, 2012). Döring *et al.* (2012) differentiated between (i) naturalist and normativist approaches; (ii) negative and positive health definitions; (iii) reductionist versus holistic perspectives; (iv) a focus on either functionality or resilience; (v) materialist versus vitalist approaches; and (vi) biocentric versus anthropocentric views. However, none of these views is argued to be without inherent contradictions and has hitherto succeeded to unequivocally define health (Döring *et al.*, 2012).

For the remainder of this chapter, a more normativist approach to health along the lines of Nielsen (1999) is agreed upon, which presumes that health is not a science *per se*, but a social construct whose defining characteristics evolve with time and circumstances, and typically involve biological, physical, ethical and aesthetic points of view. For example, the 1948 World Health Organization (WHO) definition for human health was "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1958). Although this definition was groundbreaking at the time due to its breadth and because it overcame the negative definition of health as the mere absence of diseases, it has been criticized over the past 60 years (Huber *et al.*, 2011). A central point of critique is the absoluteness of the term "complete", which would leave most of society unhealthy most of the time, and is claimed to be neither operational nor measurable (Huber *et al.*, 2011). The definition was revised, defining health as "the extent to which an individual or group is able to realize aspirations and satisfy needs and to change or cope with the environment…" (WHO, 1984). Although the vagueness of the wording "realize aspirations and satisfy needs" again forestalls distinct measurements and renders the exact meaning dependent upon interpretation, the "change or cope with the environment" aligns with an increasing number of views that relate health to similar sub-concepts or criteria such as adaptability (Lancet, 2009), self-management (Huber *et al.*, 2011), homeostasis (Nielsen, 1999), or resilience (Döring *et al.*, 2015).

An important differentiation here is the shift from a definition towards a sub-concept (Huber *et al.*, 2011) or criteria (Vieweger and Döring, 2015). Huber *et al*. (2011) argue that sub-concepts or criteria represent, as a reference, a characterization of a generally agreed upon direction in which to look, whereas a definition implies clearly defined boundaries and a precise meaning. This agrees with other authors like Nielsen (1999), claiming that health, in its most general conception, can be seen as an orientation towards an overarching goal that helps to guide action for human affairs. Similarly, Calow (1995), a critic of the ecosystem health concept, argues for a redefinition of ecosystem health in terms of clear management goals and criteria.

Thus, where health cannot be clearly defined, it could at least be assessed, for which sub-concepts and criteria can be practical, since they are "half-way between concrete measuring or assessment procedures and an abstract definition of health" (Vieweger and Döring, 2015). Vieweger and Döring (2015) analyzed 50 papers to study what criteria are used to describe soil, plant, animal, human, and ecosystem health. Over 40 terms were used in one way or another to describe health, although many criteria are not used across all domains and there tend to be domain-specific concepts of health and different 'languages' spoken. Nevertheless, some terms were used more frequently. 'Function', 'maintenance', and 'resilience' were mentioned in all five domains, whereas other terms like 'resistance' were particularly used for plant health, 'well-being' for human health and, interestingly, for ecosystem health. For animal health, the least criteria were found, and the most common criteria was 'maintenance'. For soil health, the five most used criteria were 'productivity', 'sustainability', 'function', 'maintenance', and 'capacity' (Vieweger and Döring, 2015), which are in accordance with the most common definitions of soil health.

2.3 Soil Health

One of the earliest and most influential definitions of soil health was "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health" (Doran and Zeiss, 2000; Doran *et al.*, 1996). This definition encapsulates the five most frequently used criteria found by Vieweger and Döring (2015). Today, soil health is widely defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/) (Lehmann *et al.*, 2020). However, the concept and terminology of soil health is still evolving (BOX 2), and new definitions have recently been proposed (Janzen *et al.*, 2021).

Before these definitions and the more scientific onset of studying soil health, the interconnected role of soils for sustaining life on this planet has been acclaimed by various naturalists, environmentalists, poets, and farmers.

BOX 2 – History of soil health

Although 'soil health' has only been used more regularly in the scientific and popular literature since the early 2000s (Doran and Zeiss, 2000; Lehmann et al., 2020), the analogy of the soil ecosystem to an organism reaches back to ancient times. Soils are reoccurring parts in the creation of myths (Winiwarter and Blum, 2006), and deep spiritual connections with soils is shown in songs (Capra et al., 2017), paintings (Jenny, 1968), and performing arts (Feller et al., 2015). Since the 1700s, biological dimensions have underpinned the perception of soils as an ecosystem that can be endangered as much as any other ecosystem (Carson, 1962). One of the first mentions of the soil health concept was in 1910 by Henry A. Wallace, who would later become the Secretary of Agriculture by President Franklin Roosevelt. However, the term soil health was not frequently used, even less so in scientific debates, and was basically analogous to soil fertility (Brevik, 2018). From the 1940s onward, pioneers in organic farming like Howard, Balfour, and Rodale were of particular importance for forwarding soil health. A more scientific appreciation of soil biological processes has been largely enabled by substantial advances in analytical capabilities since the 1980s (Lehmann et al., 2020), exemplified by global mappings of soil biodiversity (Tedersoo et al., 2014; van den Hoogen et al., 2019). The 1990s were characterized by more elaborate efforts to distinguish soil health from its conceptual predecessor soil quality. Although the terms are still used interchangeably (Bünemann et al., 2018), it is argued that soil health presents the soil as a finite non-renewable and dynamic living resource, and is broader in its scope, as it extends its scope to include effects on Planetary Health, One Health and the SDGs (Lehmann *et al*., 2020). In contrast, it is argued that soil quality focuses more on inherent soil properties and ecosystem services with particular reference to humans (Lehmann et al., 2020). In science, there is a tendency to prefer soil quality, whereas soil health is preferred by farmers - debatably because it invokes the notion that soil is an ecosystem full of life that needs to be carefully sustained to function optimally (Moebius-Clune et al., 2016). Soil fertility is nowadays commonly aligned to crop yields and is claimed to be the narrowest of the soil concepts (Bünemann et al., 2018; Lehmann et al., 2020), although there is a rich history of definitions (Patzel et al., 2000). In the recent decade, the number of soil health publications has increased exponentially, and the interest in soil health has moved beyond academia and farmers, and now includes government agencies, private institutions, and the public (Janzen *et al.*, 2021).

Charles Kellogg (1938) stated that “essentially all life depends upon the soil - there can be no life without soil and no soil without life; they have evolved together”, whereas the regenerative and connecting power of soils has been described by Wendell Berry (1977), opining that “the soil is the great connector of lives, the source and destination of all. It is the healer and restorer and resurrector, by which disease passes into health, age into youth, death into life.” Similarly, Aldo Leopold (1949) recognized the interconnectivity of soils and the other spheres, emphasizing that the land is “not merely soil; it is a fountain of energy flowing through a circuit of soils, plants, and animals”.

A major recognition that emerged from these earlier conceptual understandings is that soils are not merely growing media for plants, but that they are key components of the terrestrial ecosystem that fulfill various essential functions at the interface between the atmosphere, the biosphere, the lithosphere and the hydrosphere (Doran *et al.*, 1996; Doran and Zeiss, 2000). Although this functional definition of soil health is one among many definitions and the critique about it does not abate (Baveye, 2021b; Powlson, 2020), it is one of the most widespread approaches to soil health and thus the following sections will focus on it.

The scientific onset of studying these various essential functions of soils was in the late 1970s, with Brümmer (1978) appearing to have been the first to propose a classification of various soil functions, although the functions were not defined explicitly (Baveye *et al.*, 2016). About a decade later followed the first comprehensive and highly influential compilation of soil functions by Blum (1988), which evolved over more than two decades and today encompasses in its most recent form ecological and non-ecological functions (Blum *et al.*, 2018). There are three ecological functions, (i) including biomass production, (ii) filtering, buffering, and transformation capacity, (iii) and serving as a gene reservoir. Whereas the three non-ecological functions comprise (iv) the provision of a physical basis for human activities, (v) the provision of raw materials, (iv) and the preservation of geogenic and cultural heritage. Starting from the 2000s, the terminology of soil ecosystem services (ES) evolved, building on the Ecosystem Service framework emerging in the late 1990s (Adhikari and Hartemink, 2016). The soil ecosystem services are similar to the soil functions, but are categorized in different ways, and comprise (a) provisioning services such as food, fiber, and water, (b) regulating services such as climate regulation, and flood and diseases control, (c) supporting services such as water and nutrient cycling, and habitat provision, and (d) cultural services, such as a recreational and spiritual benefits (Stavi *et al.*, 2016). Nowadays, soil functions and ES are often used interchangeably (Baveye *et al.*, 2016; Adhikari and Hartemink, 2016; Stolte *et al.*, 2016), whereas some authors acknowledge the similarities, but consider soil functions as the basis of soil ES (Tóth *et al.*, 2013; Pereira *et al.*, 2018; Greiner *et al.*, 2017) or combine functions and ES in integrated frameworks (Figure 3, and Bünemann *et al.*, 2018).

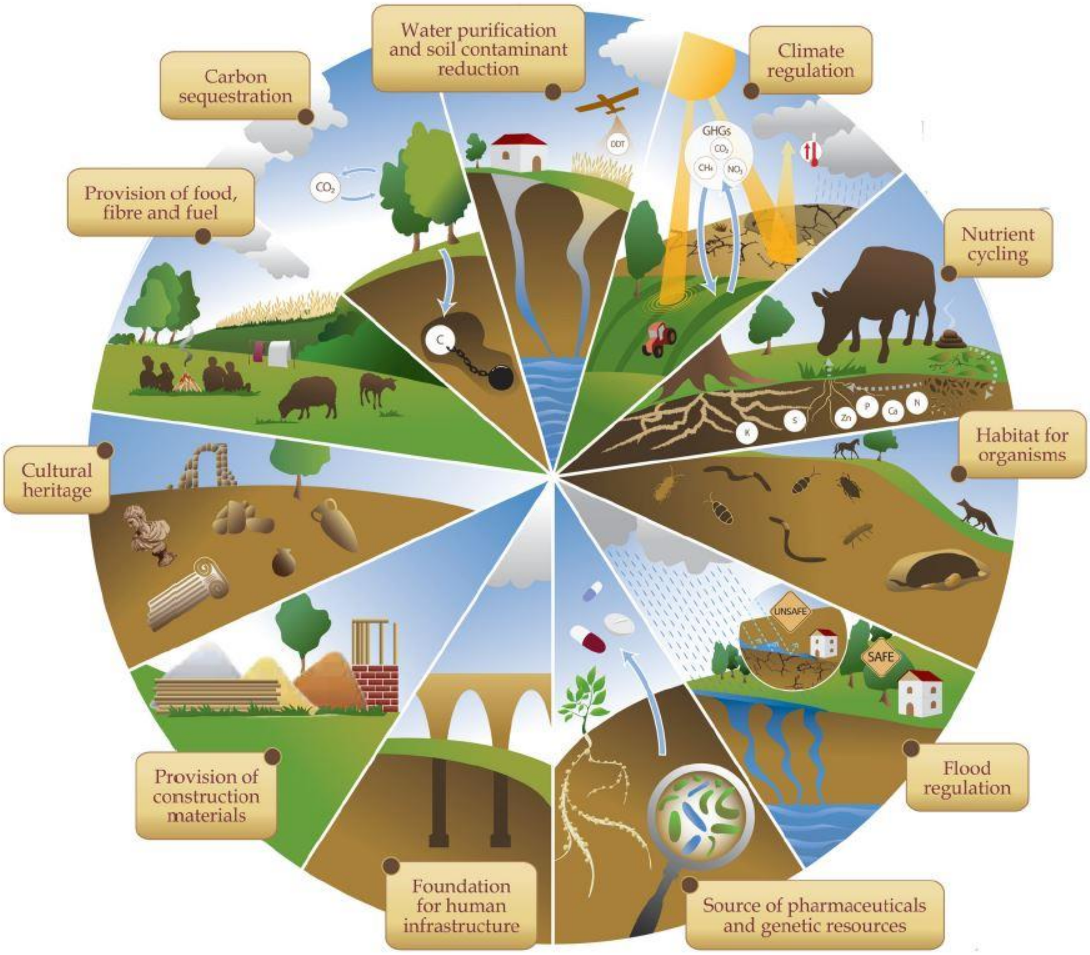

Figure 3:This picture is part of an infographic of the FAO (http://www.fao.org/resources/infographics/infographics-details/en/c/284478/) that integrates soil functions and services. The title is "Soil functions" and the subtitle "Soils deliver ecosystem services that enable life on earth". Source: Baveye et al., 2016

In the context of the soil functions and ES services, a related body of scientific literature developed that focused more explicitly on the links of soils to human health (Brevik and Sauer, 2015). Although the importance of soils to health was recognized since ancient times and many soil functions and ES services suggest several (in-)direct effects on health, more detailed accounts of various links to health only emerged in the later part of the 20th century (Brevik and Burgess, 2015; Brevik *et al.*, 2020).

2.4 Linking soil to plant, animal, and human health

Although some connections between soil health and 'One Health' have recently been suggested (Keith *et al.*, 2016; Ohno and Hettiarachchi, 2018), most studies focus on the influence of soils on human health (Abrahams, 2002; Brevik and Burgess, 2015; Hough, 2007; Oliver and Gregory, 2015; Pepper, 2013; Nieder *et al.*, 2018), and the overall approaches of linking soils with the other health spheres are methodologically inconsistent and fragmentary (Lal, 2020; Brevik *et al.*, 2020).

In this context, Vieweger and Döring (2015) proposed various methodological categories for health research in agriculture, which could provide a basis for summarizing the health linkages from soils to the other domains. The categories comprise (1) nutritional, (2) toxicological, (3) pharmacological, (4) epidemiological, (5) cognitive and behavioral, (6) cultural, (7) economic and (8) political. Several recent examples found in the literature linking soil to human, animal, and plant health can be allocated within these groups, and thus, the following overview of the linkages between soil health and the other health spheres will be orientated on this methodological approach.

However, these categorical approaches do not focus on soils, but on health across all domains, and so not all categories are viable when the perspective shifts towards the effects that soil health has on the other domains. Therefore, the 'cognitive and behavioral', 'cultural', 'economic' and 'political' categories will be left out. In the case of 'cognitive and behavioral', the reason is that Vieweger and Döring (2015) did not outline any links for soil health and no studies were found that provided examples for this category. Likewise, even though there are (1) cultural differences in the perception of soil health (Winiwarter, 2006), (2) policies on the protection of soil health (EC, 2006), and (3) economic approaches towards soil health (Stevens, 2018), the effects of these linkages are on a more abstract level than the other linkages and no comprehensive studies were found that elucidated on their health connections in more detail.

Overall, the potential methodological health approaches and the number of publications linking soils to the other health domains is too numerous to be comprehensively synthesized for the scope of the following sections. Therefore, the following sections provide examples of how soil health is connected to plant, animal, and human health via nutritional, toxicological, and microbial links (Figure 4).

2.4.1 Soil nutritional links

Macro- and micronutrients constitute a common indicator for functional soil health approaches outlined in section 2.3 (Soil Health Institute, 2021), which defines soil health, amongst others, according to its ability to promote plant, animal, and human health (Doran and Zeiss, 2000; Lehmann *et al.*, 2020). Importantly, this functional definition of soil health is circular since it necessarily defines soil health according to its capability to promote plant, animal, and human health, and not according to the soil itself. Although sufficient nutrients are also crucial for the soil itself, since e.g. many microorganisms exist under starvation conditions and tend to be dormant within nutrient limited environments (Welbaum *et al.*, 2004; Weil and Brady, 2017), the following sections will focus on this functional and circular definition of soil health.

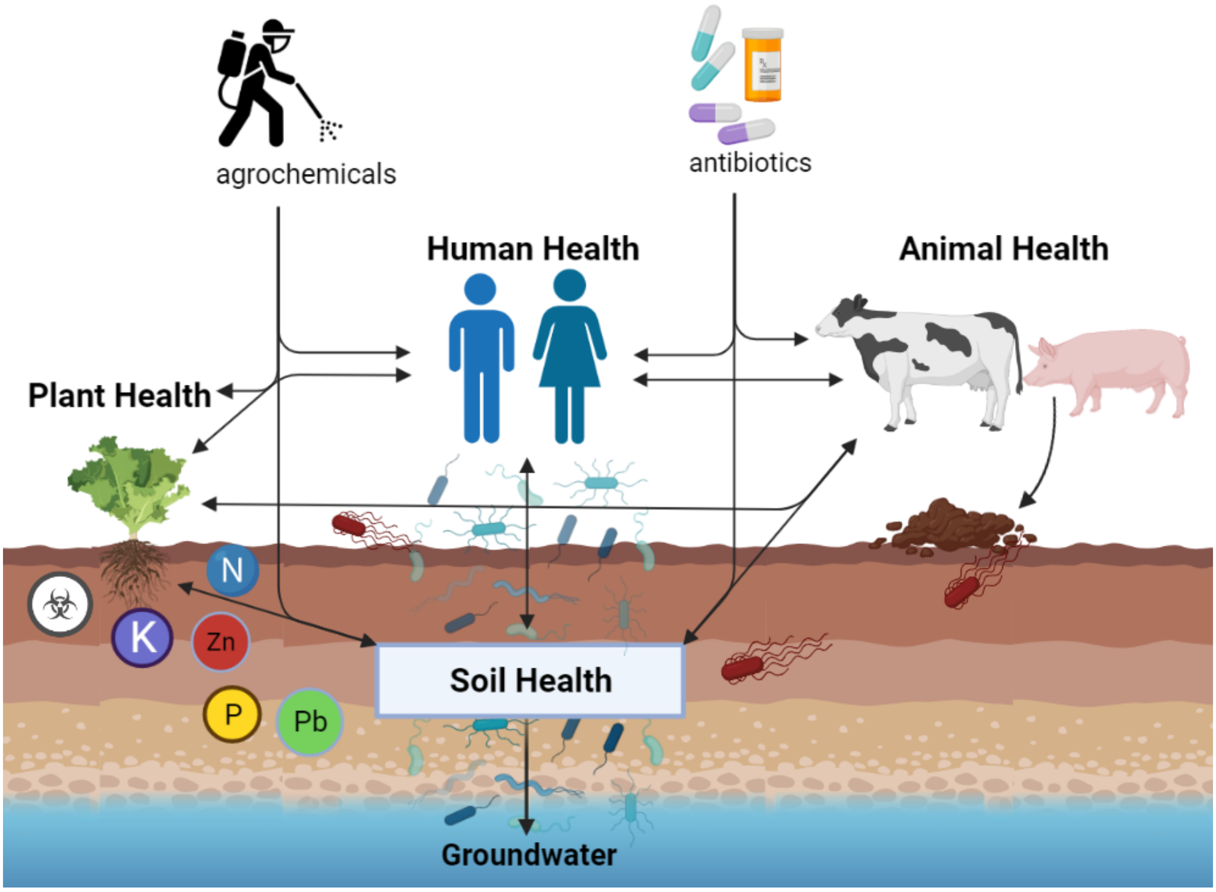

Figure 4: Exemplary interactions of how soil, plant, animal, and human health are connected via nutritional, toxicological, and microbial linkages. Author´s graphic.

2.4.1.1 Soil nutritional links to plant health

Among the numerous approaches to plant health, the functional approach (e.g. in terms of growth, photosynthesis, and reproduction) (Döring *et al.*, 2012) is again focused on in the following sections. Soil health influences plant health through the provision of the 14 essential mineral nutrients: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), chlorine (Cl), boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), and molybdenum (Mo) (Marschner, 2002), although the essentiality of nickle (Ni) and chlorine (Cl) is yet restricted to some specific plants. The content and availability of these essential nutrients is influenced by soil properties such as mineralogy, texture, pH, and soil organic matter (SOM) (Reeve *et al.*, 2016). Insufficient or excess amounts of one or more nutrient elements in the soil can lead to plant nutrient deficiencies or toxicities (excess), which can cause various nutrient dependent symptoms shown in Table 1. Table 1 furthermore shows the nutrient element dependent symptoms for animals and humans, alongside the average elemental concentration range in plant dry matter and the elemental fraction of the total human body mass, whereas such data were not found for animals. For Ni, there is so far no clear evidence for deficiency symptoms in soil-grown plants (Marschner, 2002), and it is thus not included in Table 1. Many plant nutrient deficiencies can have similar symptoms, particularly for micronutrients, which are used by plants to process other nutrients (Hosier and Bradley, 1999). Besides low soil nutrient stocks, improper soil nutrient management with only N-P-K fertilization can lead to imbalances of other nutrient elements (Haes *et al.*, 2012; Dordas, 2008). For example, although P fertilization can increase forage growth, an excess of P fertilization is associated with lower plant-available zinc, iron, and copper (Suttle, 2010).

In contrast, adequate nutrient supply can affect the disease tolerance and plant resistance to pathogens, although many factors are hitherto not well understood (Dordas, 2008). For instance, although high N supply can increase the infection severity of obligate parasites like *Puccinia graminis* and *Erysiphe graminis*, it can decrease the severity of infection for facultative parasites like *Alternaria*, *Fusarium* and *Xanthomonas* spp (Dordas, 2008). Moreover, sufficient K supply can decrease host plant susceptibility to diseases and improve abiotic stress resistance (Römheld and Kirkby, 2010). Among the micronutrients, the most important nutrients that have been shown to be capable of reducing several diseases are Mn, Zn, and B (Dordas, 2008). Importantly, it is estimated that of the world´s most important agricultural soils, 49% are deficient in Zn, and 31% in B (Sillanpaeae, 1990; White and Zasoski, 1999). Concerning the non-essential nutrient Si, several studies have shown positive effects against various plant diseases and increased abiotic stress resistance (Epstein, 2009).

2.4.1.2 Soil nutritional links to animal health

Soil health affects animal health through the provision of healthy plants and a concomitant intake of sufficient essential mineral nutrients. All nutrients essential for plants are also essential for animals (and humans), who additionally require other elements like chromium (Cr), iodine (I), sodium (Na) and selenium (Se) (Graham, 2008; Whitehead, 2000). Some typical forms of nutrient deficiencies and toxicities are shown in Table 1 (additional elements like Cr, I, Na, and Se are not shown). The soil properties affect the mineral content and balance of the plants that animals eat, and thereby influence animal health. The most common nutrient deficiencies in animals involve the macronutrients Ca, Mg, K, P, S, and Cl (Sivertsen and Bernhoft, 2017).

Under modern agricultural conditions pigs and poultry are typically fed grain-based, industrially produced concentrates with defined amounts of nutrients. Therefore, it is mainly in the ruminant species – cattle, sheep, and goats – that a sufficient nutrient supply is more influenced by local herbage and soil conditions (Sivertsen and Bernhoft, 2017). However, this does not imply that industrially raised pigs, poultry, or ruminant species are “healthier”. To the contrary, some studies suggest that various animal health and welfare aspects are higher in organic compared to conventional farming systems (Rutherford *et al.*, 2009; Wagner *et al.*, 2021; Luangtongkum *et al.*, 2006), although more data are needed to conclude about the differences for various species between the two production systems (van Wagenberg *et al.*, 2017; Sutherland *et al.*, 2013).

Impaired ruminant health often occurs from too much P uptake in comparison to Ca, leading to Ca:P imbalances, which is a major cause of osteodystrophy, and too much K in the feed compared to Mg can lead to an imbalance of Mg:K, often resulting in grass tetany (Suttle, 2010; Whitehead, 2000). Both diseases are among the most widespread nutrient deficiencies in ruminants and are correlated with soil levels of K, which are, besides the soils natural K stocks, strongly dependent upon K fertilization in the form of soluble fertilizers and K-rich manure (Whitehead, 2000).

Comprehensive regional forage analysis are scarce, yet the limited evidence suggests that mineral deficiencies are more widespread than expected (Kemper *et al.*, 2020). Corah and Dargatz (1996) conducted a forage analysis from cow/calf herds in 18 states and found deficient forage levels of copper (14%), manganese (5%), zinc (63%) and selenium (64%). Additionally, very high levels of iron and molybdenum were found in 10% of the samples that were sufficient to cause copper deficiency due to antagonistic effects on copper availability.

Table 1: Essential soil mineral nutrients and their deficiency or toxicity (excess) effects on plant, animal, and human health: Source: table adapted from Kemper *et al.* (2020), additional data for elemental concentration dry plant tissue from Jones and Jacobsen (2005), fraction of total human body mass Emsley (2011), plant deficiencies effects from Hosier and Bradley (1999) and (2002); additional data for animal diseases from (NRC, 2005), additional data for human diseases from (Lavie *et al.*, 1986; Bryan and van Grinsven, 2013; Castro and Sharma, 2021; Takeda *et al.*, 2012)

Soil mineral nutrient	Concentration range dry plant tissue	Fraction of total human body mass	Nutrient deficiency symptoms associated with impaired (functional) plant health	Animal diseases	Human Diseases
Nitrogen (N)	1-5%	2.6%	Slower growth, yellowing of older leaves typically at the bottom, rest of plant light green.	Nitrate toxicosis resulting in e.g. methemoglobinemia.	Nitrite toxicosis: blue baby syndrome. Nitrate toxicosis: methemoglobinemia.
Potassium (K)	0.5 - 0.8%	0.2%	Older leaves may wilt, interveinal chlorosis, scorching starting from leave edges.	Deficiency or excess distorts acid-base regulation.	Deficiency: muscle cramps, rhabdomyolysis, myoglobinuria.
Calcium (Ca)	0.2 - 1.0 %	1.4%	Younger leaves are distorted or dead, blossom-end rot, impaired fruit development.	Deficiency: Osteodystrophy, milk fever/parturient paresis (hypocalcemia).	Deficiency: rickets and osteomalacia.
Phosphorus (P)	0.1 - 0.5%	1.1%	Leaves turn reddish-purple up to total black, reduced fruit or seed production.	Deficiency leads to bright alert downers, muscle weakness, hemolysis.	Deficiency: proximal myopathy
Magnesium (Mg)	0.1 - 0.4%	270ppm	Lower growth and leaves turn yellow on outer edge, new leaves may be yellow with dark spots.	Deficiency: tetany. Toxicosis: reduced muscle tone, recumbence, bradycardia, diarrhea.	Deficiency: Constipation, irritability, anxiety, fatigue, weakness, hypertension.
Sulphur (S)	0.1 - 0.4%	0.2%	Younger leaves turn yellow. Stunted growth.	H_2S toxicosis: isothiocyanates (thyroid function), hemolytic anemia.	Deficiency: impaired detoxification, fatigue, impaired glucose metabolism.
Iron (Fe)	50-250 ppm	60ppm	Interveinal chlorosis in young leaves. Morphological and physiological root changes.	Iron deficiency: anemia. Iron toxicity: liver, heart, pancreas damage.	Deficiency: Anemia, fatigue, weakened immune function, inattention.
Chlorine (Cl)	0.1-1.0%	0.12%	Wilting and reduced leave surface area. Subapical swelling.	Toxicity: distorts acid-base regulation. As NaCl: emesis (vomiting)	Deficiency (rare): hypoventilation
Manganese (Mn)	20-200 ppm	0.2ppm	Slower growth. Reduced leave, shoot, and fruit size. Younger leaves turn pale yellow or dark	Limited toxicity in large animals.	Deficiency: Impaired carbohydrate metabolism, poor wound healing.
Boron (B)	6-60 ppm	2ppm	Reduced plant size, swollen and discolored root tips. Brittle, curled and yellow leaves.	Toxicosis: ataxia, occasional convulsions, nephritis	Deficiency: osteoporosis, poor concentration, weak muscles.
Zinc (Zn)	25-150 ppm	33ppm	Terminal leaves may be rosetted and yellowing between the veins of new leaves	Deficiency: Carbonic anhydrase. Toxicity: Cu deficiency.	Deficiency: Acrodermatitis enteropathica, diarrhea
Copper (Cu)	5-20ppm	1ppm	Stunted plant and leaves become limp, curl, drop, or dark green.	Chronic toxicity: Liver damage, hepatic necrosis, hemolysis.	Deficiency: anemia, neuropathies, arrhythmias, osteoporosis.
Molybdenum (Mo)	0.05-0.2 ppm	0.1ppm	Yellowing of older leaves while rest of plant is often light green. Misshaped central leaves.	Deficiency: Cu toxicosis and loss enzymatic reactions. Toxicosis: Cu deficiency.	Deficiency: Intellectual disability; seizures; opisthotonos, renal failure;

2.4.1.3 Soil nutritional links to human health

The foremost health link from soils to humans is the provision of food, with more than 95% of our food being derived from soil based production (Singh *et al.*, 2017). Various soil properties influence the amount of food that can be harvested, among which soil nutrient content and bioavailability are particularly important. Low nutrient stocks in e.g. highly weathered soils prevalent in tropical countries are a major reason for low yields, resulting in food insecurity, malnutrition, and poor health of the people depending on these soils (Sanchez, 2002, 2019). However, the properties of the soils do not only influence the quantity of plants that can be harvested, but also their nutrient content. Nutritionally poor plants and diets contribute to another form of malnutrition – mineral malnutrition or "hidden hunger", a chronic lack of nutrients and vitamins (Stein, 2010), which is particularly pronounced for micronutrients (Watson *et al.*, 2012). Estimates suggest that billions of people suffer from some form of micronutrient deficiency, mostly in developing countries (Alloway, 2008; Ahmed *et al.*, 2012), although developed countries are also affected (Sinclair and Edwards, 2008).

For example, the fact that about half of the world´s agricultural soils are deficient in the essential micronutrient zinc (Zn) is related to human deficiency symptoms such as hair loss, impairment of immune system functions, and fertility (Weil and Brady, 2017; Cakmak, 2002). Selenium (Se) deficient soils in the north-east to south-west belt of China are associated to a high prevalence of Keshan disease (KD), an endemic degenerative heart condition (Chen *et al.*, 1980). Sulfur (S) deficient soils occur widely and produce wheat or other crops like beans that are low in sulfur-containing amino acids essential for the human body to utilize the protein in food (Alloway, 2008). Sustainable soil nutrient management is thus essential for human health in that it contributes to the provision of enough and nutritionally adequate food.

2.4.2 <u>Toxicological links</u>

2.4.2.1 Soil toxicological links to plant health

Another key research area regarding soils influence on various health domains is the exposure to toxic substances (Brevik *et al.*, 2020). Toxic soil substances have traditionally been studied in relation to heavy metals, including arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), and zinc (Zn) (Abrahams, 2002; Karaca *et al.*, 2010; Brevik and Burgess, 2015). Although some heavy metals are essential for plant growth, their presence in high concentrations in the soil can have various detrimental effects on plant health. For example, several heavy metals reduce seed germination, impair root growth, reduce the acquisition of other nutrients, affect chlorophyll production, reduced protein content, cause genotoxic effects, and significantly reduced yields (Kemper *et al.*, 2020; Singh *et al.*, 2015; Peralta *et al.*, 2001; Nagajyoti *et al.*, 2010). However, there are substantial differences between heavy metal uptake and tolerances between and within plant species (Goyal *et al.*, 2020). In some soils, heavy metals accumulate naturally via the weathering of heavy metal rich rocks, whereas reducing conditions in the soil and a low pH can furthermore increase the solubility of heavy metals in minerals (Weil and Brady, 2017). Heavy metals can also accumulate in soils via human induced activities related to mining, emissions from industrial areas, leaded gasoline and paints, fertilizers, sewage sludge, electronic waste landfills, and pesticide use, amongst others (Brevik *et al.*, 2017). Additionally, soil can contain residual amounts of toxins like persistent organic pollutants (Dioxin, PCB, BPA, PBDEs, DDT, phthalates etc.) and pesticides (Aktar *et al.*, 2009), which can disturb numerous functions within plants like the synthesis of RNA, lipids, proteins, and photosynthetic pigments (Zhang *et al.*, 2017).

2.4.2.2 Soil toxicological links to animal health

When animals consume plants that contain critical amounts of toxic substances, their health can be impaired. Most of the non-essential heavy metals (As, Cd, Cr, Pb, Hg) can cause a broad range of health impairing symptoms (reviewed by Kemper *et al.* (2020), table 2.4, p.46) and can lead to death when higher amounts are consumed (Gupta, 2007). Lead (Pb) poisoning is the most common heavy metal toxicosis in domestic animals, of which cattle are the most affected (Gupta, 2007; Mavangira *et al.*, 2008; Bischoff *et al.*, 2012). As an example, Bischoff *et al.* (2012) found Pb poisoning in grazing cattle that consumed forage grown on Pb-contaminated soils. Despite the harmful (diarrhea, blindness, bruxism, or seizure) and fatal effects of lead poisoning through very high dosages, an equally severe problem is the subclinical chronic exposure to lead, that in further consequence poses additional risks to humans.

Other toxic substances like persistent pesticide residues consumed through feed or taken up via direct contact with soil can e.g. reduce milk productivity, cause appetite and weight loss, alopecia, and calf loss (Kemper *et al.*, 2020; Smith and Oehme, 1992). Pesticides have furthermore shown to cause SLUD (salivation, lacrimation, urination, diarrhea) signs, lung edema, tremors, ataxia, and even death for ruminant species, (Aktar *et al.*, 2009; Gupta, 2007). Importantly, in an analysis of 314 EU agricultural soils, 76 different pesticide residues were found, with 83% of the soils contained at least one pesticide and 58% contained mixtures of pesticides, which need particular attention due to widely unknown combined effect (Silva *et al.*, 2019). Moreover, the high loading of pesticide residues raises concerns due to still little understood effects on soil functions and biodiversity (FAO and ITPS, 2017). Also, negative effects of pesticides on non-target insects like bees are accumulating (Main *et al.*, 2020; Walsh *et al.*, 2020).

Another threat to animal health is when ruminants graze on microplastic polluted soils. Beriot *et al.* (2021) showed that sheep that grazed on soils containing plastic mulch residues took up substantial amounts of microplastic. Additionally, after sheep ingested microplastic, plastic residues were found in their faeces, and they thus could become a source of microplastic contamination when grazing on another field. Although there is hitherto little research about adverse health effects of plastic ingestion, potential effects include indigestion, ruminal impaction, recurrent ruminal tympany and intestinal obstruction (Kühn and van Franeker, 2020; Priyanka and Dey, 2018). Plastic debris might additionally sorb toxic chemicals during its degradation such as heavy metals and other toxic substances used during manufacturing. Increased levels of heavy metals were found in rumen fluid, blood, liver, kidney and muscles of buffaloes ingesting microplastics (Mahadappa *et al.*, 2020).

2.4.2.3 Soil toxicological links to human health

The major toxicological focus of soil-human health links is also on heavy metals (Li *et al.*, 2018; Lal, 2020). High levels of heavy metals can negatively affect liver, brain, kidneys, and lungs, and even low levels of heavy metal exposure can result in neurological and physical degenerative processes (such as Parkinson disease and Alzheimer disease), and cancer (Järup, 2003). The impacts of heavy metal exposure on humans has recently been summarized in various studies (Song and Li, 2015; Adimalla, 2020; Azeh Engwa *et al.*, 2019).

Other soil toxins that can be harmful to humans are organic chemicals often derived from pesticide use, which are associated with an increased risk of developing several chronic diseases like diabetes, cancer and asthma, as well as multiple short-term problems like dizziness, nausea, skin and eye irritation, and headaches (Kim *et al.*, 2017). Many of them are considered “persistent organic pollutants” due to their very long half-life in soils. These organic chemicals are typically highly diluted in the upper soil layers where they can also form various chemical mixtures about which there are very little toxicological studies (Brevik and Sauer, 2015).

One form of direct exposure to soil toxins that has received considerable attention is geophagy, the ancient practice of deliberate ingestion of soil that is still practiced today (Abrahams, 2003). Although “dirty eating” can have positive health effects such as the supply of Ca, Cu, Fe, Mn, Mg and Zn contained in the soil, it is also associated with nutrient deficiencies due to elemental absorption in the gastrointestinal tract, nutrient toxicities due to excess supply of one or more elements, or the concomitant ingestion of various toxic substances (Abrahams, 2002; Abrahams, 2003).

Soils indirectly influence human health through their effect on water quality, since their biophysico-chemical properties influence the relationship between runoff versus infiltration (Wall *et al.*, 2015) and their capacity to filter pollutants (Zimnicki *et al.*, 2020). Water quality is increasingly compromised through pollution with heavy metals, agrochemicals, and other harmful agents, and when soil health is impaired by e.g. erosion or surface sealing, that polluted water can more easily reach adjacent water bodies, groundwaters and aquifers (Wall *et al.*, 2015). In contrast, a healthy soil amount of agricultural runoff and associated contamination of adjacent land areas, (2) improves the water-use efficiency of crops, and (3) filters out toxins and pathogens, for which the soil biology enhances the infiltration and percolation of water through the soil profile and thereby (1) limits the is of particular importance (Lehmann *et al.*, 2020; Wall *et al.*, 2015).

2.4.3 Soil microbial links

The emerging soil health literature has a strong focus on soil biology, which was up until recently underrepresented in comparison to soil chemistry and physics (Doran and Zeiss, 2000) (BOX 1). Although soil macroorganisms like e.g. earthworms are long known to be key components of healthy soils (Darwin, 1881; Griffiths *et al.*, 2018), soil microorganisms have been more extensively researched, particularly in relation to the health of plants, animals, and humans (Hirt, 2020; van Bruggen *et al.*, 2019). Soil microorganisms are crucial for most soil functions, including biomass production, climate regulation, nutrient cycling, and the provision of clean water and air (Lehmann *et al.*, 2020). Major research areas in the context of One Health are antibiotics (Tyrrell *et al.*, 2019; Durso and Cook, 2019), individual soil pathogens (Hough, 2007) as well as the role of the soil microbiome (van Bruggen *et al.*, 2019; Hirt, 2020; Pepper and Brooks, 2021).

Soil microorganisms are an essential source of medicine. Between 1983 and 1994, 60% of new cancer drugs were derived from soil organisms, and roughly 40% of all prescription drugs have their origin in soils (Pepper *et al.*, 2009). Within the same time period, 78% of all approved antibiotic agents had their origin in soil microorganisms, whereas the first antibiotic ever to be discovered, penicillin, was isolated from a soilborne fungus *Penicillium* by Sir Alexander Fleming in 1929 (Fleming, 1942). In 1943, the Noble Prize was awarded to Selman Waksman for discovering streptomycin, an antibiotic isolated from *Streptomyces griseus* (Pepper *et al.*, 2009). However, although antibiotics have been highly successful in treating various bacterial infections, their overuse and misuse has substantially increased the occurrence of antibiotic resistant bacteria, significantly threating ‘One Health’ (Zhu *et al.*, 2018; Wang *et al.*, 2021).

The soil microbiome has received increased attention in the recent years (Flandroy *et al.*, 2018; Blum *et al.*, 2019). A microbiome comprises a characteristic microbial community - Prokaryotes (Bacteria, Archaea) and Eukaryotes (e.g., Protozoa, Fungi, and Algae) - in a well-defined environment with distinct physicochemical properties, such as the human gut (Berg *et al.*, 2020). The microbiome not only refers to the entire collection of microbial communities (microbiota), but involves their collective “theatre of activity” that forms specific ecological niches (van Bruggen *et al.*, 2019; Berg *et al.*, 2020). Microbiomes are considered dynamic and interactive micro-ecosystems that are integrated in macro-

ecosystems such as eukaryotic hosts like humans and animals. The health of the host is considerably influenced by the microbiome since it affects the development and functioning of almost all organs, contributes to adaptation, and protects against pathogens and toxins (van Bruggen *et al.*, 2019). Health research has laid particular focus on the effects of the mammalian gut microbiota (Fan and Pedersen, 2021; Lee and Hase, 2014), although it remains a challenge to define “health-promoting” and “disease-predisposing” gut microbiomes (Flandroy *et al.*, 2018). More recently, cross-kingdom similarities in microbiome functions have been revealed between the mammalian gut and the plant rhizosphere (microbiologically rich area around the plant roots), which, like the gut, promotes the breakdown of food (in the plant´s case breaking down organic materials, rocks and minerals, and subsequently releasing their constituent nutrients), and influences the plant´s tolerance to (a)biotic stress resistance (Mendes *et al.*, 2011). Furthermore, the significance of the soil microbiome has been equally stressed for its role in e.g. for nutrient cycling, greenhouse gas emissions, and pest and disease resistance (Hultman *et al.*, 2015; Wall *et al.*, 2015; Pepper and Brooks, 2021). Importantly, microbial communities are continuously cycled between the soil, plants, animals, and humans, and thereby influence the condition of all organisms and habitats involved (van Bruggen *et al.*, 2019).
Within the soil microbiota, various pathogens occur, including bacteria, viruses, fungi and protozoa (Pepper, 2013). These pathogens can infect and impair plant health, and thereby threaten the health of animals and humans consuming it. Furthermore, numerous cases report pathogen transmitted diseases for humans and animals via direct exposure to soils (Kemper *et al.*, 2020; Cook, 2000). There are various pathogens that are indigenous in soils, although a substantial number can be introduced via contaminated water, municipal and clinical waste streams, and animal and human excrements (Brevik *et al.*, 2020). In the following, examples will be given regarding the effects of soil microbes on plant, animal, and human health, focusing on the soil microbiome, soil pathogens, and antibiotics.

2.4.3.1 Positive soil microbial effects on plant health

The soil microbiome can positively effect plant health by influencing the soils suppressiveness to diseases (Schlatter *et al.*, 2017). Depending on the soil’s microbial makeup, pathogens do not establish or persist so that plant diseases are prevented or reduced. Diseases suppressiveness in soils is rendered by a ‘general’ and a ‘specific’ suppression, which exist on a continuum to each other (Weller *et al.*, 2002).
General suppression is provided by the collective antagonistic activity of the whole soil microbiome competing with the diseases causing pathogen(s) and is thus favored by an increased diversity of the soil microbiome (Cook, 2014). An early example was the suppression of Phytophthora root rot in an avocado grove in Queensland, Australia, which remained healthy for several decades despite the soil’s infection with the root pathogen Phytophthora cinnamomic, whereas the neighboring groves were

severally affected by Phytophthora root rot. The suppressiveness was associated with significantly higher soil organic matter, the diversity, and the size of the microbial biomass (Schlatter *et al.*, 2017). Likewise, soils with increased microbial activity showed a reduce severity of tomato corky root (Workneh and van Bruggen, 1994) as well as lettuce corky root (van Bruggen *et al.*, 2015). Another example highly relevant for One Health is the fate of the enterohemorrhagic Escherichia coli (EHEC) O157:H7, for which survival rates have been found to have an inverse relationship to soil microbial diversity (van Elsas *et al.*, 2012).

In contrast, specific suppressiveness results from individual species or select group of microorganisms which are transferable between soils (Schlatter *et al.*, 2017). Examples include specific suppressiveness against take-all, an agronomically severe root diseases for wheat, barley, rye, and triticale, against which breeding has been unsuccessful and methods for chemical control are limited. Successful transfer of take-all suppressiveness has been shown by adding 1-10% of the suppressive soil and adding it to previously conducive soils (Raaijmakers and Weller, 1998; Weller *et al.*, 2002; Cook, 2007). Similarly, Wei *et al*. (2019) found that soil transfer induced a microbiome-mediated protection of tomatoes from *Ralstonia solanacearum* bacterium under field conditions.

Interestingly, soil diseases suppressiveness is in turn also influenced by the respective plant community, which, depending on the species, exerts various changes in biotic and abiotic soil properties, particularly related to mechanisms of the rhizosphere (Latz *et al.*, 2016). Again, diversity in plant communities is suggested to foster a diverse and beneficial soil microbiome that limits excess proliferation of pathogens (Flandroy *et al.*, 2018).

The patterns of general and specific soil diseases suppressiveness have been compared to those of innate and adaptive immunity in animals (Raaijmakers and Mazzola, 2016). General soil suppressiveness and innate animal immunity both provide an immediate and non-specific defense against pathogens, whereas both specific soil suppressiveness and adaptive animal immunity need time to react to a pathogen, are pathogen specific, and develop a memory of the previously encountered pathogen (Raaijmakers and Mazzola, 2016).

Importantly, several studies have found that organically managed soils increase the diseases suppressiveness against various soil borne pathogens (van Bruggen and Termorshuizen, 2003; Gu *et al.*, 2013; Hiddink *et al.*, 2005; Workneh and van Bruggen, 1994; Bonanomi *et al.*, 2018). The overall mechanisms are still poorly understood, although most of the outlined studies associated the increased diseases suppressiveness in organically managed soil with a higher microbial diversity and the occurrence of specific bacterial genera, as well as the combination with crop rotations and high-quality organic amendments.

2.4.3.2 Negative soil microbial effects on plant health

Although there have been significant advances in plant health management against above ground pathogens and pests arriving through air, comparably little progress has been achieved against below ground soil pathogens (Cook, 2000). Apart from the emerging insights about diseases suppressiveness of soils outlined in the previous section, the eradication of soil borne pathogens is more difficult than the control against discrete above ground pathogen infestations since common pathogens like *Rhizoctonia* spp, (Sturrock *et al.*, 2015), *Sclerotinia* spp. (Smolińska and Kowalska, 2018), *Pythium* spp. (Martin and Loper, 1999), *Fusarium* spp. (Summerell *et al.*, 2010), and *Verticillium* spp. (Goicoechea, 2009) can survive in the soil even when their previously infected host crops are no longer present (Cook, 2000). Furthermore, there are currently few plant species with resistant varieties against soilborne pathogens, since selective breeding is difficult given complex belowground microbial interactions and specific environmental conditions influencing microbial dynamics (Cook, 2014). Soil pathogens can impair plant health in various ways, for example damping-off seedlings, aerial blights, root rots, and stem cankers (Kemper *et al.*, 2017). Furthermore, many of these pathogens affect major staple crops, such as *Rhizoctonia solani*, a soilborne pathogen that can cause severe diseases pressure and yield losses for soybean (Meyer *et al.*, 2006) and tomatoes (Gondal *et al.*, 2019).

Additionally, rising health concerns regarding the increased usage of antibiotics and the spread of antibiotic resistant genes (ARG) have mostly been related to animal and human health, although plant health can be equally affected. Kumar et al. (2005) have shown that corn (*Zea mays* L.), green onion (*Allium cepa* L.), and cabbage (*Brassica oleracea* L. Capitata group) all take up chlortetracycline from soil amended with antibiotic containing hog manure. This uptake can lead to phytotoxic, hermetic (stimulation of positive impact by a toxin in subinhibitory concentration) as well as mutational effects in plants, dependent on the species and the antibiotic used (Tasho and Cho, 2016). Overall effects seem to depend on the antibiotic amount and the plant species (Tasho and Cho, 2016), since some studies found significant growth inhibition when grown on antibiotic laden soils and substrates (Migliore *et al.*, 1997; Wei *et al.*, 2009; Li *et al.*, 2011; Abou-El-Seoud and Abdel-Megeed, 2012), whereas Michelini *et al.* (2014) found increased growth for willow plants.

2.4.3.3 Positive soil microbial effects on animal health

Although it is suggested that environmental microbiomes affect mammalian health particularly through effects on the gut microbiome, there is currently very limited evidence about the influence of the soil microbiome on the health of agricultural animals (Pepper and Brooks, 2021). The studies found in this context analyzed differences between caged and free-range chickens, for which a major difficulty is to discern between the specific influence of the soil and the other environmental factors. It has been shown that free-range chickens have different gut microbial community compositions and an significantly increased diversity compared to indoor housed or caged chickens (Hubert *et al.*, 2019; Chen *et al.*, 2018; Xu *et al.*, 2016), whereas Schreuder *et al.* (2020) found that outdoor environments were responsible for only a relatively small proportion of the gut microbial community variation of layer chickens.

For non-agricultural animals, more specific studies were conducted. Grieneisen *et al.* (2019) found that soil was the most dominant predictor for the gut microbiota of 14 baboon populations living in geographically distinct areas. Soil was a 15 times stronger predictor than host genetics, likely because baboons are terrestrial and incidentally consume soil with their food. Particularly, baboons from high pH and sodium rich soils had the lowest alpha diversity, agreeing with typically less diverse and stable soil microbial communities on alkaline and sodic soils (Fierer and Jackson, 2006; Rietz and Haynes, 2003), thereby supporting the connection of soil biodiversity and gut biodiversity.
Gut microbial diversity of mice was significantly enhanced when they were exposed to a soil from a farmhouse compared to a sterilized soil, while all other variables like diet and genetic background were identical (Zhou *et al.*, 2016). The authors relate the specific increases in gut microbial diversity to an increased immune system functioning. Bai *et al*. (2016) showed that merely adding environmental microbes to sterilized bedding material increased the gut biodiversity of mice but had little effect on the composition of dominant bacteria in the gut microbiota. In contrast, Zhou *et al.* (2018) found that unsterilized soil increased the diversity and the community composition of mice gut microbiota to a similar degree as diets.
Among the most researched soil inhabiting microorganisms is *Mycobacterium vaccae*, a bacterium with anti-inflammatory, immunoregulatory, and stress resilience properties (Smith *et al.*, 2019). *M. vaccae* has been shown to promote stress resilience in mice (Reber *et al.*, 2016) and to attenuate stress related reductions in gut microbiome diversity (Foxx *et al.*, 2020). Similarly, Matthews and Jenks (2013) provided evidence that ingestion of *M. vaccae* decreases anxiety-related behaviour and improves learning in mice.
Importantly, some of the outlined studies (Matthews and Jenks, 2013; Bai *et al.*, 2016) were criticized for unrealistic microbiota exposure not representative of passive natural exposure (Liddicoat *et al.*, 2020). Liddicoat *et al.* (2020) thus exposed mice to realistic amounts of trace level dust from various soils, and found that soils with a high microbial diversity (compared to low diversity soils, or no soil) significantly altered the gut microbiota of mice and increased rare microorganisms that correlated with reduced anxiety-like behavior.
However, the soil microbial composition is furthermore not only influencing animal health, but is in turn also influenced by animals, which is not further addressed here, since it was reviewed comprehensively elsewhere (Rayne and Aula, 2020).

2.4.3.4 Negative soil microbial effects on animal health

Animal health can be threatened by various infections with soil borne pathogens, including (1) bacteria like *Clostridium* genera (Palmer *et al.*, 2019), E. Coli (Ercumen *et al.*, 2017), *Salmonella* sp. (Jacobsen and Bech, 2012), and *Leptospira* spp. (Alonso-Andicoberry *et al.*, 2001), (2) parasites like various hookworms (Smout *et al.*, 2017; Otranto and Deplazes, 2019), (3) viruses like goat pox (Kemper *et al.*, 2020), and fungal diseases that – although rare – can e.g. transmit avian respiratory aspergilliosis (Pepper and Brooks, 2021). The majority of the pathogens found in soil are indirectly transmitted via contaminated forage (Driehuis *et al.*, 2018), whereas a smaller part is vectored over direct contact with soils (Pepper and Brooks, 2021). Poultry for example, whether industrialized or wild, often feed on soil or litter and thereby increase the exposure to pathogens like *Clostridium perfingens*, which preferentially grows where feces has been deposited (van Immerseel *et al.*, 2004). Furthermore, tall nutrient-rich swards typically grow around fecal deposits and are attractive for ruminats (Smith *et al.*, 2009). However, such swards surrounding feces (from the ruminants themselves or other animals) pose considerable risk for parasite or diseases transmission, since pathogens can reside in the feces as well as in the surrounding soil. Several studies suggest that grazing close to e.g. badger feces contaminated soils poses the risk of tuberculosis transmission to cattle, either by direct ingestion of contaminated swards or via aerosolized inhalation (Hutchings and Harris, 1997; Jenkins *et al.*, 2008; Scantlebury *et al.*, 2004).

Another threat to herbivorous animals is Bacillus anthracis, the bacteria that causes anthrax. Although significant successes have been achieved since the early last century in reducing Anthrax infections, increased incidence rates were reported in the last decades, especially in Sub-Saharan Africa (Driciru *et al.*, 2020). One typical route of infection is via contaminated soils, since Anthrax causing spores can survive in soils for several decades (WHO, 2008). Soil properties play a role in the survival of B. *anthracis*, and tends to be higher in moist, nutrient rich, and alkaline soils (van Ness, 1971; Horvath and Reid, 1984). For prions, “pathogenic proteins” that can cause fatal neurological diseases in animals and humans, increased infection transmission rates were observed for clayey soils (Walter *et al.*, 2011; Saunders *et al.*, 2012).

2.4.3.5 Positive soil microbial effects on human health

The recently postulated microbiome hypothesis proposes evolutionary and ongoing interlinkages between the soil and the human intestinal microbiome (Blum *et al.*, 2019). Phylogenetically, humans evolved in close contact to soils as their basis for living, and the intentional and unintentional ingestion of soil thereby supported the potential transmission of soil microbiota for gut colonization

(Blum *et al.*, 2019). Recent evidence supports the microbiome hypothesis, showing that environmental microbial soil taxa were found among the host-associated gut taxa (Schnorr, 2020).

However, modern urban lifestyle limits the exposure of humans to soil and its microbial diversity, which is proposed as a key factor for the decreasing human gut microbiota diversity of urban citizens compared to hunter-gatherer populations (Rook *et al.*, 2014; Flandroy *et al.*, 2018; Blum *et al.*, 2019). Consequently, the 'hygiene'- or 'old friends' hypothesis suggests that reduced exposure to environments rich in microbial diversity contributes to an uneducated immune system that increases the prevalence of allergies and autoimmune disorders (Rook *et al.*, 2014). Human health benefits are hereby not only induced by diverse commensal microbes, but also by an exposure to possible soil pathogens that trigger immunoregulatory reactions necessary for developing tolerance (Djordjevic *et al.*, 2013).

Several studies have shown a decreased prevalence in allergic diseases when humans were exposed to soil microorganisms (Matricardi and Bonini, 2000; Kay, 2000; Hanski *et al.*, 2012; Haahtela *et al.*, 2008). Reintroducing humans to their "old friends" is thus proposed as an intervention to increase human health. Accordingly, Roslund *et al*. (2020) analyzed the effects of a biodiversity intervention on the commensal microbiome of daycare children. For the intervention, the yards of the daycare centers were enriched by covering them with forest soil and grass After 28-days, those children exposed to the intervention showed a significantly diversified skin microbiome and modulated gut microbiota, with suggested beneficial stimulations of immunoregulatory pathways (Roslund *et al.*, 2020).

2.4.3.6 Negative soil microbial effects on human health

Soil pathogens include the tetanus causing *Clostridium tetani* and the anthrax causing *Bacillus anthracis* that kill millions of people worldwide (Singh *et al.*, 2017). Other diseases causing pathogens include fungi like *Blastomyces sp* or *Cryptococcus* and several protozoa. Recently, the inclusion of soils in One Health studies revealed hitherto neglected transmission mechanisms about the public health threat *Ancylostoma ceylanicum,* the common hookworm of cats and dogs throughout Aisa (Traub *et al.*, 2007). *A. ceylanicum* is currently emerging in tropical northern Australia, but little is understood about its mechanisms of transmission (Smout *et al.*, 2017). An analysis of six rainforest locations in Indigenous Australian communities, which are popular tourist attractions, found presence of *A. ceylanicum* infections in domestic dogs of indigenous communities and, for the first time, in various soil samples across the six rainforest locations. The authors stress the importance of further integrating soils in risk reduction of hookworms, since many residents, particularly children, are barefoot during the warmer months and thus potentially come into direct contact with infected soils (Smout *et al.*, 2017).

2.5 Debate on soil health

The previous chapter has presented examples of how soil health is connected to plant, animal and human health. However, apart from the outlined health connections *per se*, when can a soil be considered healthy? And how can soil health be measured and operationalized? In contrast to yield as prime indicator for soil fertility, the most common approach to measure soil health is to assess multiple soil chemical, physical, and biological properties. For example, chemical indicators involve nutrient content and pH, physical indicators like water storage and bulk density, and biological indicators such as N mineralization, microbial biomass, and enzymes (Moebius-Clune *et al.*, 2016). A popular set of soil health indicators is provided by the Soil Health Institute, comprising 19 'Tier 1' and 12 'Tier 2' soil health indicators that are shown in Table 2. In contrast, soil fertility is mostly described according to the soil´s ability to supply sufficient nutrients and water for plant growth (Bünemann *et al.*, 2018), although some author´s like e.g. Mäder *et al.* (2002) extend the scope of soil fertility to "a diverse and active biotic community". Nevertheless, soil fertility is generally operationalized in terms of crop nutrients and water only (Bünemann *et al.*, 2018).

Table 2: Tier 1 Soil Health indicators in black and Tier 2 indicators in blue font. Source: Soil Health Institute (2021)

Chemical	Physical	Biological
Base saturation	Available water holding capacity	Crop yield
Cation Exchange capacity	Bulk density	Nitrogen mineralization
Electrical conductivity	Infiltration rate	Organic carbon
Nitrogen	Erosion rate	Carbon mineralization
Micronutrients	Penetration resistance	Active Carbon
pH	Texture	Soil Protein Index
Phosphorus	Water stable aggregation	B-Glucosidase
Potassium	Aggregate Stability	N-Acetyl-B-D Glucosaminidase
Sodium Adsorption Ratio (SAR)	Soil Stability Index	Phosphomonoesterase
	Reflectance	Arylsulfatase
		Phospholipid Fatty Acid (PLFA)
		Genomics (e.g. 16S rRNA, shotgun metagenomics)

Although the number of suggested indicators steadily increased in the last years and likely further grows in the coming years, and despite numerous proposals about their integration, no consensus has been reached about which indicators to select and how to operationalize them (Lehmann *et al.*, 2020; Baveye, 2021b). These difficulties in measuring and operationalizing soil health have been the cornerstone of long-standing debates and critical views (Lehmann *et al.*, 2020). Besides three recent critical papers about soil health (Baveye, 2021b; Powlson, 2020, 2021), several in-depth critiques have been published against the soil quality concept already several decades ago (Letey *et al.,* 2003 and references therein), including one co-written by the "father of the green revolution" and Noble Laureate Norman Borlaug (Sojka *et al.*, 2003) and one by the 2002 World Food Prize recipient Pedro Sanchez and co-authors (Sanchez *et al.*, 2003). However, these critiques are often bypassed in the literature, thus leading to the impression that soil health is unequivocally embraced by the scientific community (Powlson, 2020). Baveye (2021b) argues that in the absence of a generally agreed upon definition for soil health, an operational means to measure it, and a common rational of how to proceed, future research and debates will likely lead to further confusion among scientists, environmentalists and decision makers.

Given the exponential increase in soil health publications (Janzen *et al.*, 2021) and the increasingly widespread usage of the term outside academia, it is crucial to re-visit and review the concerns as well as the potentials of soil health, in order to channel future research into feasible directions.
The major aim of the following section is to first summarize some of the major and mostly by-passed concerns regarding the soil health concept. Then, those potentials of soil health will be outlined that are also acknowledged by its critics, and, finally, the concept will be discussed in the context of recent projects and some propositions will be made regarding its operationalization.

2.5.1 Problems

Measuring soil health aims to quantify the various functions that soils fulfill, yet there is consistent disagreement about which indicators are best suited to capture the multifunctionality of soils. Bünemann *et al.* (2018) conducted one of the most comprehensive reviews about soil quality, its assessment, and indicators. Despite some differences regarding the conceptual approaches between soil quality and soil health, particularly regarding biological indicators, the overall findings from Bünemann *et al*. (2018) are equally important and expressive for soil health. Although they found at least 65 different soil quality indicator sets, including 27 frequently (mentioned in at least 10% of the studies) proposed indicators, and despite 24 years having been passed since initial conference proceedings devoted specifically to this topic (Doran and Jones, 1997), there is no consensus regarding a robust and generally agreed upon way to measure soil quality or health (Bünemann *et al.*, 2018; Lehmann *et al.*, 2020; Baveye, 2021a). Particular critique is targeted towards the aim to synthesize various chemical, physical, and biological indicators into a final soil health index (Lehmann *et al.*, 2020).

The underlying premise - the possibility and necessity to create one single, top-down, ‘measure everything’ soil health index - is argued to be the central underlying flaw, since soils are highly heterogenous and naturally differ in their capacity to fulfill various functions, and so the approach and benchmarks have to differ according to the soil’s context (Sojka and Upchurch, 1999; Letey *et al.*, 2003; Sanchez *et al.*, 2003). Various critics thus opine that any soil health index value means nothing in isolation, but only derives meaning when it is related to a specific function of a specific soil. For example, within the context of a forest ecosystem, an acidic and low nutrient soil could be regarded as ‘healthier’ in regard to growing trees, yet the same soil would likely be less ‘healthy’ when growing horticultural crops are considered (Powlson, 2021). Furthermore, if a more alkaline forest soil developed from calcareous parent material and various well-adapted trees and shrubs grow well on this soil, one could hardly conclude that this soil is more or less healthy than the other forest soil. Similarly, in the context of agricultural soils, different crops require different soil properties such as pH, nutrient content, or physical conditions (Letey *et al.*, 2003). A deep loamy soil may be ideal for growing wheat or corn, yet it would not offer the type of hydric stress required for vineyards (Baveye, 2021a). Therefore, what constitutes a healthy soil will depend on which function is under consideration (Weil and Brady, 2017), or in other words ‘different soil attributes are required depending on the use the soil is put’ (Powlson, 2020). When the eminent soil scientist Hans Jenny was asked what makes a soil good, he wisely replied: “Good for what?” (Logan, 1995, p.65).

Moreover, a major difficulty is that soils fulfill various functions simultaneously and that the capacity to fulfil one function can be in direct conflict with the capacity to fulfill another function (Baveye, 2021b). This is often represented by the function biomass production (yield) being in conflict with the functions of water purification or biodiversity conservation (Letey *et al.*, 2003). For example, Doran and Werner (1990) report that an organic farming system had higher levels of microbial biomass and potentially mineralizable nitrogen compared to a conventionally managed system, but lower levels of nitrate nitrogen in early spring. Lower potentially leached nitrate and higher microbial biomass were considered positive in regard to the soil functions water purification and habitat for soil organisms, whereas less nitrate at the beginning of the growing season had negative effects on the function biomass production. However, how should one decide upon which function weighs more or which soil is healthier? One way to tackle this problem is multicriteria decision making (MCDM), although the underlying problem is a substantial lack of primary quantitative data to underpin these decisions (Baveye *et al.*, 2016), with e.g. Keyvanfar *et al.* (2020) including soil health within MCDM, however, soil health is not further specified in terms of exact measurements or evaluation. Up to date, despite numerous efforts, no single soil health measurement proposal has achieved to properly assess various functions simultaneously (Bünemann *et al.*, 2018). This is largely because any endeavor to quantify and weigh various soil functions simultaneously would “quickly move toward unimaginable

complexity" (Powlson, 2020, p.248), since it would require a numerical synthesis of highly heterogeneous measurements into a final single value score, adapted to numerous individual soil types and other site-specific factors (Sojka *et al.*, 2003).
It is furthermore argued that a single soil health value would likely be of little utility for the practitioner, since interpreting the final soil health value would likely require deconstructing it again. For example, given a low soil health value, the farmer needs to know the specific cause, i.e. whether it is due to acidity or due to low specific nutrient contents, so that he or she can decide upon the proper management intervention like liming or a specific fertilizer (Powlson, 2020).

Another issue is to find appropriate benchmarks for a given soil health indicator. A common proposal is that indicator benchmarks for a given soil should be orientated to the same soil under "natural" uncultivated conditions (Dick, 2018; Sojka and Upchurch, 1999). However, this would often create distorted and not attainable benchmarks, particularly for biological properties like biodiversity. Again, the conflict occurs most obviously for the productivity function versus other functions related to safeguarding the environment, since modern soil management aiming to improve yields often impairs biodiversity or water quality (Letey *et al.*, 2003; Foley *et al.*, 2005). Sojka *et al*. (2003) argues that aiming to tie soil indicators to levels believed to be reflective of natural benchmark conditions runs danger of working at cross purposes with the utilitarian *raison d´etre* of agriculture, which is humankind´s strategy for survival by vastly exceeding the low productivity of soils in their natural unmanaged benchmark state.

Furthermore, even if there would be a theoretical agreement on several soil health indicators and their benchmarks, the feasibility of their practical measurement and wide-scale assessment is questioned (Baveye, 2021b; Letey *et al.*, 2003). For each indicator several measurements exist, the assessment of which partly requires multiparametric analysis. When a single indicator like microbial biomass is considered for the average EU farm size of 16.1 hectare (Henrard and Forti, 2016), how many samples would adequately characterize the soil condition without risking improper spatial representation? How does one decide where, when, how and how often samples would have to be taken? Who decides about the analytical approach? How long will the assessment take and how much can it cost for farmers with limits determined by time, space and money? Most of these questions can be repeated for each indicator and measurement choice (Letey *et al.*, 2003; Sojka and Upchurch, 1999). Bünemann *et al.* (2018) outlined that even the average number of 11 soil health indicators is likely economically and practically not feasible under most circumstances.

Concerns are also uttered regarding the measurement method of the indicators. One example are biological indicators, which have received increased attention as indicators for soil health in the recent decade (Lehmann *et al.*, 2020). Most of the soil biological processes are governed by soil microbes, and thus soil microbial counts and activity are key biological indicators for soil health. However, representative soil microbial measurements are difficult, exemplified by the shortcomings of the current gold standards for evaluating microbial counts and activity, namely heterotrophic plate counts (HPCs) and dehydrogenase activity (Pepper and Brooks, 2021). The reasons are that HPC counts obtained through dilution and plating detect only a small portion of the total microbial population since many bacteria are non-culturable and that culture dependent analysis can capture “the rare biosphere”, which are oftentimes atypical members of the microbial community (Shade *et al.*, 2012). In fact, estimate suggest that >98% of soil microorganisms have never been cultivated in the laboratory, and so their mechanisms are unknown (Daniel, 2005). Similarly, dehydrogenase activity analysis does not appear to give sensitive enough information useful for soil health interpretation (Pepper and Brooks, 2021).

Overall, a major claim of the soil health critics is to stop focusing on increasingly complex, arbitrary and holisitc indices that are based on ill-defined concepts, and instead focus on site-specific soil management of known and discrete problems (Letey *et al.*, 2003; Sanchez *et al.*, 2003; Sojka *et al.*, 2003). Although the value of multiple soil measurements is recognized, it is argued that ‘even health assessments rely on “triage” to prioritize action’, such as an open chest wound takes priority over a blistered foot in the emergency room (Sojka *et al*., 2003, p.39). Similarly, for soil management, there is a need to focus the attention towards clearly identifiable, known, and critical problems. The philosophical basis of the soil health paradigm is claimed to be worrisome, since it suggests that entirely new soil assessment constructs are needed to identify the farmer’s most critical problems regarding food production and environmental protection. Quite the opposite, “the most important problems facing agriculture are simple to identify but usually frustratingly complex to solve” (Sojka et al., 2003, p.9), and the major difficulty arises in finding solutions that are viable for farmers with spatial, monetary, and time limitations.

2.5.2 Potentials

“All of our knowledge goes unused if people are not aware of” (Brevik *et al.*, 2020, p.15).

There are certain soil health aspects that even sceptics outline as important. One of them is the concept’s aptitude as a communication tool and stimulating metaphor (Dick, 2018; Powlson, 2020; Baveye, 2021b; Janzen *et al.*, 2021). Effective communication between soil scientists and non-specialists, especially with politicians, has become crucially important, since they are mostly the ones capable to influence land-use decisions and the management of soils (Powlson, 2020; Brevik *et al.*, 2020). In Germany for example, the protection of soil has been legally regulated since more than two decades (BMJV, 1998). One decisive historical event in this regard was the establishment of a soil quality committee in 1994 by the Soil Science Society of America. The aim of this committee was to "define the concepts of soil quality, examine its rationale and justification, and identify soil and plant attributes that would be useful for describing and evaluating soil quality" (Karlen *et al.*, 1997). Interestingly, this committee, and by and large the term soil quality, were established due to prior inabilities of soil scientists to effectively communicate the importance of soils (Powlson, 2020, 2021; Karlen *et al.*, 1997).

Thus, some of the major drivers of the soil quality concept were rooted in efforts to communicate the significance of soils more effectively. Importantly, the soil quality concept itself was widely accepted in the late 1990s within the soil science community, whereas one disputed aspect already back then was the previously discussed quantification aspect (Powlson, 2020). Nevertheless, soil quality, and later soil health, have since then been effective in this incipient aim to communicate soil science more effectively.

Today, soil health is receiving unprecedented recognition by professional organizations, public institutions, and the popular press (Dick, 2018; Griffiths *et al.*, 2018). For example, 2015 was declared as the Year of soils by the United Nations, the Noble Foundation recently established the Soil Health Institute, and the U.S. National Academy of Science is conducting several soil health workshops. Similar soil health initiatives are now in place in various other countries (EJP, 2021), and the European Union has launched "Soil Health and food", which is 1 of only 5 large EU horizon 2021-27 research programs (European Commission, 2020).

In this context, Janzen *et al.* (2021) argues that soil health is a metaphor and its communicative power lies in evoking an instinctive intellectual and emotional response in the reader. Soils are thereby associated with a sense of vulnerability to stress, a desire for renewal, and a striving for persistence – based on subconscious reflections of our own health (Janzen *et al.*, 2021). The power of the health metaphor, and likely the reason for its widespread appeal, could be its ability to incite a meaningful response towards the maintenance and sustenance of the given domain, be it humans, animals, plants, soils, or whole ecosystems (Ross *et al.*, 1997). An incentive to maintain and sustain soils is triggered irrespective of the degree to which the respective audience has grasped the complexity of soils (Janzen *et al.*, 2021).

Metaphors like soil health are not only capable to communicate with domains outside academia, but they also offer connective vocabulary between disparate disciplines and between sub-disciplines (Janzen *et al.*, 2021), which are particularly widespread in soil science (Hartemink, 2006). Health has "etymological roots of wholeness and completeness" (Mallee, 2017), and the potential of soil health as a metaphor is based on that it arguably implies a systems perspective. In contrast to earlier concepts like soil fertility and quality, soil health reflects the interwoven connectedness of soils with its environment. Soils are thus not perceived as stand-alone entities, but as dynamic constituents entangled in a complex web of ecological processes (Janzen *et al.*, 2021). Scientists from various disciplines can identify with the health metaphor, so that it provides a focus and rallying point for integrating and thereby forwarding knowledge (Lehmann *et al.*, 2020).

"When the human mind deals with any concept too large to be easily visualized, it substitutes some familiar object which seems to have similar properties" (Leopold, 1939).

It is important to remember that science relies on metaphors as concepts become more abstract and academic language fails to capture their complexity with precise wording (Brown, 2003; Janzen *et al.*, 2021). In fact, science builds on metaphorical foundations (Larson, 2014; Olson *et al.*, 2019) that seek to illuminate the opaque with the familiar (Janzen *et al.*, 2021). Examples involve white dwarfs, RNA editing, genetic blueprints, the greenhouse effect, or black holes (Montgomery, 2003). Such metaphors help to explain non-intuitive phenomena by augmenting stiff literalism with elastic imagery that draws from common human experience (Janzen *et al.*, 2021). Scientists tend to forget that our knowledge foundations rests upon metaphors (Brown, 2003). For example, the concept of electronic orbitals is first introduced by metaphors such as energy bands that electrons can jump between, and not by initially speaking of probabilistic distributions of electrons within resonance structures (Schimel, 2012). Lastly, as can be seen within the current debates about soil health, metaphors stimulate creative discussions that draw out insights not yet fully formed (Brown, 2003).

2.6 Discussion

The various One Health connections of soil health as well as its operational problems and potentials warrant a differentiated usage of the concept. A crucial starting point for any usage of soil health is a clear definition of the objectives, i.e. is the objective (1) a management recommendation for the land manager, (2) a tool for communication and education, or (3) a monitoring program (Bünemann *et al.*, 2018). In the following, the previously outlined problems, potentials, and interlinkages are discussed in the context of these three major objectives.

2.6.1 Management recommendations

The most important end-user of any soil health assessment is the land manager. In this context, the pursuit of a universal soil health index remains questionable and is arguably not meaningful since soil health is best assessed and managed in relation to a specific function of a specific soil type.

In this regard, the Cornell Soil Health Framework Manual (Moebius-Clune *et al.*, 2016) is unique since it includes not only a comprehensive soil health assessment, but also a subsequent section for soil health management including a farm orientated planning process. This is crucial because soil

health research has a strong focus on developing soil health indicators without further elaborating on potential management interventions or practical feasibility (Rinot *et al.*, 2019; Bünemann *et al.*, 2018; Amsili *et al.*, 2021; Xue *et al.*, 2019; Lehmann *et al.*, 2020). Fewer studies actually assess how different management practices influence soil health (Williams *et al.*, 2020; Idowu *et al.*, 2009) and no study or work was found that provides an equally comprehensive soil health management approach like the one from Cornell. As several other soil health studies conclude (Nunes *et al.*, 2018; Williams *et al.*, 2020; Norris and Congreves, 2018), the Cornell Soil Health Manual outlines reduced tillage options, crop rotations, cover crops, and organic amendments as major management options to improve soil health. However, the Cornell soil health management plan further includes a structured approach that takes into account the (1) farm background and management history, (2) agronomic goals and soil health samples, (3) constraints identification and prioritization of intervention, (4) identification of feasible management options, (5) creation of a short term and long term soil health plan, and (6) implementation, monitoring, and adaptation.
Importantly, even though the Cornell framework includes a 'soil health score', it is stated that "it is of greater importance to identify which particular soil processes are constrained in functioning or suboptimal, so that these issues can be addressed through appropriate management. Therefore, the ratings for each indicator are more important information." Soil health thus appears to be mainly used as an umbrella term to summarize the individual measurements (Powlson, 2021).

In reality however, comprehensive soil health assessments that are followed by soil management recommendations and interventions are rare, and only about 25% and 30% of American and Australian farmers, respectively, are conducting basic soil tests, of which the frequency furthermore varies strongly (Lobry de Bruyn and Andrews, 2016). Most of these tests are basic nutrient analysis aiming to determine fertilizer requirements, and many farmers who conduct these tests do even lack the necessary resources to interpret their tests.

Correspondingly, despite increasing publications and policy initiatives about the importance of soil health, most farmers still primarily focus on soils productivity function, the reasons for which were reviewed by Schroder *et al.* (2011). However, the persistent difficulties in resolving the dilemma between balancing the productivity function of soils and the other functions is not a weakness of the soil health concept but represent one of the core challenges towards a more sustainable agriculture. In other words, deciding upon an adequate weighting between yield and e.g. biodiversity conservation has not been a typical task for soil scientists. Soil health is a holistic concept that "cuts across ethnic, cultural, and economic strata of society…" (Dick, 2018) and the questions it raises exceed the frame of consideration of those aiming to preserve the "value-neutral tradition of edaphology" (Letey *et al.*, 2003). Measuring soil properties can be done in objective and reductionistic ways, however, the question of how soils can and should be managed in more sustainable ways cannot be answered in purely reductionistic ways since the facts gathered by these measurements are "almost always wrapped in multiple layers of value-laden contexts" (Döring, 2019). Accordingly, Bouma (2021) argues that these questions cannot be answered in the common reductionist way of scientific reasoning ("define problem, do research and find solution"), since science and its research agenda are part of a dynamic real-world nexus that involves farmers, nature conservationists, the public and policy. Within this nexus, scientific insights, boundary conditions, and values change constantly, and so definitions, insights, questions, and answers change constantly and cannot be finally answered. Therefore, although it is important to remain practical and focus on clearly identifiable problems, there is no escape from confronting the complexity of dynamic and interdisciplinary boundary conditions that cannot be tackled by purely reductionistic means. In this context, soil health should not be seen as a rigid measuring construct, but as a metaphor that aids to jointly approach the essence of a concept too complex to be ultimately conceived (Janzen *et al.*, 2021) and to stimulate necessary debates.

2.6.2 Educational and communication tool

It is beyond the scope of any single discipline to resolve the interconnected challenges that threat soils and thereby animal, plant, and human health. This can only be achieved by integrated transdisciplinary efforts that involve policy makers, farmers, citizens, and scientists from various domains. A pre-condition for successful collaboration is effective communication, for which soil health has become an important tool, since it enables stakeholders from various domains to speak a common language (Bünemann *et al.*, 2018). Importantly, soils are in the tension field of various interdependent stakeholders that have contrasting demands (Ng and Zhang, 2019). Hereby soil health constitutes a boundary concept that enables various stakeholders to develop a common language and envision a joint roadmap for action (Schleyer *et al.*, 2017; Bünemann *et al.*, 2018).

Besides the stakeholders more directly involved into the management of soil health like politicians and land managers, involving the broader public into ongoing debates about the importance of managing soils sustainably is crucial (Brevik *et al.*, 2020; Lehmann *et al.*, 2020). This demands educating the public about the huge significance that soils have on their lives, since only an educated citizenry will be able to enforce appropriate decisions or support them through democratic channels (Baveye *et al.*, 2016). We are far from that. Ehrenfeld (1988) noted that the fact that we need to write articles about the value of soils (and nature in general) shows the extent to which they are in trouble, and this conclusion still holds true up until today (Brevik *et al.*, 2019). In this respect, soil health constitutes an easy and attractive entry point for didactic programs that aim to explain the nature and importance of soils to the broader public (Baveye *et al.*, 2016).

Nevertheless, it is argued here that soil health, and health in general, are social constructs (Nielsen, 1999) and metaphors (Janzen *et al.*, 2021), and it is thus questionable if it will ever be possible to quantify all the functions that soil health conceptually encapsulates (Powlson, 2020; Baveye, 2021b). However, the fact that such functions cannot (yet) be fully measured does not negate their capability to advance our understanding of soils. Similarly, a conceptual understanding of soil´s interconnections to food security and the sustainable development goals (SDGs) is not invalidated only because one cannot measure *all* of these interconnections. Our inability to quantify the world should not deter research, or as Meadows and Wright (2009, p.3) argue: “pay attention to what is important, not just what is quantifiable”.

2.6.3 Monitoring programs

Despite the importance of context-dependent and farm specific soil management, national and international soil monitoring schemes are equally important since they are a prerequisite for top-down policies that can enforce soil health promoting management on a wider scale (Ng and Zhang, 2019). Without adequate policies, farmers will remain reluctant to implement novel and more sustainable soil management practices. In this respect, large international projects like those conducted under the European Joint Program (EJP) on soils, including RECARE, CATCH-C, SmartSOIL, and LANDMARK (EJP, 2021) are crucial, since they were jointly created with politicians and farmers, and recently translated into a roadmap towards a more climate-smart and sustainable soil management (EJP, 2021). Another major project is the “Soil Health and Food” mission within the Horizon European research program for 2021-2027 (Bouma, 2021). The main goal of this mission is that 75% of European soils are healthy by 2030 (compared to the current baseline of approximately 60-70% unhealthy soils) (European Commission, 2020). Herein, 8 indicators have been chosen for evaluating soil health, although the final operationalization challenge remains, which is to agree upon threshold levels for each indicator that separate healthy from unhealthy soils. To do this, new potential approaches are proposed, such as those by Bonfante *et al.* (2019) or Seaton *et al*. (2020).

It could be argued that none of these approaches fully encapsulates soil health or will ever be universally agreed upon. However, as with most complex problems, the pursuit of perfect knowledge is asymptotic, and “uncertainty, ignorance and indeterminacy are always present” (Jasanoff, 2007). Therefore, ongoing struggles in quantifications should not distract from the fact that national and international soil monitoring projects have and likely will substantially forward our knowledge about soils.

2.7 Conclusion

It remains questionable if we ever derive with ultimate definitions and measurements about concepts and metaphors like soil health (or One Health) - and if we need to. Eventually, what is needed is to sustain and better understand soils and their relation to plant, animal, and human health - and if such concepts and metaphors can assist us in doing so, they should be used. “Metaphors are an indispensable component of science, and should not be appraised as true or false, but rather in terms of how they help or hinder knowledge” (Proctor and Larson, 2005). Soil health is an important element within the necessary transition from a purely production focused agriculture towards a more sustainable one, not only through forwarding more comprehensive and international soil assessments extending beyond ‘yield only’, but also by stimulating discourse and by confronting various stakeholders with the unescapable complexity of agriculture. However, even though compiling soil health indicators and outlining various health linkages to other domains is important, the widespread tendency of soil scientists to “dwell on the complexity and knowledge gaps rather than to focus on what we do know and how this knowledge can be put to use” (Smith *et al.*, 2015) must be overcome. Instead of turning soil health into an arbitrary and overly holistic “art form” (Powlson, 2021), a stronger focus should be put on transdisciplinary and context-dependent soil management of known and discrete problems.

3 The agricultural usage of silicate rock powders. A review[5]

3.1 Background

A crucial agricultural challenge is to increase or maintain yields without further degrading the Earth's environmental systems, particularly soils (Kopittke *et al.*, 2019). Global soil degradation, of which agriculture is a major driving force, proceeds at alarming rates with about 10 million ha of cropland rendered unproductive each year (Scherr, 1999; Hossain *et al.*, 2020). Simultaneously, additional arable land is limited, trends in crop yields decline or have reached plateaus in many countries (Brisson *et al.*, 2010), and climate change is expected to further constrain future food production (Ray *et al.*, 2019; Hari *et al.*, 2020). On the other hand, agricultural intensification would result in considerable pressure on existing farmlands and requires profound advancements in soil sustaining crop production (Cakmak, 2002).

Among the major contributors to enhanced crop production are mineral nutrients, which are extracted from the soil with every harvest and must be adequately replaced by fertilizers, manures, or other amendments. In many countries however, food production currently depends on depleting large quantities of soil mineral nutrients without adequate replacement, resulting in substantial global rates of nutrient mining (Jones *et al.*, 2013). Despite a common focus on N and P (Vitousek *et al.*, 2009; Bouwman *et al.*, 2017), it has been suggested that global soil nutrient depletion rates are of greatest concern for K (Sheldrick *et al.*, 2002; Sheldrick *et al.*, 2003; Sheldrick and Lingard, 2004; Tan *et al.*, 2005) and that K inputs would need to at least double to replace the amounts removed from crops (Manning, 2015). Furthermore, the importance of K for plant stress resistance as well as human and animal health is increasingly emphasized (Römheld and Kirkby, 2010). Current and future K fertilization, however, faces profound challenges. Conventional K fertilizers such as KCl are often not affordable and accessible for farmers in developing countries since potash prices roughly doubled since the beginning of the century (Manning and Theodoro, 2020) and production is dominated by the Northern hemisphere (Manning, 2010). More than 80% of global potash is produced by five countries (Belarus, Canada, China, Germany and Russia), leaving many developing countries almost completely import dependent (Manning, 2015; Ciceri and Allanore, 2019). Additionally, KCl is prone towards leaching in several tropical environments due to low cation exchange capacity (CEC) (Werle *et al.*, 2008; Rosolem *et al.*, 2010), and losses may account for 70% of fertilizers applied in tropical sandy soils (Rosolem *et al.*, 2018).

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[5] This chapter is based on the paper: SWOBODA, P.; DÖRING, T. F., HAMER, M. (2020) Remineralizing soils? The agricultural usage of silicate rock powders. A review. *Science of the Total Environment.* https://doi.org/10.1016/j.scitotenv.2021.150976

Besides K and other macronutrients, global nutrient mining is equally alarming for micronutrients like B, Fe, Cu and Zn (White and Zasoski, 1999; Jones *et al.*, 2013). The extent of micronutrient deficiencies has been seriously underestimated and predominant NPK fertilization schemes have widely failed to address the fact that plants extract, to varying degrees, all 14 mineral macro- and micronutrients (Jones *et al.*, 2013). If micronutrient deficiencies are not adequately addressed, yield responses to NPK can become very small or zero, depending on the soil type (Cakmak, 2002).
The situation is particularly severe in the tropics, the center of global food insecurity and future population growth (FAO, 2017), where more than 40% of the soils are nutrient depleted oxisols and ultisols (Sanchez, 2019). Soil nutrient depletion is the biophysical root cause for low average yields in the tropics (Sanchez, 2015), and nutrient management will be decisive to close yield gaps (Mueller *et al.*, 2012). However, managing tropical soils is challenging since soluble NPK fertilizers are often not affordable or accessible (van Straaten, 2006), and do not replenish micronutrient deficiencies. Therefore, finding sustainable ways to manage tropical soils is of crucial importance.
One way to improve plant growth and simultaneously ameliorate soils is the usage of ground rocks. Amending soils with ground rocks is an ancient practice and their use is commonplace in agriculture, like e.g. carbonate (limestone) and sulphate rocks (gypsum) for liming and phosphate rocks (apatite) as P fertilizers (van Straaten, 2007). There is however less knowledge about the usage of silicate rocks. Rock forming silicates are by far the most abundant mineral class on Earth and contain, to varying degrees and excluding N, all mineral elements essential for plant growth (Deer *et al.*, 2013). The release of elements through silicate weathering is one of the fundamental geochemical processes shaping the environment of the planet, and the primordial source of mineral nutrients in the soil (Schlesinger and Bernhardt, 2013). Finely ground silicate rock powders (SRPs) [6] - also called rock dust, stone meal, agrominerals or remineralizers - have therefore been proposed as slow-release fertilizers and soil amendment (Leonardos *et al.*, 1987; Fyfe *et al.*, 2006; van Straaten, 2007). However, although pioneering work with SRPS has already shown several benefits in the 1930s (Albert, 1938; Hilf, 1938), research on rock powders is still limited, dispersed and partly contradictory, with results ranging from significant yield and soil improvements up to no benefits at all (van Straaten, 2007; Harley and Gilkes, 2000). The contradictions are related to the complexity of the central process, rock weathering, which is dependent upon several factors like rock type, soil type and plant species. Methodological inconsistencies and a virtual uniqueness of each trial further complicate structured approaches (Manning, 2010). For example, so far almost no study determines or controls for the soil mineralogy, although this is known to be a crucial factor influencing the effectiveness of rock powder applications (Manning and Theodoro, 2020).

[6] Silicate rock powders (SRPs) will be used as term for rocks containing only or mostly silicate minerals, since some rocks like basalt can typically contain trace amounts of oxide minerals or phosphate minerals.

In recent years however, SRPs have received renewed interest from various directions. In the Anglo-Dutch literature, research has focused on the concept of "enhanced weathering", which aims to sequester CO_2 via silicate rock powder weathering (Hartmann *et al.*, 2013; Beerling *et al.*, 2018). In the tropical context, beneficial results accumulate, especially in Brazil, which is currently the epicenter of research and where the 'Rochagem' movement has led to an institutionalization of using rock powders in agriculture (Manning and Theodoro, 2020). Organic agriculture has a longstanding use of rock powders and its expansion increases the demand of suitable soil amendments that meet the organic growers' criteria (Abbott and Manning, 2015). Moreover, rock powders arise in massive amounts as waste products from the global mining industry, and their agricultural usage could help to resolve serious challenges regarding their management (Bian *et al.*, 2012). There are thus pressures and potentials of global magnitude that justify a comprehensive assessment of SRPs.

SRPs have been reviewed from different perspectives: van Straaten (2002; 2007) laid out foundational work for 'agrogeology', Manning (2010) reviewed 20 SRP studies in terms of K nutrition, Zhang *et al*. (2018) outlined the historical background and recent geochemical developments in weathering studies, Manning and Theodoro (2020) report about the use of SRPs with a focus on Brazil, whereas Ramos *et al*. (2021) recently focused on adsorption of contaminants and enhanced weathering. What is still missing, however, is a review that provides a structured overview of the heterogeneous literature and summarizes the most important factors for practically approaching SRP usage as a basis for future research.

The purpose of this review is therefore to first present an operational framework including the most important factors for the weathering and thus effectiveness of SRPs. Then, based on the work of Manning (2010), an overview of crop trials with SRPs is presented, summarizing the most important factors and major findings of each study, to answer the question: how and under which circumstances can SRPs improve yield and ameliorate soils? Then, potential co-benefits, agronomic and environmental aspects are discussed. Finally, we aim to identify the most pertinent knowledge gaps and recommendations for future research.

3.2 Relevant factors for the usage of silicate rock powders

The weathering and thus efficiency of SRPs depends on a complex interplay of several factors (Figure 5). Relevant factors include soil type, plant species, and rock/mineral type, rock particle size, application amount, study duration and modifications e.g. with compost or silicate dissolving bacteria (Harley and Gilkes, 2000; van Straaten, 2006; Manning, 2010; Bamberg *et al.*, 2017). The majority of prior SRP trials insufficiently addressed the complexity of factors involved, which is mirrored in inconsistent study designs and lacking report of the relevant factors (Manning, 2010). Furthermore, many insignificant results with SRPs may have been caused by a poor selection of appropriate rocks and environmental conditions (van Straaten, 2007). Below, we discuss the individual factors influencing SRP weathering along with their interconnections.

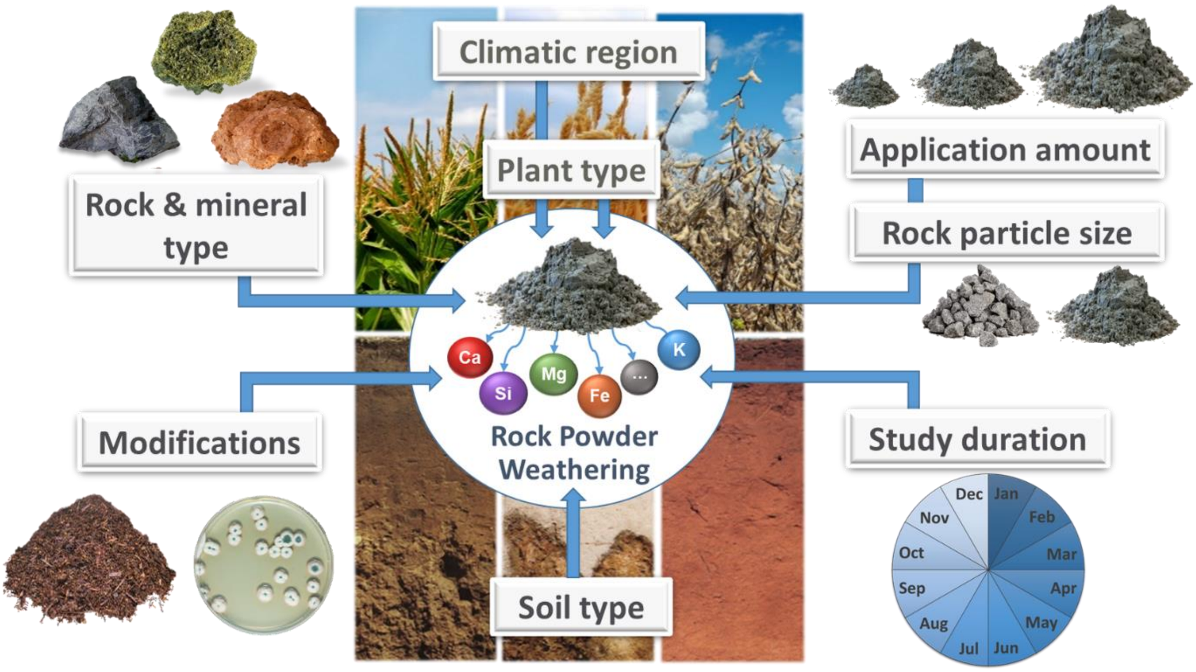


Figure 5: Framework for the usage of silicate rock powders including the most relevant factors influencing the weathering of the rock powders. Interactions are not depicted.

3.2.1 Rock and mineral type

Silicate minerals have diverse structures and elemental compositions and thus exhibit diverse weathering characteristics and dissolution rates. Table 3 provides dissolution rates for major silicates and most of the minerals that were investigated in the crop trials reviewed in chapter 3. The mineral formulations in table 3 represent the main structural elements, although many silicate minerals can contain trace amounts of several macro- and micronutrients (see Harley and Gilkes (2000) for a detailed list of plant nutrient distributions in major rock forming minerals). Generally, dissolution rates of felsic rock (e.g. granite) forming minerals such as K-/Na-rich feldspars, muscovite and biotite mica are lower compared to mafic rock (e.g. basalt) forming minerals such as Ca-feldspar, amphibole, pyroxene and olivine (Deer *et al.*, 2013). The feldspathoids are structurally similar to feldspars but have lower Si and K contents, yet higher weathering rates.

For example, K-feldspar typically contains 3-4 times more K than nepheline but dissolves several orders of magnitude more slowly (Table 3). This implies that for a given rock not only the overall content of an element of interest must be considered, but especially the dissolution rates of its constituent minerals (Manning, 2018).

Dissolution rates (Table 3) are mostly obtained under laboratory conditions and are typically several orders of magnitude higher than those observed under natural conditions (White and Brantley, 1995). In laboratories, key dissolution parameters like pH, temperature and water flux remain constant, whereas in the soil environment they are dynamic and may exhibit interdependent and attenuated effects. Additionally, the reactive surface of a mineral might gradually change due to encapsulation in secondary mineral precipitation or cation depleted/silica rich surface areas that act as protective layer, limiting the dissolution rate. Natural weathering rates have therefore repeatedly shown inverse dependence on time, i.e. getting slower over time (White and Brantley, 2003; Maher, 2010).

Recent evaluations, however, report dissolution rates that challenge hitherto assumed slow in-field weathering rates. Two weathering stages can be differentiated, the first is the exchange of surface K+ with H_3O^+ from soil solution, and the second is the proton catalysed hydrolysis of the Si-O and Al-O bonds in the framework structure. Ciceri and Allnore (2015) focused on first stage weathering processes, about which little is known, and found significantly higher dissolution rates for feldspars compared to second stage weathering rates.

These results are in agreement with field observations of feldspar grains that weathered several orders of magnitude faster than theoretical rates would suggest, likely due to plant and soil microbiological processes (Manning, 2018).

Besides laboratory and field rate discrepancies, compiling predictive dissolution rates for SRPs is challenging since rocks are typically composed of more than one mineral, so bulk dissolution rates need to consider all minerals, their intergrowth within the rock and textural relationship (Manning and Theodoro, 2020).

Another major challenge is that in many studies the rock names are incorrect, and experiments are thus difficult to repeat. Many studies are led by crop scientists who are often not aware of the rigor and intricacies involved in naming rocks (Glazner *et al.*, 2019). Quarry owners rarely use the correct rock name and instead use names representing the habitual usage in their construction markets. Therefore, in studies on SRPs, correct terminology needs to be observed to improve reproducibility and consistency; igneous rocks should be named in reference to Le Maitre *et al*. (2002), metamorphic rocks according to Fettes and Desmons (2011) and sedimentary rocks in line with Boggs (2009).

Table 3: Dissolution rate constants (25°C, pH = 0) of silicate minerals. Relative dissolution rates show the dissolution rate of a given mineral relative to that of K-Feldspar (Dissolution rates from (Palandri and Kharaka, 2004), mineralogical data adapted from (Klein and Philpotts, 2017) and (Manning and Theodoro, 2020).

Mineral sub-group	Mineral	Formula	Dissolution rate log mol.m^{-2}.s^{-1}	Relative dissolution rate
Tectosilicates				
K-Feldspar	Orthoclase	$KAlSi_3O_8$	-10.06	1
Plagioclase-Feldspar	Albite	$NaAlSi_3O_8$	-10.16	0.794
Plagioclase-Feldspar	Anorthite	$CaAl_2Si_2O_8$	-3.50	3,630,000
Feldspathoids	Nepheline	$(Na,K)AlSiO_4$	-2.73	21,400,000
Feldspathoids	Leucite	$KAlSi_2O_6$	-6.00	11,500
Phyllosilicates				
Mica	Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	-11.85	0.016
Mica	Biotite	$K(Fe,Mg)_3(AlSi_3O_{10})(OH)_2$	-9.84	1.66
Mica	Glauconite	$(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$	-4.80	182,000
Serpentine	Lizardite	$Mg_3Si_2O_5(OH)_4$	-5.70	22,909
Inosilicates				
Pyroxene	Wollastonite	$CaSiO_3$	-5.37	49,000
Pyroxene	Diopside	$CaMgSi_2O_6$	-6.36	5,010
Pyroxene	Enstatite	$MgSiO_3$	-9.02	11
Amphibole	Hornblende	$Ca_2(Mg,Fe)_4Al[Si_2AlO_{22}](OH)_2$	-7.00	1,150
Amphibole	Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$	-5.60	28,840
Nesosilicates				
Olivine	Forsterite	Mg_2SiO_4	-6.85	1,620

3.2.2 Rock particle size

The rock particle size influences weathering rates since it relates to the reactive surface area, which increases with decreasing particle size. Several trials have shown that decreasing particle size increased the solubility of e.g. alkali feldspars (Holdren and Speyer, 1985), gneiss (Wang *et al.*, 2000), basalt (Gillman *et al.*, 2001) and alkaline volcanic rocks (Basak *et al.*, 2018). Converging weathering rates were reported for several felsic rocks, with initially higher dissolution rates for particles finer than 60µm compared to particle sizes ranging from 60-140 and 250-350µm, whereas all rates became similar after 6 weeks (Niwas *et al.*, 1987).

Mohammed *et al*. (2014) report that applying coarser grained biotite (10-2000 µm) resulted in significantly higher yields than fine grained (99% <63 µm) microcline and nepheline on an artificial soil (volume ration 9:1 silica sand to compost), but not on a natural soil. These results are unexpected, since biotite and microcline have similar weathering rates, whereas the weathering rates of nepheline is several orders of magnitude higher. It is assumed that the platy sheet structure of biotite compared to the 3-dimensional framework structure of microcline and nepheline could have promoted additional weathering (Mohammed *et al.*, 2014). The relationship of weathering rate and surface area is thus a complex one and they are not necessarily proportional to each other. It is suggested that weathering does not affect the mineral surface uniformly, but to preferentially occur at highly localized sites of crystalline defects (Holdren and Speyer, 1985). Such imperfections include holes and dislocations in the mineral structure that are likely to have major effects on dissolution kinetics, specifically in the early stages of weathering. The specific surface area of a mineral is thus important for weathering, although not equivalent to the reactive surface area.

3.2.3 Application amounts

There is no general agreement about optimal application amounts of silicate rock powders, which is mirrored in amounts ranging from <1 t ha-1 ha up to >100 t ha-1. Australian farmers typically apply 0.5 to 4 t ha-1 (Bolland and Baker, 2000), which corresponds to recommended doses of 1-3 t ha-1 from rock powder providers in Austria and Germany (brand “Biolit” and “Eifelgold”), and doses of 5-20 t ha-1 by REMIN (Scotland) Ltd (www.reminscotland.com), although this comes without any scientific underpinning. Similarly, Theodoro and Leonardos (2006) report application amounts of up to 6 t ha-1 from rural small-scale farmers. Most of the trials reviewed in section 3 applied amounts in the range of 1 to 20 t ha-1. This agrees with liming rates for oxisols, which mostly span between 1 and 20 t ha-1, and typically reach highest agronomic efficiency at 4-6 t ha-1 (Fageria and Baligar, 2008). Very high application amounts in the range of 50-100 t ha-1 can lead to nutrient imbalances due to antagonistic interactions of elements, especially when rock powders primarily supply one nutrient. 100 t ha-1 gneiss and feldspar increased K supply but reduced the concentrations of Ca, Mg, P, Cl, Cu and Zn in dry tops of ryegrass (Priyono and Gilkes, 2008), which was also observed for equally high K amounts supplied via K2SO4.

3.2.4 Soil type

Silicate rock powders (SRP) are mostly proposed for highly weathered soils prevalent in the humid and sub-humid tropics, such as oxisols and ultisols (Leonardos *et al.*, 1987; van Straaten, 2006). These soils differ from many soils found in temperate zones particularly in and due to their mineralogy. The reserve of weatherable minerals is large in temperate (90%) and boreal (92%) soils, whereas about 37% of tropical soils have less than 10% reserves of weatherable minerals (Sanchez, 2019). In oxisols and ultisols, most of the primary silicate minerals have weathered to oxy-hydroxide minerals and 1:1 clays, thereby reducing CEC, pH and natural geogenic nutrient supply. Artificial nutrient supply via soluble fertilizers is equally restricted due to high cation leaching rates and anion fixation particularly for P (Weil and Brady, 2017; Baligar and Bennett, 1986). In turn, the physio-chemical properties of such tropical soils suggest sufficiently high dissolution rates for SRPs to be used as alternative fertilizer and soil amendment (Bamberg *et al.*, 2017; Harley and Gilkes, 2000; Manning and Theodoro, 2020).

It is noteworthy that Pleistocene glaciation, erosion, alluviation and volcanism remineralized (or rejuvenated) many temperate soils and thereby rendered much of their fertility, whereas many tropical soils have not been exposed to such processes in the recent geological past, and owe much of their infertility to prolonged periods of intensive weathering (Chesworth *et al.*, 1983; Hartemink, 2002; Fyfe *et al.*, 2006). From a pedological standpoint, remineralizing such highly weathered soils thus appears to be a plausible intervention.

For practical purposes, an important yet widely neglected issue is to consider the soil mineralogy in relation to the mineralogy of the rock applied, since dissolution occurs when there is ionic non-equilibrium between the mineral surface and the soil solution (White, 2003). Assuming that soil ionic equilibrium is roughly reached between the solution and the native minerals, adding rocks of the same mineralogy will likely not disturb the equilibrium, and weathering will thus be limited (Manning, 2018). For example, Ramezanian *et al.* (2013) and Ramezanian *et al*., (2015) tested the same rock powder with identical particle sizes and application amount for a grass/clover mixture, but the respective soils varied in their pH and mineralogy. No yield response was found when the soil and rock powder mineralogy were similar (Ramezanian *et al.*, 2013), whereas grass yields significantly increased when the soil mineralogy overlapped less and the pH was lower (~1.0 unit) (Ramezanian *et al.*, 2015).

Importantly, future studies must include physiochemical topsoil properties like texture, mineralogy, and pH, since common soil taxa alone are insufficient as they typically focus on agronomically less relevant pedogenic factors and subsoil properties (Sanchez, 2019).

3.2.5 Plant species

Mineral dissolution rates have been repeatedly underestimated by not accounting for the influence of higher plants on weathering kinetics (Bormann *et al.*, 1998; Hinsinger *et al.*, 2001). Plants influence the biological and physical condition of the soil particularly in the rhizosphere, where conditions can differ greatly from those in the bulk soil. Temperature, pH, moisture levels, elemental and gas concentrations fluctuate in these spheres and thereby alter the rate and quasi-equilibrium of reactions between the solid mineral phase and the soil solution (Marschner, 2002; Harley and Gilkes, 2000). Several studies report not only considerable weathering increases through plants, but also significant interspecies differences. Hinsinger *et al*. (2001) showed that in the presence of various plants the release of Si, Ca, Mg and Na from basalt increased by a factor ranging from 1-5 compared to a control without plants. Additional element release was the lowest for Ca, whereas in the presence of bananas and especially maize (*Zea mays*) the Fe amounts released increased 100- to 500-fold. This agrees with the widely accepted view that graminaceous species (grasses) like maize have a distinctly efficient mechanism for Fe acquisition characterized by an enhanced synthesis and release of strong Fe chelatants called phytosiderophores (Römheld and Marschner, 1990). Consistent with this, several silicate rock powder studies confirm a favourable and superior response of maize compared to Italian ryegrass (*Lolium multiflorum*), perennial rygrass (*Lolium perenne*) and pak-choi (*Brassica campestris* ssp. *chinensis*) (Wang *et al.*, 2000), eucalyptus (*Eucaliptus urograndis*) (Santos *et al.*, 2016), holy basil (*Ocimum tenuiflorum*) (Basak *et al.*, 2018) and black oat (*Avena strigosa*) (Ramos *et al.*, 2019). Interestingly however, Akter and Akagi (2005) and Haque *et al*. (2019) report even higher weathering rates for soybean (*Glycine max*) than for maize, which was linked to the additional H^+ release during N fixation of legume associated rhizobia.

The influence of roots on weathering is furthermore related to their morphology and symbiosis with arbuscular mycorrhizal fungi (AMF). Wang *et al*. (2000) relates the larger and denser root systems of maize and perennial ryegrass, to their higher K acquisition from gneiss compared to pak-choi and alfalfa (*Medicago sativa*), whose roots were less entangled and in less direct contact with the rock particles. The presence of AMF has been shown to additionally increase weathering of scots pine (*Pinus sylvestris*) seedlings (Wallander and Wickman, 1999) and of buffalo grass (*Bouteloua dactyloides*) (Burghelea *et al.*, 2018), and was recently reviewed by Verbruggen *et al*. (2021).

3.2.6 Climate and weather

The two major climatic factors influencing rock weathering are precipitation and temperature. Warm temperatures tend to accelerate weathering rates of minerals due to increases in activation energy (Kump *et al.*, 2000). Ample laboratory work by Lasaga *et al.* (1994) and field studies by White *et al*. (1999) confirmed the temperature dependence of mineral dissolution, which is consistent with high weathering rates in several tropical climates (Sanchez, 2019). Precipitation in turn is crucial since water is central to all forms of chemical weathering in the soil (Weil and Brady, 2017) and because a high water flux promotes a soil solution that is in ionic disequilibrium with the mineral surface, thereby promoting weathering. Using SRP is therefore particularly suitable for climatic conditions prevalent in the humid and sub-humid tropics. Importantly, trials often last only several months so that fluctuating weather conditions within a given climate may contribute to the differences of SRP trial outcomes, as discussed in the next section.

3.2.7 Duration

Compared to water soluble fertilizer salts, SRPs are relatively slow-release fertilizers and soil amendments with potential medium- to long-term effects. Evidence for long-term ameliorations with rock powders can be drawn from forest trials, typically ranging from several years up to several decades. Single applications of fast-weathering wollastonite (3.4 t ha^{-1}) and dolomitic limestone (22.4 t ha^{-1}) improved soil pH and exchangeable base cations in several acidic forest soils for up to 15 (Taylor *et al.*, 2021) and 21 years (Long *et al.*, 2015), respectively. Similarly, a single application of rather slow-weathering biotite mixed with apatite ameliorated a spodosol for up to 10 years, although incipient effects on soil pH only started after 2 years (Aarnio *et al.*, 2003), showing that potential SRP effects can be delayed. Delayed effects also occurred for phonolite rock powder applied to various K-depleted forest soils, where base cation supply only started to increase after the first year (Wilpert and Lucas, 2003). The time dimension is relevant since the duration of agronomic trials with SRPs typically ranges from several months up to two years, which might not adequately capture medium- to long-term soil changes. Some authors report beneficial effects for several years (Bakken *et al.*, 2000; Theodoro and Leonardos, 2006), whereas others showed attenuated effects after the first year (Ramezanian *et al.*, 2015) or after the second growing cycle (Barak *et al.*, 1983), which was related to a fresh surface effect and other hitherto little understood effects. Overall, several authors agree that more long-term field experiments are needed to assess the full extent of potential effects (Leonardos *et al.*, 2000; Winiwarter and Blum, 2008; Manning, 2010).

3.2.8 Modifications

The low dissolution rate of many silicate rocks is a major obstacle of SRPs that could be overcome by physical, chemical, or biological modifications. Physical modifications include several high-energy milling methods to decrease the particle size and the structural disordering of minerals, both of which have shown to improve dissolution kinetics considerably (Harley, 2002; Kleiv and Thornhill, 2007). Ten minutes of high-energy milling produced a feldspar powder that had dissolution rates similar to K_2SO_4 (Priyono and Gilkes, 2008). Priyono and Gilkes (2004) found significantly increased weathering rates for high-energy milled basalt, dolerite, gneiss and K-feldspar incubated in various soils for 10 months. However, none of the studies provides a life cycle analysis (LCA) or a cost-benefit evaluation regarding the additional energetic requirements for high-energy milling.
Physio-chemical modifications involve the fusion of K-rich silicate minerals with alkali materials ($Ca(OH)_2$ or NaOH) under hydrothermal conditions (Ciceri *et al.*, 2017; Liu *et al.*, 2015; Mbissik *et al.*, 2021). The initial mineralogy is thereby significantly altered, resulting in substantially higher weathering rates and a multi-phase mineral structure that can additionally ameliorate soil physio-chemical conditions (Liu *et al.*, 2017).
Chemical modifications include mostly acid treatments that aim to corrode the mineral structure and thereby increase nutrient release. Successful examples involve acidification of phlogopite (Weerasuriya *et al.*, 1993) and glauconite micas (Santos *et al.*, 2015) with nitric acid (HNO_3),

hydrochloric acid (HC1) and sulfuric acid (H_2SO_4), whereas H_2SO_4 was the strongest dissolvent in both cases.

Biological modifications have been most extensively researched and involve mixing rock powders with silicate dissolving microorganisms (SDM) or organic materials like compost and manure. Several trials have shown that silicate dissolving bacteria and to a lesser extent silicate dissolving fungi are capable to substantially enhance the nutrient release from minerals (see the reviews by Basak *et al*. (2017), Meena *et al*. (2016) and Ribeiro *et al*. (2020)). Since SRPs contain several essential mineral nutrients except N, a rock powder enriched compost or manure could theoretically supply all needed macro- and micronutrients (Leonardos *et al.*, 2000). Contrasting evidence exists whether the composting process itself could already increase rock weathering via microbiologically produced organic acids, raised temperatures and enhanced CO_2 concentrations (Tavares *et al.*, 2018; Li *et al.*, 2020; Garcia-Gomez *et al.*, 2002). The limited evidence, however, is not directly comparable since various composting substrates were tested and differing analytical methods employed.

3.3 Crop trials with silicate rock powders

This section reviews 48 crop trials using silicate rock powders (Table 4). Searching the platforms Web of Science, ScienceDirect and Google Scholar for “rock powder” or “rock dust” only yields a limited number of papers, since most of the titles and keywords only include the respective rock/mineral type. The literature research was therefore mostly conducted by screening references of papers. Exclusion criteria were leaching studies without crops or trials with phosphate rocks.

The subsequent sections review the trials according to the rock/mineral class used, although several trials used various rocks, in which case the study was allocated to the most effective rock/mineral type. Application amounts are reported in different ways (e.g. kg K per ha^{-1}, g K per kg^{-1} soil or tons rock powder per ha^{-1}) and were converted into tons of SRP per ha^{-1}, since this is the most common and practically relevant unit. Information on soil properties was inconsistently reported, encompassing either soil types of various taxonomies or only specific topsoil properties.

3.3.1 Trials with feldspars

Several trials with feldspars have been conducted in Egypt, where conventional K fertilizers such as K_2SO_4 and KCl are oftentimes unaffordable for farmers (Ali and Taalab, 2008; Hellal *et al.*, 2013). Moreover, KCl can be inefficient and even problematic in arid and semi-arid regions due to salinization of soils, concomitant plant chloride toxicity and inhibition of soil nitrification, amongst other issues (Khan *et al.*, 2014; Vieira Megda *et al.*, 2014). In a trial with two okra cultivars as test crops, feldspar was compared with phosphate rock, compost and NPK (Abdel–Mouty and El-Greadly, 2008). All treatments increased the yields of both cultivars, and the best results were obtained with compost or phosphate rock, although feldspar mixed with compost had similar and partly higher yields as NPK. Ali and Taalab (2008) found that onion (*Allium cepa*) yield increased with increasing feldspar rates and was about 15% lower than for the equivalent dose of K_2SO_4, although no control treatment was included. However, no significant difference was found when using K_2SO_4 alone or in a 1:1 combination with feldspar. Insignificant effects on K supply and yields are reported by Badr (2006) for tomatoes under feldspar fertilization alone, although combining feldspar with compost significantly increased yield and K uptake compared to compost alone. Yields peaked and even outyielded K_2SO_4 when the feldspar compost was inoculated with silicate dissolving bacteria (*Bacillus cereus*). In contrast, Hellal *et al*. (2013) found significant effects on sugar beet (*Beta vulgaris*) growth for feldspar alone and in combination with compost. Manning *et al*. (2017) grew leek (*Allium ampeloprasum*) in pure quartz sand and peat in which the only potential sources of K were KCl, feldspar or phlogopite mica. A dose dependent response was shown for both rocks on K uptake and yield, whereas the highest mica dose resulted in similar growth and K uptake as KCl.

In Colombia, Scovino and Rowell (1988) applied feldspar (sanidine) to an ultic hapludox and found small yet statistically insignificant effects on growth and K-uptake for a forage mixture of the grass *Brachiaria dyctioneura* and the legume *Pueraria phaseoloides*. The lack of significant response was related to the unexpectedly high amounts of native K in the soil and thus good yields in the control plot, suggesting that K was not a serious limitation on this site. Also, little rainfall during the trial period potentially reduced weathering.

Ciceri *et al*. (2019) and Liu *et al.* (2017) report notable effects for hydrothermally altered feldspar (HAF). Ciceri *et al.* (2019) showed that tomato (*Lycopersicon esculentum*) fresh weight obtained with HAF was equal to or exceeded that of KCl, whereas unaltered feldspar was ineffective. KCl led to highest leaf K content, but did not ameliorate soil acidity such as the HAF did (Ciceri *et al.*, 2019). In China, Liu *et al.* (2017) found that HAF significantly increased the pH and reduced Al concentration in a moderately (5.8) and strongly (5.3) acidic clayey soil. In a preliminary field trial with rice (*Oryza sativa*), the hydrothermal product effectively decreased high cadmium (Cd) concentrations in the soil, plant and grains, which was partly related to its tobermorite and carbonate content, and pH improvements.

3.3.2 Trials with feldspathoids

The main feldspathoid mineral tested in most studies was nepheline. Already in the 1920s, nepheline syenite has been investigated as a source of K in Norway by the father of modern geochemistry, Goldschmidt (1922). More recent Norwegian trials compared rocks and mine tailings rich in nepheline, biotite and feldspar with KCl (Bakken *et al.*, 1997; Bakken *et al.*, 2000). In pot trials with Italian ryegrass (*Lolium multiflorum italicum*), the highest yield and K supply was obtained for KCl and those nepheline and biotite containing rocks that were associated with carbonatites (calcite) (Bakken *et al.*, 1997). K from feldspar was hardly available, whereas those nepheline and biotite rich rocks with little calcite content had intermediate effects. Bakken *et al.* (2000) tested mostly the same rocks in a 3-year trial on various grassland sites. Likewise, feldspar was ineffective and KCl outyielded the rock treatments in the first and second year, whereas in the third and last year when no K fertilizers or feldspar were supplied, residual nepheline/biotite rich carbonatites supported grass growth as much as residual KCl.

Similarly, feldspar (microcline), biotite and nepheline were compared with KCl for growing leek on an artificial soil consisting of silica sand and compost (9:1 ratio) and on an alfisol (Mohammed *et al.*, 2014). KCl significantly increased yield on both soils, whereas biotite at 3 t ha^{-1} increased K uptake in both soils, produced similar yields to KCl on the artificial soil and had borderline significant effects on the natural soil. Feldspar and nepheline did not show significant effects on yield compared with the control, which the authors partly ascribe to the short trial period and the high K stocks in the natural soil.

Phonolite rock, a fine grained extrusive variety of nepheline syenite, was tested in various regions. A commercial phonolite rock powder (Ekosil®) containing K-feldspar, andesine and nepheline was tested for coffee (*Coffea arabica*) on a Brazilian oxisol (Mancuso *et al.*, 2014). Similar yields were obtained for both K sources in two growing seasons, whereas equivalents of 150kg K_2O per ha of both treatments produced more yield than equivalents of 300kg K_2O, which the authors ascribe to excess K supply and resulting imbalances of other nutrients.

Tavares *et al*. (2018) tested a phonolite rock powder containing feldspar and feldspathoids, without further specifying the mineralogy. The SRP was either applied alone or in combination with compost on an oxisol with brachiaria grass (*Urochloa decumbens*) as the test crop. Phonolite powder alone insignificantly affected yield and its combination with compost did not differ significantly from the yield of compost alone. However, the rock powder enriched composts resulted in the highest K and Si levels in the grass and the residual soil.

In a 5-year forest trial with spruce trees on a K-deficient gleyic luvisol, phonolite was compared with dolomite and K_2SO_4 (Wilpert and Lukes, 2003). K_2SO_4 sufficiently increased K in spruce needles but led to antagonistic effects on Ca and Mg contents and caused short-term acidification pulses accompanied by enhanced Al concentrations exceeding critical thresholds. K_2SO_4 showed no effects in ameliorating soil pH or the base concentrations, but phonolite and dolomite increased these variables until 30 and 60cm, respectively. Phonolite plots had less nitrate leaching than the dolomite plots and

Table 4: Review matrix of silicate rock powder studies including the most relevant factors of each study. Mineral and rock abbreviations from Whitney and Evans (2010) : Ep – Epidote, Kfs – K-feldspar, Bt – Biotite, Glt – Glauconite, Mc - Microcline, Ms – muscovite, Ne – Nepheline, Phl – Phlogopite, Qz – Quartz, Znw – Zinnwaldite. Trials are orderd according to how they appear in section 3.

Rock / Mineral	Plant	Application amount (t/ha)	Soil (pH)	Particle size (µm)	Duration (months)	Trial type	Main Results (trial type)	Source
Feldspar	Okra	1.4	Clay (7.7)	-	24	Field	Increased yield. Feldspar plus gibberellic acid similar yield as NPK.	Abdel–Mouty and El-Greadly (2008)
Feldspar	Onion	0.9 - 2.6	Loamy clayey sand, (7.8)	-	3.5	Field	Increasing yield with dosage, 15% less yield than K_2SO_4	Ali and Taalab (2008)
K-feldspar	Tomato	1.3 - 4	Sandy soil	125-250	5	Field	Kfs insignificant, Kfs + compost: increased K uptake and yield	Badr (2006)
Feldspar	Sugar beet	0.4 - 1.2	Calcareous clay (8.4)	<2000	2x7	Field	Increased yield. Kfs + compost outyielded K_2SO_4	Hellal et al. (2013)
Feldspar	Grass	1.1	Oxisol (4.2)	<150	14	Field	Insignificant for yield and K supply	Scovino and Rowell (1988)
K-feldspar	Tomato	1 - 8.6	Nutrient poor acidic substrate (4.6)	10-30	3	Pot	Kfs insignificant, hydrothermally altered Kfs: increased yield, pH, plant K and Ca	Ciceri et al. (2019)
Feldspar	Rice	0.6 - 1.2	Clayey paddy soils (5.82 / 5.32)		-	Pot	Improved pH, decreased bulk density and Al / Cd toxicity, improved soil porosity	Liu et al. (2017)
Kfs , Ne+Bi rich mine tailings	Ryegrass	12 - 23	Peat / loamy sand /silty loam	a)100%<590 b) K-sp finer	6	Pot	Kfs insignificant, Ne+Bi: increased K uptake and yield	Bakken et al. (1997)
Kfs , Ne+Bi rich mine tailings	Meadow-grass	1 - 2.5	15 different grassland soils	a)<1000 b) K-sp finer	36	Field	Kfs insignificant, Ne+Bi: increased K uptake and yield in 3rd year similar to KCl	Bakken et al. (2000)
Mc, Bt, Ne-syenite	Leek	0.6-3	Artificial soil (6.4), sand (6.1)	<100	2 ½	Pot	Bt: Increased yield and K uptake, Ne and Mc insignificant	Mohammed et al. (2014)
Phonolite	Coffee	0.9-3.7	Oxisol (pH4.9)	-	24	Field	Increased K and Si supply. Plant growth similar to KCl	Mancuso et al. (2014)
Phonolite (+compost)	Grass	5.4 (+33)	Oxisol	-	2 ½	Field	Insignificant for yield, increased plant Si content and soil K, Si and Na	Tavares et al. (2018)
Phonolite	Spruce	10	Alfisol (3.7 – 4.1)	90%<100	60	Field	Increased base saturation, reduced nitrate leaching compared to lime	Wilpert and Lukes (2003)
Greensand	Grass mixture	5.3-7.3	Acidic (4.9) soil	1) 250-600 2) 125-250	2 ½	Pot	Similar yield as KCl, particle size 1 & 2 similar effects	Franzosi et al. (2014)
Glauconite	Durum wheat	2	(6.0)	<2000	4	Field	Increased yield, soil Ca and pH, reduced soil Mg, higher smectite content	Rudmin et al. (2019)
Glauconite	Oat	2	(6.3)	<2000	3 ½	Field	Increased yield and small but statistically insignificant soil K, Ca, Mg, P, NH4	Rudmin et al. (2020)

Table 4: continued

Rock / Mineral	Plant	Application amount (t/ha)	Soil / substrate (pH)	Particle size (µm)	Duration (months)	Trial type	Main Results (trial type)	Source
Glauconite	Coffee	0.5 - 4.8	Oxisol (4.5)		28	Field	Both rocks increased yield, only modified Glc increased CEC, pH, K, P, Ca, Zn, Fe.	Dias et al. (2018)
Verdete rock	Eucalyptus, maize, grass	0.6-2.6	Oxisol (5.6)	<150	3, 4	Pot	Increased yield only for grass. Modified rocks similar yield and K supply as KCl	Santos et al. (2016)
K-feldspar, phlogopite	Rice	0.2 – 0.5	Inceptisol	<149		Pot	Acidulated mica 41% higher yield than KCl, feldspar insignificant	Weerasuriya et al. (1993)
a) syenite b) phlogopite	Leek	a) 1-400 b)1-70	Sand with 20% mosh peat	a) 90%<150 b) 90%<60	2 ½	Pot	Dose-dependent positive effect for K supply and growth	Manning et al. (2017)
Muscovite	Sudan grass	0.2 - 2	Alfisol (6.1), (5.6)	100%<2000	6	Pot	Increased soil available K, K uptake and yield. Additional benefits with bacteria	Basak and Biswas (2009)
Kfs, Znw, waste mica	Spring barley	2-7	Alfisol: loamy (5.8), sandy-loamy (5.1)	2-63	1 ½	Pot	Increased yield and plant K in the order Znw>waste mica >Ksp. Zn outyielded KCl in higher dose	Madaras et al. (2012)
Serpentine	Pasture herbage	1.3	Andisol (6.3)	<500	32	Field	No effect on yield, increased Mg supply	Hanly et al. (2005)
Granite	a) Wheat b) Clover	2 - 20	Acidic soils (>5.2)	42%>1000 58%< 1000	a) 7 b) 1	Field / Pot	Insignificant, 20 t/ha decreased yield in field trial but not in pot trial	Bolland and Baker (2000)
Granite and Diorite	Wheat	20	Sandy soil (4.7)	45-90	2	Pot	Diorite no effect, granite increased growth and K supply	Hinsinger et al. (1996)
Granite	Clover and ryegrass	20	Sandy podzols	<2800	1 ½, 3	Pot	Increased yield and K uptake for 2 out of 3 soils.	Coroneos et al. (1996)
Granite	Grass	25, 50, 100	Loamy sand (4.6)	<50	3 ½	Pot	Increased yield and soil pH, CEC, Na, Ca, Mg, K. reduced Al saturation	Silva et al. (2013)
Gneiss	Ryegrass	30	Sandy loam (7.2) and pure sand	90%< 40.8	2	Pot	Small but statistically insignificant increase in yield, K supply but Mg supply only in sand.	Gunnarsen et al. (2019)
Gneiss, steatite (+vermicompost)	Maize	0.6-2.5 (+10-12)	Oxisol (5.0)	150-53	2 ½	pot	Yield increase and additional effects with vermicompost,	Souza et al. (2013)
Gneiss (+vermicompost)	Maize	4 (+16)	Oxisol (6.2)	>106 <212	2	Field	Increased plant growth and K, Ca, Mg, K + Ni, Cr, Pb uptake	Souza et al. (2018)
Gneiss, steatite (+vermicompost)	Maize	6.6 (+43.4)	Oxisol (5.1)	>106 <212	1 ½	Pot	Increased plant and earthworm growth. Gneiss Zn source, steatite heavy metal release	Souza et al. (2019)
a) gneiss b) Kfs	Ryegrass	a)25-100 b)5-20	loamy sand (4.8) sand (5.0)	-	12	Pot	High-energy milled rocks increased yield, soil pH, plant K and Si content.	Priyono and Gilkes (2008)
Basalt/ Andesit	Grass	40	Sandy loam pH 6.2	30%>2000 70%<2000	36	Field	No effects on yield, soil chemistry or microbiology	Campbell (2009)

Table 4: continued

Rock / Mineral	Plant	Application amount (t/ha)	Soil / substrate (pH)	Particle size (µm)	Duration (months)	Trial type	Main Results (trial type)	Source
Basalt, andesite	Ryegrass wheat, clover	5-50	Peat (6.8), clay (6.9), sand (6.3),	30%>2000 70%<2000	36	Pot	No effects on yield, nutrient composition or soil biology	Ramezanian et al. (2013)
Basalt, andesite	Ryegrass, clover	50	Sandy loam (5.4), silt loam (5.5)	30%>2000 70%<2000	24	Pot	Increased grass yield, but only in first year. Not significant for clover.	Ramezanian et al. (2015)
Basalt, andesite	Clover-grass mix	50	Silt loam (4.8) sandy loam (5.2)	30%>2000 70%<2000	12	Pot	Increased clover growth, no effect on grass	Dahlin et al. (2015)
Andesite	Eucalyptus	3.3 – 6.6	Ultisol	100%<74	5	Field	K supply but insignificant plant growth, 50% SRP + 50% NPK outyielded 100% NPK	Dalmora et al. (2020)
Dacite rock	Black oat, maize	1-7.2	Oxisol (~5)	100%<2000 57%<300	2x 2 ½	Pot	Increased yield, soil pH and K, P, Ca, reduced Al toxicity	Ramos et al. (2019)
Basalt	Cocoa	5 - 20	Oxisol (4.3)	100%<250 53%<50	24	Field	Increased yield and soil K, Ca, Mg, Si, Na, . Reduced Al and Mn toxicity	Anda et al. (2013)
a) basalt b) tuffs	Peanut	5-50	Calcareous soil (7.8)	a)1-250 b)100-1000	1	Pot	Increased plant Fe, reduced effect in the 2nd harvest	Barak et al. (1983)
Basalt (+manure)	a) grass b) maize	3.2 (+12.8)	Sandy soil (5.3)	Ø = 24	a) 5 b) 4	Field	Reduced NH3 emissions of manure, increased yield and N recovery of manure	Shah et al. (2018)
Six rock types[7]	Rice	2.5 - 40	Oxisol	125-1000	4	Pot	Varying effects on yield, pH, micro- and macronutrients. Ultramafic rocks best results	Silva et al. (2014)
Basalt, diabase, bentonite.	Beech, fir, spruce	4.7	Forest soils (3.8), (5.8), (2.8)	-	36	Field	Increased pH in all soils, varying effects on soil biology	Mersi et al. (1992)
Dunite	Maize	0.04 - 1.5	Clayey oxisol (5.2) sandy oxisol (5.4)	-	-	Pot	Increased yield, biomass, Mg and Si concentration.	(Crusciol et al. (2019)
Dunite	Soybean	0.04 - 1.5	Clayey oxisol (5.2) sandy oxisol (5.4)	-		Pot	Increased yield, soil pH, both crop and soil Si, Mg content,	Moretti et al.(2019)
Rock mix[8] (+rice straw)	Tomato	10	(5.13)	<2000	2	Pot	Increased yield, soil pH, Ca, Mg. Decreased disease resistance and soil Mn and Zn	Li and Dong (2013)
Rock mix[3] (+ compost)	Apple	10.4 (+15.6)	Sandy loam (7.5)	<2000	24	Field	Increased yield and fruit quality. Stimulated microbiology of compost and soil	Li and Dong (2020)
Basalt, porphyry graywacke,	Barley, oat, rape, clover	150 - 600	Sandy (5.3), clay (7.6)	60%<63	1 ½ - 5	Pot / field	Yield and nutrient supply mostly positive on sandy soils, mostly insignificant on clay soil	Kahnt et al. (1986)

[7] breccia, biotite, biotite schist, ultramafic rocks, phlogopite, manganese ore
[8] olivine, plagioclase, quartz, K-feldspar and biotite

supplied more K to spruce trees, although the K levels in spruce needles remained below the deficiency threshold.

3.3.3 Trials with micas

Various micas were tested, of which glauconite obtained the best results, corresponding to its highest weathering rates among the mica species (Table 3). In Argentina, Franzosi *et al*. (2014) compared KCl and glauconite for a grass mixture grown on an acidic (pH 4.9) soil that was not further specified. KCl produced slightly higher yields in the first harvests, although glauconite had higher overall yields after five harvests.

In western Siberia, a single application of glauconite improved the yield of durum wheat (*Triticum durum*) in the first year (Rudmin *et al.*, 2019) and of oat (*Avena sativa*) in the second year (Rudmin *et al.*, 2020). Glauconite slightly improved soil pH, Ca, and K of the non-specified ‘dark grey’ soil, although none of the differences were statistically significant.

Dias *et al*. (2018) compared two glauconite rich rocks, of which one was pyrometallurgically altered, with KCl in a 2.5-year coffee trial. Both rocks increased yield, however only altered glauconite had similar yields as KCl and significantly improved soil pH, CEC, available P, K, Ca, Zn, whereas KCl only improved K.

In a similar trial, Santos *et al*. (2016) tested pure and altered (acidified and calcinated) verdete rock (glauconite and K-feldspar rich) on an oxisol in two crop experiments: (a) maize followed by grass (*Panicum maximum*) and (b) eucalyptus. Interestingly, untreated verdete was ineffective for maize and eucalyptus but achieved the highest yield and K supply for subsequent grass growth. The altered rocks and KCl equally increased K uptake in eucalyptus and maize, whereas dry matter production only increased for maize.

Acidification was also employed by Weerasuriya *et al*. (1993) for phlogopite mica, which increased yield by 41% compared to KCl and limestone with the lowest application rate so far reported (0.2 t ha^{-1}). Acidulated feldspar in turn was ineffective, likely because its framework structure is less susceptible to acidification than the mica sheet structure. Superior results of mica treatments compared to KCl could have been due to multi nutrient supply from the acidified rock.

In a pot trial with pure quartz sand, in which phlogopite mica and syenite (>90% K-feldspar) were the only sources of K, Manning *et al*. (2017) showed that leek can obtain sufficient K for growth from the rock powders. A dose-dependent positive response was found for leek, whereas the highest amount of phlogopite outyielded KCl, and the highest amount of syenite resulted in equal yields as KCl.

The most weathering resistant mineral across the studies reviewed, muscovite mica, increased various soil K pools (water soluble, exchangeable and non-exchangeable), K uptake and yield of Sudan grass

(*Sorghum vulgare*) on two alfisols. Yields additionally increased by inoculating muscovite with silicate dissolving bacteria (*Bacillus mucilaginosus*) (Basak and Biswas, 2009).
Zinnwaldite, a mica mineralogically similar to biotite but containing Li, was directly mined or obtained as a waste product from a mining sludge in the Czech Republic, and tested together with feldspar as KCl alternative for spring barley on pure quartz sand and two luvisols (Madaras *et al.*, 2012). All treatments increased the total plant biomass and K uptake in the order zinnwaldite> waste zinnwaldite>feldspar, although the waste product released critical amounts of heavy metals (Pb, As, Cr). Zinnwaldite outyielded KCl in the higher dosage although the plant K content was lower, suggesting other growth promoting factors other than K.
In New Zealand, Hanly *et al*. (2005) found significant Mg supply to grasses by serpentine rock, which is a hydrated magnesium silicate mineralogically similar to micas. After 29 months, yield was however not increased by the rock powder.

3.3.4 Trials with granites

In Western Australia, the same biotite containing granite tested on similar acidic sandy soils with low exchangeable K showed contrasting results (Bolland and Baker, 2000; Coroneos *et al.*, 1996; Hinsinger *et al.*, 1996). No significant effects on yield or K-uptake were found for wheat grown in the field and clover grown in the glasshouse (Bolland and Baker, 2000). For unknown reasons, 20 t ha^{-1} granite decreased wheat yields in the field trial compared to the control with no fertilizer added (Bolland and Baker, 2000).
Hinsinger *et al*. (1996) found that granite significantly increased K uptake and yield (10-20%) of wheat, whereas a diorite with low K content (0.3% K_2O) was ineffective.
Granite treatments were tested for ryegrass (*Lolium rigidum*) and subterranean clover (*Trifolium subterraneum*), which were grown for 7 weeks, harvested, and then regrown for another 13 weeks (Coroneos *et al.*, 1996). After 7 weeks, granite increased the K content of both species, whereas yield only increased for clover. After 13 weeks, granite resulted in higher growth and K uptake for both species in two out of three soils.
Waste granite powder was tested in Galicia (north western Spain), where more than 90% of the national granite production takes place, on an highly acidic (pH 4.6) nutrient deficient loamy sand with ryegrass as test crop (Silva *et al.*, 2013). The rock waste contained additional amounts of Ca incorporated during prior processing. Very high application amounts (25-100 t ha^{-1}) increased yields, soil pH, CEC, available Ca, Na, Mg and K, reduced exchangeable Al and released no critical amounts of potentially toxic elements.
Several gneisses (metamorphic rocks) with similar mineralogical compositions to granites (quartz, K and Na feldspars, micas and amphiboles) were tested pure or modified. Gunnarsen *et al.* (2019) found

that gneiss only increased ryegrass growth and root biomass when K was omitted in the growth medium. In Brazil, Souza *et al.* (2013; 2018; 2019) evaluated the effects of gneiss and steatite powder mixed with vermicompost on maize grown on several oxisols. Vermicompost was prepared with cattle manure and the red earthworm Eisenia andrei, to which the rock powders were mixed at 5, 12 and 20% (w/w). In all trials, rock amended vermicompost significantly increased yields, whereas the earthworm weight increased in the vermicompost with 20% gneiss addition (Souza *et al.*, 2013) and even doubled with 12% gneiss addition (Souza *et al.*, 2019). Gneiss vermicompost significantly increased plant and residual soil nutrient concentrations (Souza *et al.*, 2018). The content of heavy metals in maize shoots reached critical limits for steatite (Souza *et al.*, 2019) and for gneiss (Souza *et al.*, 2018), although national heavy metal thresholds only exist for grains and vegetables, and not for the arial parts of plants, so longer trials are needed to analyze the transport of heavy metals to grains. High-energy milled gneiss achieved a similar agronomic effectiveness as K_2SO_4 for ryegrass grown on Plinthic Eutrudox and a Dystric Xeropsamment, whereas milled feldspar was less effective (Priyono and Gilkes, 2008). However, the application rates of gneiss were 5-times higher than for feldspar and decreased the nutrient content of Ca and Mg to nominally deficient levels.

3.3.5 Trials with andesitic and intermediate rocks

A commercially available 'volcanic' rock powder (SEER center, Scotland) with a coarse particle size (60%> 0.6mm) was used in four trials (Campbell, 2009; Ramezanian *et al.*, 2013; Ramezanian *et al.*, 2015; Dahlin *et al.*, 2015). It had an andesitic composition with over 70% feldspars (albite, anorthite and orthoclase) and varying amounts of pyroxene and quartz. Although the rock powder was obtained from the same provider, Ramezanian *et al.* (2013; 2015) and Dahlin *et al.* (2015) report substantial (~15%) amounts of clay minerals, which would not be expected to occur as primary minerals in igneous rocks, whereas the rock powder analyzed by Campbell (2009, p.170) did not contain clay minerals but therefore more pyroxene and iron oxides.

After 3 years, neither Campbell (2009), evaluating the effects on a mixed grass pasture, nor Ramezanian *et al.* (2013), growing two wheat (*Triticum aestivum*) cultivars and a forage/grass mixture, found significant effects on yield, soil chemistry or microbiology (Ramezanian *et al.*, 2013). Interestingly, Dahlin et al. (2015) found significant yield increases for red clover (*Trifolium pratense* L., cv. Nancy) but not for perennial ryegrass (*Lolium perenne* L., cv. Helmer), whereas Ramezanian et al. (2015) report opposing results for the same plant species, with increased yield for ryegrass but not for clover. The ineffective results from Campbell (2009) and Ramezanian *et al.* (2013) could partly be explained by an overlapping soil-rock powder mineralogy (section 2.4), whereas the soils from Dahlin et al. (2015) and Ramezanian *et al.* (2015) contained more than 50% quartz and had a lower pH, thus potentially favoring weathering.

An equally coarse grained (<2.8mm) andesite rock by-product showed no effects on *Eucalyptus saligna* Smith clones grown on a nutrient poor ultisol, although after 9 months available K in the soil was higher for the rock treatment than for NPK (Dalmora *et al.*, 2020). However, 50% rock powder mixed with 50% NPK increased growth and residual available soil P more than 100% NPK, suggesting potential benefits of simultaneous rock powder and soluble fertilization, possibly due to additional rhizosphere acidification via NH_4^+ uptake.

Another mining by-product, dacite rock, was supplied to black oats and maize (cultivar HIB ITAP 700) grown on an oxisols in Brazil (Ramos *et al.*, 2019). The mineralogy of dacite is typically between andesitic and rhyolitic, whereas the one used for this trial was obviously hydrothermally altered, since it contained montmorillonite, saponite, and hematite. Significant improvements were reported for growth and nutrient uptake of black oat and maize growth. The highest application amount (7.2 t ha^{-1}) significantly raised soil pH and available K, P and Ca levels, whereas Al toxicity decreased.

3.3.6 Trials with mafic and ultramafic rocks

In Malaysia, basalt powder significantly increased cocoa plant growth and *in situ* soil solution concentration of Ca, Mg, K, Na and Si, while Al and Mn concentrations were effectively reduced to non-toxic levels (Anda *et al.*, 2013). Soil pH and CEC increased with application amounts, whereas the best agronomic effectiveness was obtained by mixing basalt with rice husk compost at 5t ha^{-1} each. Barak *et al.* (1983) report that ground basalt alleviated Fe-deficiency (chlorosis) of peanuts grown on a calcareous soil with equal efficiency as the commonly applied synthetic organic chelate FeEDDHA. Shah *et al.* (2018) mixed ‚*Eifelgold*‘, a commercial rock powder with basaltic composition, with cattle manure, which significantly reduced the NH_3 emissions of the manure after field application. Grass and maize growth increased, and the apparent nitrogen recovery (ANR) was 2-3 times higher compared to the unamended manure.

An ultramafic mining by-product substantially enhanced (up to 3-fold compared to control) rice (cv. Curinga) yield and shoot concentrations of K, Zn, Cu and Ni at non-toxic levels (Silva *et al.*, 2014). Other mining by-products were also tested with less but mostly significant yield improvements. Mersi *et al*. (1992) found significant pH increases for applying a basalt-diabase-bentonite mixture to three forest soils in Austria. Varying effects were found on soil biology, ranging from no effects for a highly acidic (pH 2.8) stagno-dystric gleysol, up to increases of nitrification, basal respiration, microbial biomass and varying enzyme activities for a calcaric regosol and cambisol, which were partly related to their higher pH (5.8).

Dunite, an ultramafic rock consisting mostly of olivine, improved plant growth and yield of maize (Crusciol *et al.*, 2019) and soybean (Moretti *et al.*, 2019) on a clayey and sandy oxisol in Brazil. Si and

Mg levels increased for both soils and plants, in addition to beneficial effects on plant reducing sugars and foliar glucose.

In China, a rock mixture consisting of olivine, plagioclase, quartz, K-feldspar and biotite at a weight ratio 1:1:1:2:3 promoted remarkable agronomic benefits. Li and Dong (2013) report that growth, yield, chlorophyl content and photosynthetic rate significantly improved for tomatoes (cv. Shanghai 903), whereas bacterial wilt infection was reduced by 81% and 74% in the first and second year, respectively. Soil pH was raised but not CEC, and soil enzymatic activity was increased for surcease and catalase. Superior effects for all parameters were obtained by mixing the rock with rice straw. The same rock mixture was blended with a compost and thereby raised its nutrient content, metabolic activity and functional diversity (Li *et al.*, 2020). The rock amended compost increased apple yield by 120% and 187% compared to the control in the first and second year, respectively. The fruit quality improved by means of raised superoxide dismutase, vitamin C, total sugars and hardness, and less acidity.

In a trial with basalt, porphyry, and graywacke, and the highest application amounts so far reported (150-600 t ha^{-1}), Kahnt *et al*. (1986) reports improved field capacity and mostly increased yields for barley, oat, rape, and clover when grown on a sandy soil, whereas the effects on the clay soil were mostly insignificant and even decreased yields when the highest amounts of porphyry, greywacke were applied.

3.4 Summarized effects on yield, nutrient supply and soil properties

Most of the reviewed studies in section 3.3 focus on yield and K supply, although several other effects are reported, which are summarized in figure 6. This was done by first screening all studies (n=48) for overall effects, and then analyzing each study according to each of the overall effects found. 8 studies did not conduct tests for statistical significance and were thus excluded, resulting in 40 studies that were considered for this analysis. An effect was counted as significantly positive or significantly negative when the SRP treatment showed a statistically significant higher or lower value than the unfertilized control, respectively. Several studies analyzed more than one rock powder and/or soil and/or plant. If this was the case, each rock, soil and/or plant type was considered individually, which is why the count for yield exceeds 40. The respective nutrient supply was evaluated by considering alterations in exchangeable and/or soil solution nutrient concentrations, and/or plant nutrient concentrations. Two important points are: 1) The graph shows that many of the potential effects are rarely measured, thereby potentially misrepresenting the agronomic scope of SRPs, 2) Significant effects do not yet imply agronomic effectiveness, which is dependent on how much the respective factor actually increased, on the application amount and on a range of other factors that are discussed in section 3.6.

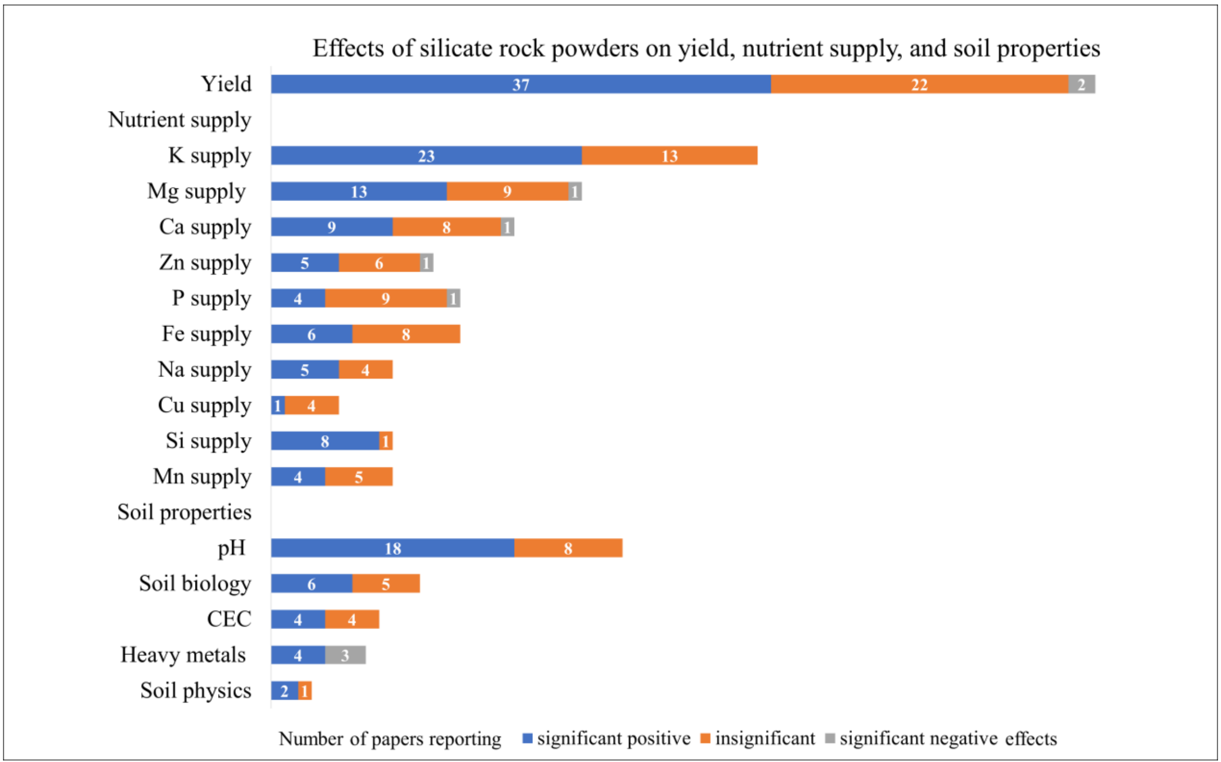


Figure 6: Summarized effects of silicate rock powders on yield, nutrient supply, and soil properties from 40 crop trials. 'Significant positive' and 'significant negative' refers to statistically significant differences to the unfertilized control treatment in the respective study. The count for yield exceeds 40, since various studies tested more than one silicate rock powder and/or soil type and/or plant species, which were all considered individually.

The detailed allocation of the effects can be looked up in the review matrix (Appendix Table 9), whereas in the following, some effects are shortly discussed.

3.4.1 Yield

As expected, most of the significant yield increases were achieved on rather acidic soils, particularly on oxisols (14 significant vs 4 insignificant), whereas results on temperate soils were mostly insignificant (5 significant vs 11 insignificant). The four insignificant results on oxisols were likely due to coarse particles sizes, low application amounts and K-feldspars/quartz rich rocks (Scovino and Rowell, 1988; Santos *et al.*, 2016; Tavares *et al.*, 2018; Ramos *et al.*, 2019). In turn, the five significant results on temperate soils were achieved with highly soluble nephelines associated with carbonates (Bakken *et al.*, 1997; Bakken *et al.*, 2000), biotite micas (Mohammed *et al.*, 2014) and in combination with compost (Li *et al.*, 2020; Li and Dong, 2013). Furthermore, all trials with mafic and ultramafic rocks improved yield (section 3.3.6), and almost all rock powder modifications (section 3.2.8) substantially increased the agronomic effectiveness of SRP, mostly equalizing commercial fertilizers. Only in two studies, and for unknown reasons, negative yield effects are reported (Kahnt *et al.*, 1986; Bolland and Baker, 2000).

3.4.2 Nutrient supply

Generally, the nutrients supplied by SRPs were above all determined by its mineralogy, and in further consequence by the trial specific factors discussed in section 3.2. Potassium (K) occurs in a wide range of silicate minerals and was a primary focus of many SRP trials. Although K supply often correlated with mineral dissolution rates, unexpected benefits occurred e.g. for a range of feldspar trials in Egypt (section 3.3.1), for which minor effects would be expected, given that feldspar dissolution rates are low and the soil pH was mostly alkaline. The importance of rock modification was shown by Dias *et al.* (2018), who tested two glauconites, but only the one pyrometallurgically altered significantly raised soil levels of K, Ca, Zn, Fe^{2+}, and, interestingly, P. The P content in the rock itself was negligible, yet the significantly higher P availability was related to the raised soil pH and to desorption of P by competing Si ions. Similar to effects on yield, the most prominent multi-nutrient supply was achieved with pure or modified mafic and ultramafic rocks applied to acidic soils. One study reports a decline of Ca, Mg, Zn, and P when very high amounts (100 t ha^{-1}) of high-energy milled gneiss and feldspar were applied, resulting from excess K supply that arguably led to an imbalance of the other nutrients (Priyono and Gilkes, 2008).

3.4.3 Soil pH

Several trials report increased soil pH, depicted as 'significantly positive' in Fig.6. All authors except Bakken *et al.* (1997), Souza *et al.* (2018), and Mersi *et al.* (1992) report that the increased pH was positive since the initial low soil pH constrained the respective crop growth. While many of them found rather small effects in the range of 0.2-0.4 pH units, some authors report increases of almost 2 pH units (Dias *et al.*, 2018; Silva *et al.*, 2013). In some cases, the pH effects were compared with lime. Mostly, the lime amendments had stronger effects on pH, although some studies suggest other benefits compared to liming, such as reduced nitrate leaching (Wilpert and Lukes, 2003), a more versatile effects on nutrient supply (Silva *et al.*, 2013) and soil biology (Aarnio *et al.*, 2003), and less CO_2 production when weathered (Dietzen *et al.*, 2018).

3.4.4 Soil biology

Li and Dong (2013) showed that SRP raised soil sucrase and catalase enzymatic activity, and additionally alkaline phosphatase and urease when combined with compost. Mersi *et al.* (1992) found contrasting effects, ranging from increased nitrification, basal respiration, microbial biomass, xylanase, and protease activity on a comparably high pH regosol and cambisol, whereas no effects were measured on an acidic gleysol. The authors concluded that the SRP mixture enhanced C and N mineralization for most of the forest soils.

Li *et al.* (2020) found that for a rock powder amended compost the metabolic activity and microbial functional diversity increased compared to the control compost, and the community-level physiological profiling (CLPP) of the soil indicated increased microbial activity and shifts in the microbiome composition. In contrast, the CLPP analysis of the soils analysed by Ramezanian et al. (2013) found no significant alterations after SRP incorporation. Adding gneiss to vermicompost increased the earthworm weight, although steatite had less pronounced effects (Souza *et al.*, 2013; Souza *et al.*, 2019). This agrees with Liu *et al.* (2011), who showed that earthworms accelerated silicate weathering, and that SRP fed earthworms had a higher bacterial diversity in their guts compared to the control. Carson *et al.* (2009) showed that differing minerals attract differing bacterial communities and are thus more than an inert matrix for bacterial growth. This agrees with Bennett *et al*. (2001) and is further emphasized through the 'mineralosphere' concept, which suggests that the mineral specific physico-chemical conditions and its inorganic nutrient supply support selective microbial colonization, similar to the rhizosphere (Uroz *et al.*, 2015).

3.4.5 Heavy metals

Significant positive effects on heavy metals were related to significant reductions in toxic aluminium (Al) and manganese (Mn) levels (Anda *et al.*, 2013; Liu *et al.*, 2017; Silva *et al.*, 2013; Dalmora *et al.*, 2020), whereas significant negative findings were related to the release of heavy metals like lead (Pb) and arsenic (As) from waste mica obtained from a tungsten mining sludge (Madaras *et al.*, 2012), and chrome (Cr) and nickel (Ni) release from steatite (Souza *et al.*, 2019) and gneiss (Souza *et al.*, 2018).

3.4.6 Soil physics

Although silicate rock powders directly interfere with the soil texture, only two studies measured effects on soil physical properties. Kahnt *et al.* (1986) showed that various SRPs increased the field capacity of a sandy soil by 12 to 23% compared to the control and that the coarse pore volume (> pF1.8) of a clay soil increased by 11 % via additions of the SRPs with sandy particle sizes. However, the amounts applied were up to 600 t ha^{-1}, which are unrealistically high application amounts. Liu *et al.* (2017) tested low (≤1.2 t ha^{-1}) amounts of a hydrothermally altered feldspar and report beneficial reductions of soil bulk density and an increase in porosity. Furthermore, the moisture and nutrient retaining capacity of the soil could improve via increases in 2:1 clay minerals like vermiculite, which was reported by Rudmin *et al.* (2019) and Mohammed *et al.* (2014).

3.5 Potential co-benefits of silicate rock powders

Despite the potential of being a multi-nutrient fertilizer and soil amendment, other co-benefits might arise from the use of SRPs. Those involve potential effects on carbon sequestration, nitrous emissions and benefits of silicon for plants. In the following, some key aspects are shortly discussed.

3.5.1 CO_2 sequestration by enhanced weathering

The weathering of silicate minerals naturally consumes CO_2, which has regulated the global carbon cycle and thus the Earth´s climate over several eons (Walker *et al.*, 1981; Berner, 2004). For instance, the Cenozoic uplift of the Himalayas and the consequent increased weathering of silicate rocks likely resulted in a CO_2 drawdown from the atmosphere and a cooling of the global climate (Raymo and Ruddiman, 1992). Enhanced weathering aims to accelerate this natural process by applying ground rocks on agricultural fields (Beerling *et al.*, 2020; Hartmann *et al.*, 2013; Seifritz, 1990).
Generally, the hydration of CO_2 (Eq. 1) forms carbonic acid (H_2CO_3) (Martin, 2017):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad \text{(Eq.1)}$$

Carbonic acids reacts with silicate minerals, which releases base cations (e.g. Ca^{2+}, Mg^{2}) and forms bicarbonate (HCO_3^-), and to a lesser extent carbonate (CO_3^{2-}) anions, depending on the pH (Lefebvre *et al.*, 2019; Beerling *et al.*, 2018). The exemplary chemical weathering for wollastonite ($CaSiO_3$) is given in Eq. (2) (Lefebvre *et al.*, 2019):

$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O \qquad \text{(Eq. 2)}$$

Following Equation (2), CO_2 is sequestered as carbonate ions (HCO_3^-, CO_3^{2-}), most of which drains down to groundwater systems as can be seen from the Chebotarev sequence (Chebotarev, 1955a, 1955b), whereas some portion eventually reaches the oceans, where it has expected storage lifetimes exceeding 100,000 years (Renforth and Henderson, 2017). Additionally, oceans naturally become more alkaline through rock weathering and enhanced weathering of SRPs might accelerate this process, thereby ameliorating the problem of ocean acidity (Kheshgi, 1995; Renforth and Henderson, 2017).
A second and less efficient CO_2 sequestration pathway occurs when the base cations like Ca^{2+} react with carbonate anions to precipitate as secondary carbonate minerals such as $CaCO_3$ (Eq. 3), thereby permanently sequestering C in geological formations (Jenny, 1941; Cerling, 1984; Lefebvre *et al.*, 2019). This carbonate mineral formation will herein be referred to as carbonation.

$$Ca^{2+} + 2HCO_3 \leftrightarrow CaCO_3 + CO_2 + H_2O \qquad \text{(Eq. 3)}$$

As outlined in section 3.2.1, major gaps remain in quantifying natural weathering. These uncertainties in dissolution kinetics led to diverging extrapolations concerning the theoretical CO_2 sequestration potential of enhanced weathering (Schuiling and Krijgsman, 2006; Hartmann *et al.*, 2013). In recent years however, some studies directly measured various elemental fluxes of SRPs. Six trials were found that conducted enhanced weathering experiments (Table 5).

All authors report increased CO_2 sequestration rates, but these differ by several orders of magnitude. These differences can be explained by differing experimental setups (rock-, plant- and soil type, rock application amounts, etc.) and differing calculation methods. Importantly, reported CO_2 sequestration rates cannot be directly transferred to most SRP trials presented in section 3.3, since (i) all enhanced weathering studies used very high application amounts in the range of 50 to >100 t ha^{-1} that exceed typical application amounts (1-20t ha^{-1}), (ii) divalent cation (e.g. Ca^{2+}, Mg^{2+}) concentrations are lower in many of the rocks investigated in chapter 3, which likely lowers potential CO_2 sequestration (Gunnarsen *et al.*, 2019), (iii) all trials except Kelland *et al*. (2020) used relatively soluble silicates like wollastonite or olivine with very fine particle sizes, thereby exceeding the weathering rates of many rocks and minerals tested in section 3. Additionally, the use of olivine might eventually be limited due to releases of the heavy metal nickel (Ni) (tenBerge *et al*., 2012; Amann *et al.*, 2020).

Overall, the results of Kelland *et al*. (2020) are particularly relevant for several reasons: (a) they used basalts, which are one of the major rocks used in SRP trials and are globally abundant; (b) the particle size was relatively coarse-grained (80% < 1.25mm), which is similar to sieved unprocessed quarry waste (Hinsinger *et al.,* 1996; Silva *et al.*, 2013); (c) despite the high application rates, no critical amounts of heavy metals were released; and (d) the experiments were conducted under temperate climatic conditions, and so higher efficiency may be expected under tropical conditions.

Table 5: Summary of 'enhanced weathering' studies. CO_2 sequestration rates were adopted from Kelland *et al*. (2020).

Rock/ Mineral	Crop	Particle size (µm)	Application amount (t ha^{-1})	Soil (pH)	Duration (months)	CO_2 sequestered (t CO_2 ha^{-1})	Source
Olivine	Ryegrass	7-600	1.6-204	Sandy soil (4.7)	8	0.29-2.69	tenBerge et al. (2012)
Olivine	No crop	d50 =20	a)10 b)50	Sandy podzol (3.4)	3	a) 3.13 b) 4.16	Dietzen et al. (2018)
Olivine	Wheat, barley	80%< 43.5 /1020	220	Loamy sand (6.6)	12	0.023-0.049	Amann et al. (2020)
Wollastonite	Soybean, alfalfa	90%< 63	3 - 400	Sandy loam (6.6)	3.5	9.6	Haque et al. (2020)
Wollastonite	Beans, corn	90% < 25.9	125	Acidic soil (4.9)	2	39.3	Haque et al. (2019)
Basalt	Sorghum	80% <1250	100	Clay loam (6.6)	12	2.36	Kelland et al. (2020)

3.5.2 Reduction of nitrogenous emissions

Silicate rock powders could decrease agricultural nitrous oxide (N_2O) and ammonia (NH_3) emissions, both of which considerably compromise the sustainability of agricultural systems (Kantola *et al.*, 2017; Webb *et al.*, 2010).

Similar to liming materials like $CaCO_3$, SRPs could reduce N_2O emissions from soils by correcting soil acidity. Even though it would be excepted that increasing soil pH will increase microbial N mineralization and thus nitrification, it has been repeatedly shown that liming decreased N_2O emissions (Borken and Brumme, 1997; Samad *et al.*, 2016; Hénault *et al.*, 2019). The N_2O reduction potential and preferential pH thresholds are hitherto not well understood but could be related to increased microbial production of enzymes that reduce N_2O to N_2 at neutral pH. Although basalts (approx. 20% CaO + MgO) have a lower pH buffering capacity than lime (40% CaO by weight), preliminary data of basalt applications suggest reductions of N_2O emissions (DeLucia *et al.*, 2019; Blanc-Betes *et al.*, 2021).

NH_3 volatilization of animal manure depends upon the concentration of NH_4^+ and NH_3 in the substrate (Ndegwa *et al.*, 2008). Silicate minerals retrain NH_4^+ to varying degrees (Adams and Stevenson, 1964), which could theoretically decrease NH_3 emissions by reducing the concentration of free NH_4^+ ions in the substrate. Mixing 20% SRP (basaltic composition) with cattle manure significantly reduced its NH_3 emissions after field application and improved overall nitrogen recovery (Shah *et al.*, 2012). Earlier studies with chicken manure and 10-20% SRP addition however showed contrasting effects, for which significant NH_3 reductions occurred within the first days, but thereafter increased again to eventually result in only borderline significant reductions after several weeks (Zaied, 1999; Kistner-Othmer, 1989). However, the rock powders, substrates and measurements differed, and comparisons are thus limited.

3.5.3 Silicon for biotic and abiotic stress resistance in plants

Despite silicon's manifold roles in plants and its tissue concentrations often equaling that of macronutrients, it is considered a beneficial rather than an essential plant nutrient (Epstein, 2009). Apart unresolved debates regarding essentiality, there is general agreement and accumulating evidence that Si induces plant biotic and abiotic stress resistance (Epstein, 1999; Guntzer *et al.*, 2012; Haynes, 2014; van Bockhaven *et al.*, 2013; Liang *et al.*, 2015), mainly through two main mechanisms: Firstly, the deposition of Si as solid amorphous silica in cell walls hardens the plant skin and thereby creates a physical barrier that impedes penetration by pathogens and insects. Secondly, Si promotes the biosynthesis of considerable amounts of organic defence compounds (Epstein, 2009; Haynes, 2014). Furthermore, seven (sugarcane, rice, wheat, barley, sugar beet, soybeans and tomatoes) out of the ten most important crops (ranked by global production) are Si-accumulators (>1.0% Si on dry matter basis

(Guntzer *et al.*, 2012)), and yield increases in response to Si fertilization has been frequently demonstrated for e.g. rice and sugarcane (Korndörfer and Lepsch, 2001). These tropical crops are typically grown on highly weathered and desilicated soils with Si concentrations being usually 5-10 times less than for temperate soils. The emerging role of Si in biotic and abiotic stress resistance and the lack of Si in many tropical soils are expected to increase future demand of Si nutrition (Haynes, 2014).

The majority of positive Si supply responses, however, has been reported for highly soluble Si sources, such as calcium silicates ($CaSiO_3$), sodium silicates (Na_2SiO_3), residues of blast furnaces and straw (mainly rice straw) (Guntzer *et al.*, 2012; Meena *et al.*, 2014). Although typical SRP trials mostly use less soluble rocks and minerals such as feldspars, basalts and granites, Si supply was reported in most studies that measured it (Figure 6).

In addition, some SRP trials with less soluble Si sources report improved biotic resistance. Li and Dong (2013) found that amending tomatoes with a rock powder mixture plus straw (quartz, biotite, potassium feldspar, plagioclase, olivine, and rice straw at ratios of 1:3:2:1:1:2) reduced bacterial wilt infection and improved plant health indicators like chlorophyll content and photosynthetic rate. The authors relate the increased plant resistance to raised soil pH and a higher macro and micronutrient supply, without measuring Si. Li and Dong (2020) used the same rock mixture but with compost for apple trees. Plant resistance to biotic or abiotic stresses was not measured directly, but fruit hardness increased, which likely contributes to an improved physical barrier effect. Other studies (not included in section 3.3) report significantly reduced bacterial rot infection and insect attack for tomatoes supplied with granite, apatite and compost, although NPK promoted higher yields (Zuba *et al.*, 2011). Similarly, although KCl outyielded glauconite in a trial with sunflowers, the postharvest commercial durability of sunflowers was longer for plants receiving glauconite (Torqueti *et al.*, 2016). Faraone et al. (2020) found that foliar and/or soil applications of granite dust significantly inhibited two-spotted spider mites (*Tetranychus urticae* Koch) from migrating to and/or settling on tomato leaves. Atungwu et al. (2014) found 82 to 92% reduction of root gall damage for watermelons through 2.5 to 5 t ha^{-1} crushed rock additions. The reductions are likely not due to direct Si supply, since more than 90% of the rock particles were in the sand fraction, the soil pH (6.78) was nearly neutral and the observation period was very short (60 days). The authors do not provide further information on these significant increases in biotic stress resistance.

3.6 Agronomic, environmental and health considerations

Apart from the factors outlined in section 3.2, the agronomic effectiveness of SRPs depends upon the costs for mining, grinding, transport and spreading them on the fields, with grinding being the most energy and thus cost intensive factor (van Straaten, 2006; Strefler *et al.*, 2018). A life cycle assessment

(LCA) about the potential of basaltic rocks for enhanced weathering and soil carbonation (section 3.5.1) found transportation (related to the distance between the quarry and the place of application) as the major process negatively affecting CO_2 sequestration, whereas grinding had less effects on the CO_2 budget, which could however be related to the relative coarseness (<5mm) of the particles. The current evidence suggests that the agronomic effectiveness is highest when SRPs are obtained as fine-grained mining residues normally low or free of charge and close to the site of application, which could simultaneously resolve a serious disposal challenge of the global mining industry.

Comparing the agronomic effectiveness with soluble fertilizers is difficult, since fertilizers typically supply readily available single nutrients apt for one growing cycle, whereas the potential effects of SRPs are manifold yet usually slower, potentially longer-term, and harder to quantify. Participatory research in Brazil showed that local SRPs were well received by small-scale farmers and single applications resulted in multiple agronomic and environmental benefits that lasted for up to five years (Theodoro and Leonardos, 2006). Furthermore, SRPs can have synergistic effects with soluble fertilizers (Dalmora *et al.*, 2020), and should thus not be seen as substitute for them, but as an alternative and supplementary soil amendment.

Negative environmental impacts of SRPs are mostly related to critical concentrations of potentially toxic elements (PTEs) such as Ni, Pb, As, Cd and Cr. In Brazil, institutionalized frameworks for maximum limits of PTEs have been established, which is effectuated by regulatory petrographic and mineralogical analysis prior to any usage (Dalmora *et al.*, 2020; Manning and Theodoro, 2020). This framework brought security and increased interest to both agriculturists and the mining industry, and could serve as general foundation for future SRP applications.

Proper handling and application of SRPs is important for two major reasons. First, inhaling rock dust particles during mining, grinding and application can have negative health effects (Feigin, 1989; Castranova, 2000). Second, it is practically rarely considered that surface applications might render SRPs less efficient, given that rock weathering is particularly enhanced within the rhizosphere. Thorough mixing of SRPs and soils is therefore important.

Although rocks constitute finite materials and can thus not be considered as renewable, they are among the most abundant resources on the planet and a shortage is not likely to occur at any realistic rate of application in the coming decades (van Straaten, 2002). Importantly, the amount of globally generated silicate mining waste potentially suitable for agricultural recycling is in the order of several Pg yr^{-1}, which are considerable amounts even when worldwide SRP applications are envisioned (Renforth *et al.*, 2011). Furthermore, conventional fertilizer productions are mostly large-scale centralized industries, whereas exploitation of various locally available ‘Development Minerals’ could contribute to regional self-sufficiency and poverty reduction (Franks, 2020). Also, a rapid deployment at large scale appears to be feasible within the coming decades, since the logistical infrastructure to apply SRPs already exists owing to the common practice of agricultural liming (Beerling *et al.*, 2020). Considering the socio-economic barriers to fertilizers in the Global South and the inertia of conventional large-scale fertilizer markets, a new paradigm of a *multilocal* rather than *global* fertilizer market can be envisioned (Ciceri *et al.*, 2015).

3.7 Conclusion

We aimed to synthesise the heterogenous literature about the agricultural usage of silicate rock powders and to answer how and under which circumstances SRPs can contribute to soil sustaining crop production. Although the inherent inconsistency of SRP trials limits the degree to which they can be compared and interpreted, some major findings can be concluded: (1) SRPs must be seriously considered as soil amendment for strongly weathered soils in the humid- and subhumid tropics, since they could fill the unresolved and escalating gap for affordable and accessible K sources and micro-nutrient soil amendments, which neither conventional fertilizers nor liming can currently sufficiently address. (2) Importantly, many tropical soils are equally deficient in Si, an often overlooked non-essential nutrient for which the demand is expected to increase in the future, since 7 out of the 10 globally most produced crops are Si accumulators and ample evidence suggests that Si can induce biotic and abiotic plant stress resistance. (3) Suggested rocks are those containing fast weathering minerals like feldspathoids or glauconites, and multi-nutrient mafic-/ultramafic rocks like basalts. (4) Results on soils in temperate regions remain inconclusive and benefits will depend on a careful selection of sufficiently soluble rocks with nutrient contents that match crop demands. (5) Applications should focus on obtaining fine grained mining residues from quarries that are close to the site of application.

For future research, we suggest the following points should be considered: (i) prior consideration of the presented SRP framework to avoid a poor selection of factors, since e.g. multi-nutrient mafic rocks applied on tropical soils can still be ineffective if the particle size is too coarse; (ii) methodologically consistent and statistically rigorous trials with a minimum set of factor information, including: physiochemical topsoil properties like texture, mineralogy and pH, rock powder mineralogy, particle size and application amounts in t ha^{-1}; (iii) conducting long-term trials that assess cumulative effects and potential co-benefits over several years, and potentially decades, focusing on combining multi-nutrient rocks like basalts with Si accumulating staple crops that are capable to additionally increase weathering. ; (iv) modifying SRPs to increase nutrient release shows considerable potential and must be forwarded on various fronts, such as the combination with organic materials or acidifications and hydrothermal alterations that led to K fertilizers of at least equal efficiency to that of KCl.

Eventually, if future research is addressed strategically, SRPs could not only advance self-sufficient and soil sustaining crop production but contribute to various sustainable development goals (SDGs), such as zero hunger (SDG2), sustainable consumption and production (SDG12), climate change mitigation (SDG13), and reverse land degradation (SDG 15).

4 Effects of rock powder additions to cattle slurry on ammonia and greenhouse gas emissions, physicochemical and microbiological properties[9]

4.1 Introduction

The livestock sector is a major source of ammonia (NH_3) and greenhouse gas (GHG) emissions. Of the total agricultural emissions in the EU in 2017, livestock slurry management contributed the biggest share of the total ammonia (NH_3) emissions and around 8% of total methane (CH_4) and nitrous oxide (N_2O) emissions (EC, 2019a; Tista *et al.*, 2019). There is ample evidence about the negative consequences of accumulating GHG emissions in the atmosphere (Stocker, 2014; Hoegh-Guldberg, O., D. *et al.*, 2018), whereas NH_3 emissions can cause atmospheric deposition of nitrogen (N) resulting in the eutrophication of ecosystems, soil acidification and fine particulate air pollution (Amon *et al.*, 2006; Schneidemesser *et al.*, 2016; Sonneveld *et al.*, 2008). The annual cost of NH_3 emissions in the EU are estimated to be 18-140 billion US $, mostly from increased mortality associated with aerosols (Paulot *et al.*, 2014). There are thus several policies in place to substantially reduce GHG and NH_3 emissions from livestock management.

Most of the NH_3 in the animal slurry derives from the breakdown of urea in the urine and of undigested proteins in the faeces (Groot Koerkamp *et al.*, 1998). The total ammoniacal N (TAN = NH_3 + NH_4^+) accounts for about 50-60% of the total nitrogen in the slurry (Sommer *et al.*, 2013), and occurs in a pH dependent equilibrium according to Eq. 4:

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O \quad \text{(Eq. 4)}$$

Equation 4 implies that a higher pH will drive the equilibrium reaction to the right and favor NH_3 volatilization.

For several decades, numerous methods have been suggested and tested to reduce NH_3 emissions from livestock slurry, which can account for losses of up to 90% of the ammonium NH^{4+}-N in the slurry (Clemens *et al.*, 2002). One suggested method is the addition of nitrogen adsorbing materials (minerals, charcoal, peat moss etc.) to the slurry (Ndegwa *et al.*, 2008). The hypothesis is that slurry NH_4^+ is adsorbed on the negative charged particle surface of the materials and thereby reduces NH_3 volatilization through a decreased concentration of free NH_4^+. There is evidence for reduced NH_3 emissions when mixing various NH_4^+ binders to slurry, although their agronomic effectiveness is often questionable (Ndegwa *et al.*, 2008). As outlined in section 3.5.2, SRPs are among the potential NH_4^+

[9] This chapter is based on the revised manuscript submitted to the *Journal of Environmental Chemical Engineering* **as** SWOBODA, P.; DÖRING, T. F., HAMER, M.; TRIMBORN, M.: Effects of rock powder additions to cattle slurry on ammonia and greenhouse gas emissions, physicochemical and microbiological properties.

binders, which have been used by farmers in Germany, Austria and Switzerland for several decades (Snoek and Wülfrath, 1983; Kistner-Othmer, 1989). A limited number of studies measured effects of rock powders mixed with solid livestock manure, with contradictory evidence. Shah *et al.* (2012, 2018) report reduced NH_3 emissions of solid cattle manure mixed with rock powders whereas Witter and Kirchmann (1989) found that mixing of basalt to poultry manure slightly increased NH_3, which was linked to the basalt induced pH increase of the manure. Zaied (1999) and Kistner-Othmer (1989) report retarded NH_3 emissions when rock powders were mixed to poultry manure, which did not significantly differ from each other at the end of the experiments. Most of the trials however did not measure GHG emissions, which is a common drawback of studies analyzing the emission reduction potential of abatement options (Sajeev *et al.*, 2018).

For farmers, there are oftentimes other reasons than NH_3 emission reductions to treat their slurry. Figure 7 shows the results of a survey with 292 farmers, outlining the major goals of slurry treatments and their observation if the goal was fulfilled (Gerber, 2003). The survey was conducted almost twenty years ago and was not peer-reviewed, nevertheless it presents a pertinent snapshot of practical farmer demands, which are often bypassed in a literature focusing primarily on NH_3 and GHG emissions. These reasons agree with various beneficial claims regarding rock powders from their providers[10][11][12], for example that their products increase the slurry nutrient content, improve the microbiological properties of the slurry, and decrease the floating crust, although no single peer-reviewed study was found that measured such effects.

Irrespective of the potential to reduce NH_3 emission and improve other properties of livestock manure, rock powders are gaining increased agronomic attention as reviewed in chapter 3. A major limitation of rock powders is their low solubility, which can however be improved by various treatments, among which the mixture with cattle dung and legume straw showed to significantly increase nutrient release (Basak *et al.*, 2020). The nutrients from rock powders can be released through organic acids that are produced during organic matter decomposition (Basak *et al.*, 2020), and also by direct microbiological attack (Bennett *et al.*, 2001; Uroz *et al.*, 2015). Livestock slurry contains both organic acids and microorganisms (Christensen and Sommer, 2013), and could thus equally enhance rock powder nutrient release. Again, we could not find a single peer-reviewed study that analyzed potential effects on nutrient release from rock powders mixed with livestock slurry.

[10] https://www.biolit-natur.com/de/biolit-story.html
[11] https://www.actimin.nl/
[12] https://www.schicker-mineral.de/landwirtschaft

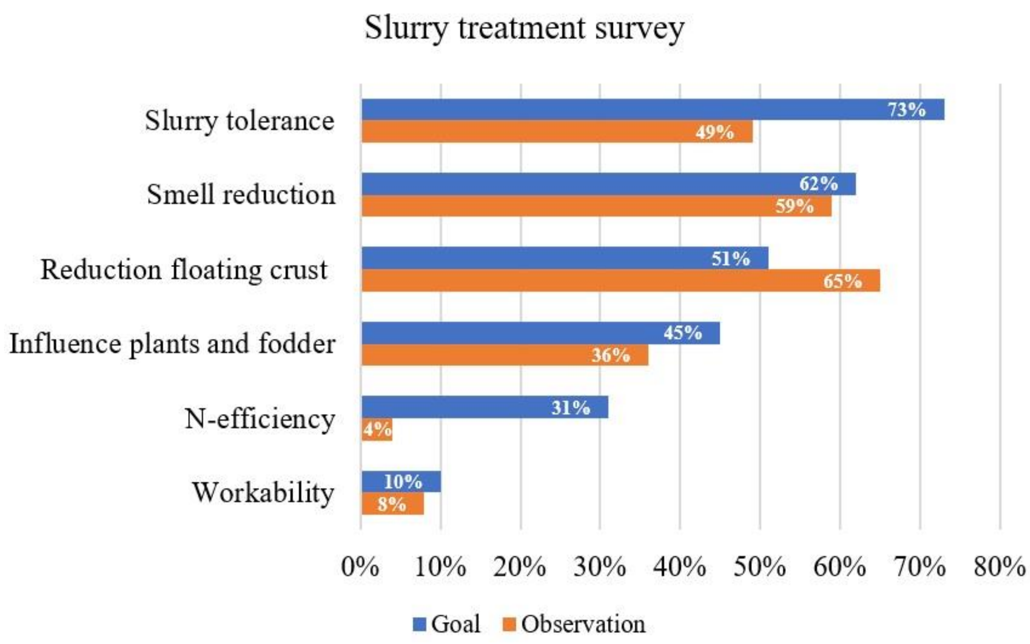


Figure 7: Farmer survey about goals vs. observations for slurry treatments (n=292). Data from (Gerber, 2003)

Overall, there are several reasons for examining the effects of rock powder additions to livestock slurry. The claim that rock powders reduce the NH_3 emissions of livestock slurry is theoretically possible and contradictory evidence exists for livestock solid manure (Kistner-Othmer, 1989; Zaied, 1999; Shah *et al.*, 2012; Shah *et al.*, 2018). Effects on other GHG emissions were however not considered before by these studies and must be equally addressed. Additionally, enhancing the nutrient release from rock powders via organic materials bears significant potential to improve their agronomic efficiency and would be practical across various farm scales and regions. Finally, a joint analysis of emissions, rock powder nutrient release, physicochemical, and microbiological properties will likely yield important biogeochemical insights.

The aim was therefore to measure the effects of mixing two commercially available rock powders to cattle slurry on NH_3, CO_2, CH_4 and N_2O emissions, and to analyze effects on its crust formation, physicochemical and microbiological properties. Finally, we discuss the usage of rock powders as slurry treatment and recommend future research directions.

4.2 Material and methods

4.2.1 Description of slurry collection, treatments, and site

Fresh cattle slurry was obtained on the 20.6.2020 from a conventional farm in Wachtberg-Werthhoven, Germany. In the summer months the animals graze and in the remaining months they are on a diet consisting primarily of maize and grass silage. Before collection, the underground slurry storage in the barn was mixed for 40 minutes to homogenize the slurry. Then, 100 l of slurry were taken in five 20 l buckets. Immediately after collection, 125 ml slurry samples were taken from each of the five buckets and mixed. From the resulting 625ml, a 100ml sample was analyzed for pH, total solids (TS), water content, organic matter, total N, total ammoniacal nitrogen (TAN), macro and micronutrient content, and one 200ml sample was analyzed for salmonellae, aerobic total bacterial count, fecal coliform baterica (*E. coli*) and enterococci. After the emission trial, the four replicates of each treatment were mixed together, from which a sample was analyzed for the same parameters. The analysis of the physiochemical and microbiological properties was done by an independent external laboratory (AGROLAB Agrar und Umwelt GmbH, Sarstedt, Germany).

After the slurry collection, the remaining slurry was stored for 6 days at 5°C in a cooling chamber. On the 26.6.2020 the treatments were prepared and on the 27.6.2020 the measurements started. The measurements were conducted in the barn of the agricultural campus Klein-Altendorf of the University of Bonn, over the period of 46 days to resemble practical temperature conditions. We tested 3 treatments with 4 replicates, resulting in 12 experimental units. The treatments were: control slurry without any additives, slurry with 5% w/w of the rock powder 'Eifelgold' and slurry with 5% w/w of the rock powder 'Biolit'. The rock powders were analysed for total elemental content and mineralogical composition via X-ray fluorescence spectroscopy (XRF) (Axios 3kW, Malvern PANalytical GmbH). For the pH measurement, rock powder samples were dispersed with sodium pyrophosphate, shaken for 15min in an end-to-end shaker and left to stand overnight. The soil suspensions were then shaken for 1min prior to pH measurement (Blume, 2000-). The particle size distribution was measured with the Laser Scattering Particle Size Distribution Analyzer LA-950 (HORIBA). All measurements were performed at the Institute of Geosciences (Department of Geology) at the University of Bonn. The particle sizes, pH, mineralogical composition, and elemental composition of the two rock powders are shown in Table 6.

Rock powder providers recommend amounts between 2-3% w/w, yet we raised the amounts to 5% w/w to detect possible changes more clearly. For optimal mixing, the rock powder was sprinkled through a sieve (mesh size: 1,5 mm) over the 20l slurry buckets, while the slurry was simultaneously mixed with a small hand mixer (Braun MultiQuck MQ100). This process of experimental mixing lasted 1.30 minutes and followed recommendations by the rock powder providers with the aim to imitate the mixing process in real settings, where the rock powders are blown into the underground slurry tanks while a rotor typically powered by a tractor stirs the slurry.

Although the slurry was mixed for 40min in the underground storage prior to collection and farmers generally mix their slurry without rock powder additions, the control slurry was not mixed before the trial start, since the additional 1.30 min mixing was considered part of the overall treatment rock powder. After mixing, 750ml slurry were taken from each 20l bucket and were filled into 1l plastic vessels (17,5cm x 13,5cm x 6cm height), which were stored on a shaded table in the barn during the

Table 6: Particle sizes, pH, elemental and mineralogical composition of the two rock powders ‘Biolit’ and ‘Eifelgold’. Only trace elements that were also measured in the slurry are depicted.

	Biolit	Eifelgold
Particle size (µm)	10%<2.3 90%<79.4	10%< 2.3 90%<77.7
pH	9,9	10
Major elements in wt%		
SiO_2	57.07	43.37
Al_2O_3	14.59	14.36
Fe_2O_3	8.01	11.22
MnO	0.13	0.18
MgO	3.99	9.06
CaO	3.00	11.06
Na_2O	3.86	3.16
K_2O	2.91	3.38
TiO_2	1.58	2.77
P_2O_5	0.35	0.51
SO_3	0.25	0.21
Trace elements in ppm		
Mn	1059	1433
Cu	20	52
Zn	83	78
Mineralogy of the rocks in wt%		
Quartz	18.97	-
K feldspar	13.37	9.17
Plagioclase	43.50	13.81
Amphibole	2.14	-
Pyroxene	-	44.59
Olivine	-	7.46
Leucite	-	10.63
Illite/Muscovite	8.74	3.45
Chlorite	10.55	-
Iron oxides	-	10.89
Titanium oxides	2.73	-

measurement period. Similar to (Kavanagh *et al.*, 2019) and Overmeyer *et al*. (2020), the plastic vessels in which the slurry was stored were covered with lids perforated with twelve 2mm-diameter holes. This was done since pre-trials without lids showed that slurry crusts formed after several days and limited longer emission comparisons. In contrast, lids without holes constitute strictly anaerobic conditions and led to no crust formation at all, a gas overpressure and a condensation of water on the slurry surface, resulting in more heterogenous and less comparable emission rates. Thus, perforated lids avoided gas overpressure and water condensation while crusts only started to form after several weeks, thereby better mimicking on-farm conditions and rendering measurements more comparable. The temperature was measured over the whole course of the experiment inside the barn every five minutes with a datalogger (EASYLOG USB-1).

4.2.2 Emission measurement design

Emissions were measured with an INNOVA 1412a photoacoustic gas monitor (LumaSense Technologies A/S, Denmark) (Dinuccio *et al.*, 2008; Shah *et al.*, 2018) that measures NH_3, CO_2, CH_4 and N_2O emissions in real-time once per minute. The INNOVA measures the gas concentrations in ppm and the detection thresholds of the gases are as follows: 0.2 ppm NH_3, 0.03 ppm N_2O, 0.4 ppm CH_4 and 1.5 ppm CO_2. The device was used with the default configurations which relate to standard conditions of 20 °C and 101.325 kPa, and with an automatic chamber flush time and a sample integration time of 5 s. The accuracy of gas measurements is ensured for changing temperatures since the device has an inbuilt mechanism to compensate for temperature fluctuations (LumaSense, 2007). At the beginning of each measurement day, the INNOVA first measured the air in the barn for 15 minutes to remove residual internal gas concentrations and to attain background air concentrations of all gases. In the same barn, the twelve slurry vessels were stored. During the storage, the slurry vessels were closed with the perforated lids. Before measuring a slurry vessel, the lid was removed and it was left open for two minutes, so that high residual gas concentrations from the headspace could dissipate. After two minutes, the vessel was placed in a box (60 x 40 x 33,5cm) equipped with a small fan (40 x 40 x 10 mm; air flow rate 13.94 m^3/h, manufacturer: WallAir) that provided a homogenous air distribution inside the box (Fig. 8). After the slurry vessel was put in the box, the box was closed, the inflow and outflow tubes of the INNOVA were connected to the box and the measurement started immediately thereafter for 10 minutes. By connecting both inflow and outflow INNOVA tubes to the box, the whole air was circulated within the measurement system (Shah *et al.*, 2018). After 10 minutes, the INNOVA tubes were removed from the box, the box was opened, the slurry vessel was put out, placed on the table again and closed with the lid. Then, the INNOVA measured the barn air for 5 minutes so that it could attain background air concentration again. Thereafter, the next randomly assigned slurry vessel was measured in the same procedure, but in a new box. Eventually, each slurry vessel was measured in a new and separate box.

In preliminary tests, this design yielded consistent real-time emission analysis, agreeing with Parker *et al*. (2017), who similarly incorporated a fan into measurement chambers.

The emission values obtained by our chamber experiment allow relative comparisons between the treatments. However, since various conditions like surface to volume ratio differ between laboratory-scale experiments and on farms (Dinuccio *et al.*, 2008), our values cannot be used to calculate manure storage or field emission rates without further validation. The slurries were measured for 46 days. Samples were measured every day until day 11, then every second day until day 21, thereafter every 3 days until day 30, and every fourth day for the remaining period.

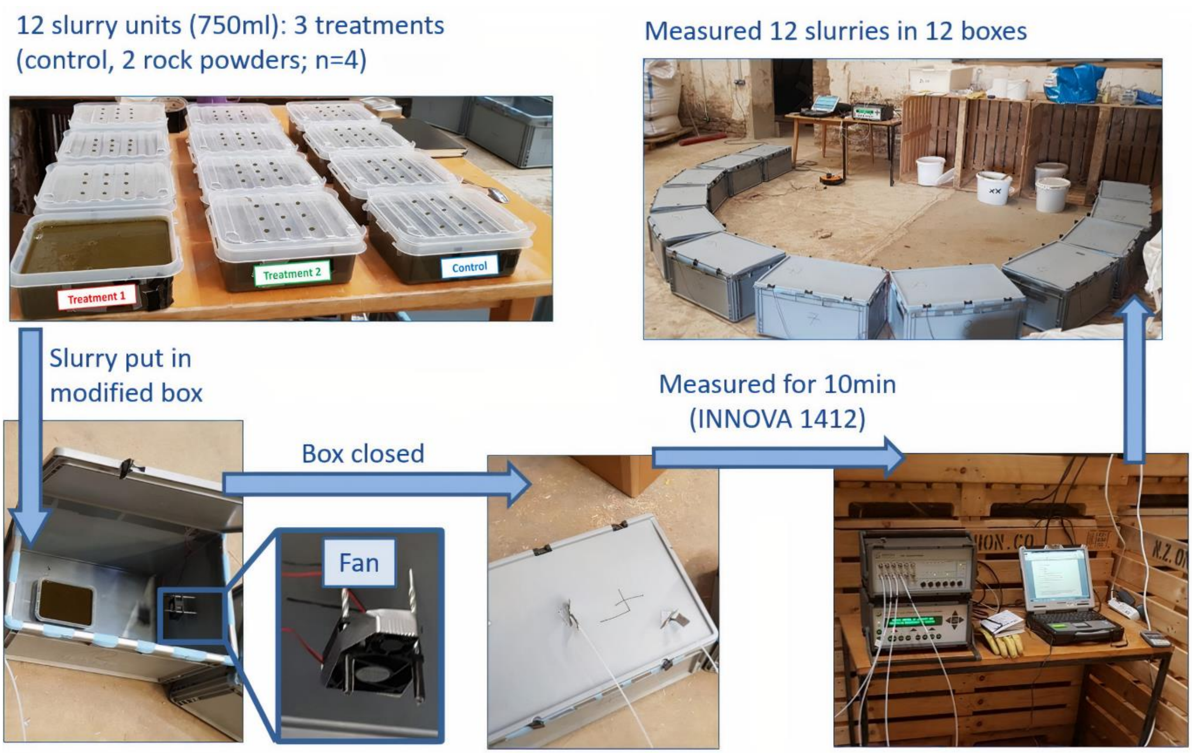


Figure 8: Emission measurement design: The lid (perforation accentuated) was removed from the slurry vessel, which was then put into a box with a fan, and measured for 10 minutes with the INNOVA 1412a. After a 5 minute break, in which the INNOVA attained background air concentration again, the next slurry vessel was measured in the next box. All 12 slurries were measured in a separate box according to this procedure

4.3 Data analysis

For the data analysis, the emission values (ppm gas l^{-1}) were converted into emission rates (mg^{-1} gas l^{-1} h^{-1}). The first of the ten values of each slurry measurement was discarded due to high fluctuations. Then, to the nine remaining emission values of each gas measurement of each day, regression curves (x-axis: time) were fitted in Microsoft Excel (Duncan *et al.*, 2017; Shah *et al.*, 2018). Our measurements were conducted in a closed system in which emissions are affected by an increasing diffusion resistance that reduces emission rates with time. This flattening out of the emissions was in the case of NH_3, CO_2, and CH_4 better depicted through a polynomial regression (polynomial function 2nd order, $y = ax^2 + bx + c$) than through a linear regression (linear function, $y = ax + b$). N_2O emissions however were very small and dispersed, and a linear regression fitted better to the values since the polynomial regression often resulted in positive ax^2 values, implying erroneous exponential emission increases. The b(x) value in the polynomial regression curve of NH_3, CO_2, and CH_4 describes the emission increase in ppm min^{-1} at time t0, whereas the ax value of the linear regression describes the emission increase in ppm min^{-1} for N_2O. To obtain emission rates, the four b(x) and ax values of each gas measurement were arithmetically averaged for each day, and standard errors were calculated. Then, the obtained ppm gas l^{-1} min^{-1} values were transformed into ml^{-1} gas l^{-1} h^{-1}. The volume of each box is 80.4l, so 1 ppm gas min^{-1} corresponds to 0,0804ml gas l^{-1} min^{-1}, and thus 4,824ml gas l^{-1} h^{-1}. According to the ideal gas law, milliliter values of the respective gas were then converted into milligram, thereby yielding the unit mg^{-1} gas l^{-1} h^{-1} (Duncan *et al.*, 2017).

Although minor emissions likely occurred while the slurry vessels were stored with the perforated lids, overall emission fluxes from the opened slurry vessels were presumably substantially higher. Therefore, cumulative emissions of the gases were calculated by only considering the measurement days (n=23) and the actual time the slurry vessels were opened (15 minutes per measurement day). The cumulative gas emissions and the emission rates (on day 5, 10, 15, 24, 38, 42, and 46) were subjected to an analysis of variance (one-way ANOVA), followed by a post-hoc Tukey test to determine the statistical significance between the treatments. For all statistical measurements, a significance level of $p = 0.05$ was applied and all calculations were conducted with SPSS (version 28.0.0.0 190).

Total greenhouse gas emissions (GHG) expressed as CO_2 equivalents were calculated from the CH_4 and N_2O emissions with the conversion factors of 310 and 21 for N_2O and CH_4, respectively (IPCC/OECD/IEA, 1997).

4.4 Results

4.4.1 Gaseous emissions

In the following, the results for the NH_3, CH_4, N_2O, and CO_2 emission measurements are presented, respectively.

4.4.1.1 NH_3 emissions

In all three treatments, the NH_3 emission rates over 46 days followed a similar course (Fig. 9a). The measurement on the first day, which was conducted immediately after the slurry was filled in the vessels, resulted in substantially lower NH_3 emissions than for the following days. From the second day onwards, and besides a peak on day 9, emission rates slightly decreased up until day 20, and remained stable up until day 30. On day 42, significant differences occurred between the control and Eifelgold, and on day 46 statistically significant ($p = 0.05$) differences occurred between Eifelgold and the control, and between Eifelgold and Biolit. This NH_3 reduction coincided with the formation of a slight surface crust of the control and Biolit slurry, emerging from day 38. The crust formation was most pronounced for the control slurry (Appendix Figure 11), followed by the Biolit samples. In contrast, no crust formation occurred for the Eifelgold samples (Appendix Figure 12). The cumulative NH_3 emissions did not differ significantly between the treatments, and yielded 217.99 mg for Biolit, 217.47mg for the control, and 231.83 mg for Eifelgold (Table 7). Some coincidence with temperature could be observed, which was most pronounced for the emission peak on day 9. The temperature depicted on the graphs does not correspond to the daily average temperature, but to the average temperature during the respective measurement period (3 hours) of all slurry vessels. After two weeks, no obvious correlation with the temperature was visible.

4.4.1.2 CH_4 emissions

For all treatments, CH_4 emissions were lower on the first days compared to the remaining measurement period (Figure 9b). We found significant differences in emission rates between the treatments, which were particularly pronounced for the Eifelgold rock powder. Starting from day 4, significant ($P<0.01$) differences occurred between Eifelgold and Biolit and Eifelgold and the control. From day 6 onwards, Eifelgold CH_4 emissions doubled compared to the other treatments and peaked on day 19, when emissions rates were on average 3 times and 5 times higher than for Biolit and the control, respectively. Emission rates between Biolit and the Control showed no statistically significant differences up until day 24. From day 24 onwards, CH_4 emissions from Biolit aligned to those of Eifelgold and showed statistically non-significant differences. CH_4 emissions rates from the control were the lowest over the whole period, gradually started to increase from day 24 onwards, and eventually aligned to CH_4 emissions from Biolit and the Control. Non-significant differences in emission rates were found between the control and Biolit from day 38 until the end of the measurements, whereas on the last measurement day, there were no statistically significant differences between all treatments. Similar to NH_3 and CO_2, a slight correlation with temperature could be observed for the Eifelgold emissions on day 9. No influence of the slurry crusts developing from day 34 onwards could be observed. The cumulative CH_4 emissions differed significantly for all treatments ($P<0.01$), with total emissions being 164.28mg for Biolit, 106.37mg for the control, and 326.46mg for Eifelgold (Table 7).

4.4.1.3 N_2O emissions

The emission rates for N_2O remained low and concentrations in the boxes did not exceed 1ppm except for some repetitions during the last three measuring days (Fig. 9c). Accordingly, emission rates showed statistically non-significant differences for all treatments up until the day 42. On day 42 and 46, N_2O emissions from the control were significantly ($P<0.05$) higher than for the Eifelgold treatment, whereas average N_2O emissions from Biolit were in between the control and Eifelgold, yet the differences were statistically non-significant. Increases in N_2O emissions correlated with the development of the slurry crust. Cumulative N_2O emissions were 0.465 mg for Biolit, 0.615 mg for the control, and 0.302 mg for Eifelgold, whereas significant differences occurred between the control and Eifelgold (Table 7). No correlation between N_2O emissions and temperature could be observed.

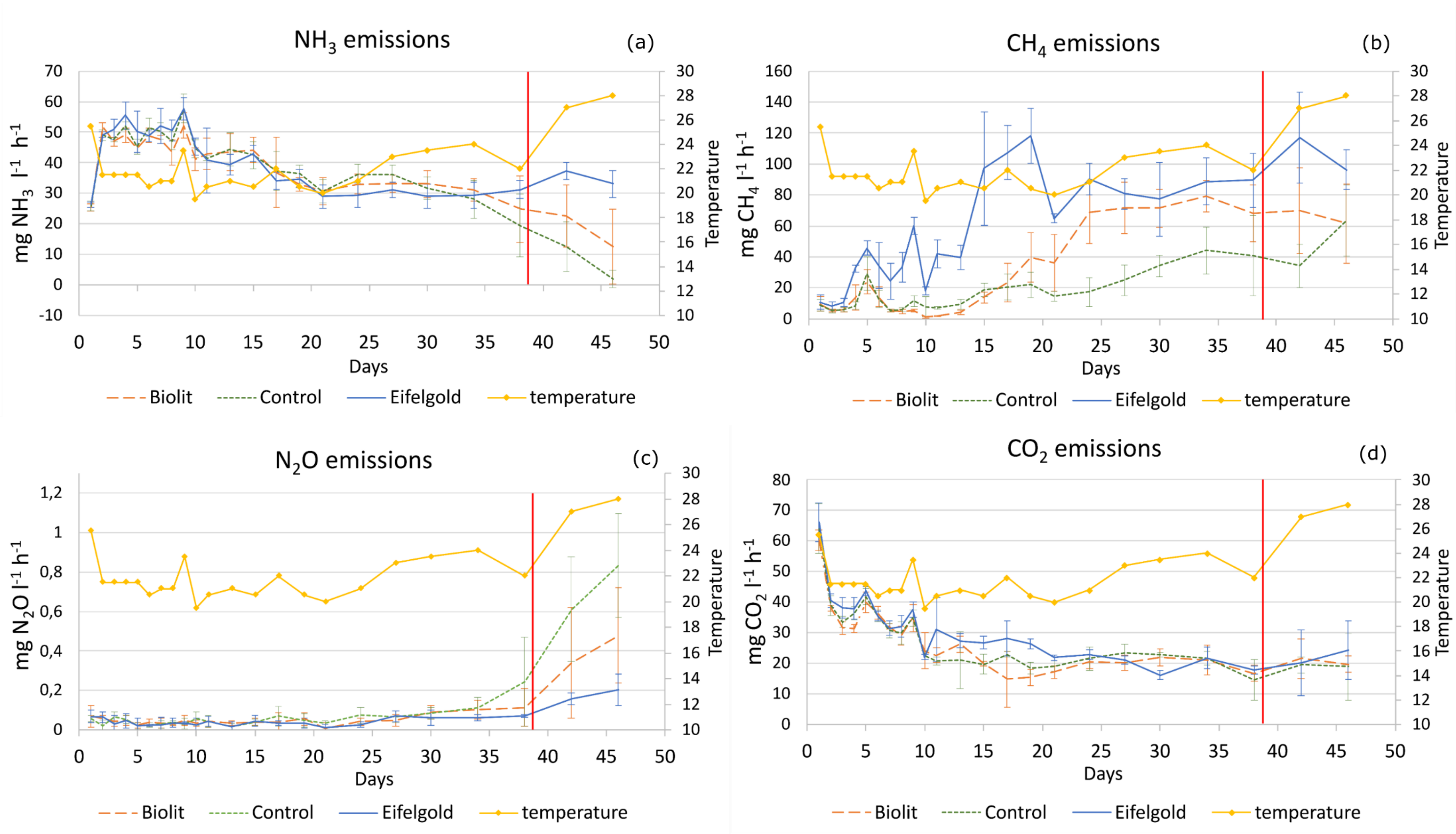


Figure 9: a) Average ammonia (NH_3), (b) methane (CH_4), (c) nitrous oxide (N_2O), and (d) carbon dioxide (CO_2) emissions of the control slurry and the slurry mixed with the rock powders 'Biolit' and 'Eifelgold'. Temperature values are the median degrees °C during each measurement period (3 hours) in the barn. The red bar indicates the formation of floating crusts starting from day 38. Vertical bars represent standard deviation of the mean (n=4).

4.4.1.4 CO_2 emissions

In contrast to the other emissions, the CO_2 emissions peaked on the first day, decreased up until day 10, and then remained stable until the end of the measurements for all treatments (Fig. 9d). Over the whole measurement period, no statistically significant differences were found for the emission rates between the treatments. However, the cumulative emissions significantly differed between Eifelgold and Biolit ($P<0.01$), and Eifelgold and the control ($P<0.01$) (Table 7). The accumulated CO_2 emissions were 397.12 mg for Biolit, 408.42 mg for the control, and 445.86 mg for Eifelgold. In contrast to NH_3, the crust formation did not reduce CO_2 emissions. There was a slight coincidence between the background temperature and CO_2 emissions, that was most pronounced within the first 10 days.

Table 7: Summary of cumulative gaseous losses from cattle livestock slurry with or without rock powder 'Biolit' and 'Eifelgold' expressed as mg gas per liter cattle slurry. Total measuring time of cumulative emissions: 5.75 hours. (n=4, values in parentheses are standard errors. Treatment means with different letters are significantly different at $P<0.05$).

Treatment	Gaseous emissions				
	NH_3	CO_2	CH_4	N_2O	Total GHG
	mg liter^{-1}	mg liter^{-1}	mg liter^{-1}	mg liter^{-1}	mg liter^{-1}
Control	217.47	408.42**b**	106.37**c**	0.615**a**	2832.84**c**
	(12.34)	(12.97)	(14.19)	(0.091)	(113.06)
Biolit	217.99	397.12**b**	164.28**b**	0.465**b**	3391.15**b**
	(4.045)	(9.940)	(15.44)	(0.226)	(134.75)
Eifelgold	231.83	445.86**a**	326.46**a**	0.302**b**	7395.14**a**
	(7.666)	(8.820)	(22.01)	(0.080)	(165.28)

4.4.1.5 Total greenhouse gas emissions

When emissions were summed up as total greenhouse gas (GHG) emissions, comprising CO_2 and CO_2 equivalents from CH_4 and N_2O emissions, Biolit and Eifelgold showed increased total GHG emissions (+41% and +161%, respectively) in comparison to the control treatment (Table 7). NH_3 was not considered since its contribution to total GHG emissions is negligible (Berg *et al.*, 2006; Fangueiro *et al.*, 2008).

4.5 Slurry physicochemical properties

Physicochemical properties of the slurry before and after the treatment are shown in Table 8. The pH of all slurries increased over the course of the trial and was slightly higher for the two rock powders, with Eifelgold being 0.1 pH unit higher than Biolit. The organic matter content decreased in all slurries in the order Biolit>Eifelgold>control. Besides the reduced slurry crust, the rock powder slurries also appeared to be more liquid and flowable. Total N and $NH^{4+}N$ after the emission trial were higher for the two rock powders than for the control. All macro- and micronutrients increased in the slurries after the 46 days. All nutrient contents were higher in the rock powder treated slurries, whereas overall nutrient release was higher for 'Eifelgold'. The major nutrient increases are shortly outlined: Potassium (K) increased by 36% for Eifelgold, magnesium (Mg) increased by more than 200% for both rock powders, calcium (Ca) increased by 72% for Biolit and 103% for Eifelgold, copper (Cu) increased by 39% for Biolit and by 112% for Eifelgold, manganese (Mn) increased by almost 250% for both rock powders, and zinc (Zn) increased by about 25%. For sodium (Na), a drastic increase of 533% occurred for Eifelgold, whereas it increased by 24% through Biolit.

4.6 Slurry microbiological properties

Salmonellae were not detected in any of the slurry samples (Table 8). The aerobic total bacterial count of changed for all slurries over the emission measurements. It increased for Biolit and even more for the control, yet it decreased for Eifelgold. *E.coli* values decreased below the detection limit for all treatments. Similarly, but less pronounced, was the reduction of Enterococci, which exceeded critical thresholds before the trial, remained over the critical thresholds for Eifelgold after the trial, and was reduced under critical thresholds for Biolit and Control.

Table 8: Physiochemical and microbiological properties of the slurry before and after the trial, with and without rock powder 'Eifelgold' and 'Biolit' addition (N=1). CFU = colony forming unit.

	Slurry before trial	Slurry after trial - day 46		
	Control	Control	Eifelgold	Biolit
Dry residue (%)	7.5	7.4	12.2	11.8
Water content (%)	92.5	92.7	87.8	88.2
pH	7	7.4	7.6	7.5
Organic matter (kg/cbm)	56.3	50.1	48.6	48.1
Total N (kg/m³)	3.32	2.15	2.56	2.25
NH_4-N (kg/m³)	1.75	0.56	0.87	0.712
P_2O_5 (kg/m³)	1.28	1.45	1.68	1.59
K_2O (kg/m³)	3.93	4.49	6.12	4.57
MgO (kg/m³)	0.77	0.89	3.16	2.67
CaO (kg/m³)	1.5	1.73	3.52	2.98
S (kg/m³)	0.35	0.39	0.422	0.411
Cu (g m³)	1.78	2.08	4.43	2.89
Zn (g/m³)	9.83	11.5	14.3	14.9
Na (g/m³)	116	146	925	181
Mn (g/m³)	16	19	67	66
C/N (kg/m³)	9.8	13.5	11.0	12.4
Salmonellae	n.m	n.m.	n.m.	n.m.
Aerobic total bacterial count (CFU/g)	6.400.000	8.600.000	4.100.000	7.000.000
E.coli (CFU/g)	4000	<3,0	<3,0	<3,0
Enterococci (CFU/g)	46000	930	7500	930

4.7 Discussion

4.7.1 NH_3-emissions

Our results do not support the hypothesis that rock powders reduce NH_3 emissions from cattle slurry. To the contrary, for the rock powder treatments NH_3 emission rates increased at the end of the trial, which coincided with a reduction in the floating crust. Reduced NH_3 emissions through floating crusts has been reported by several other authors (Misselbrook *et al.*, 2005; Smith *et al.*, 2007; Wood *et al.*, 2012). Importantly however, overall emission differences were small and cumulative emissions did not differ significantly to each other. In the literature, the only significant NH_3 reductions with rock powders that we found were by Shah *et al*. (2012, 2018), who treated solid cattle manure with >8%

w/w ‘Eifelgold’, the same rock powder we also tested. However, despite using solid cattle manure and not liquid manure (slurry), their measurements only lasted for 3-4 days after field application. Similarly, reduced NH_3 emissions were reported in the first days by Kistner-Othmer (1989) and Zaied (1999), who measured chicken manure mixed with higher rock powder additions in the range of 12-20% w/w. Importantly, after the initial NH_3 reductions with rock powders, they found increased NH_3 emissions in the subsequent weeks for the rock powder treated manures, which eventually resulted in non-significant differences between the treatments at the end of the measurement period (120 days for Kistner-Othmer (1989) and 29 days for Zaied (1999). Although there is longstanding evidence for NH_4^+ adsorption to rock surfaces (Adams and Stevenson, 1964), there are several potential reasons why no significant NH_3 reductions occurred. First, there are rock and mineral dependent differences in the adsorption capacities related to cation exchange capacity (CEC) and other specific properties related to structure. For example, the CEC of zeolite (clinoptilonite) can be 2 orders of magnitude higher than that of an equally fine-grained basalt (Witter and Kirchmann, 1989). Second, there are other cations competing with NH_4^+ for adsorption sites, particularly K^+, for which the amounts in our slurries were 4 to 6 times higher than NH_4^+, thereby likely decreasing adsorption places. This was also reported by Witter and Kirchmann (1989), who found that basalt powder placed in an exhaust air stream reduced NH_3 emissions from manure, whereas it slightly increased emissions when directly mixed with the manure. This was associated with cation competition for adsorption sites and a slight pH increase of the manure (Witter and Kirchmann, 1989).

4.7.2 CH_4, CO_2, and N_2O-emissions

Unexpected and hitherto unknown increases in CH_4 emissions occurred for rock powder treatments. The higher CH_4 emissions and the stronger decomposition of organic matter suggest increased microbial activity due to the rock powders. Microorganismal growth is often nutrient limited (Sparling *et al.*, 1981; Sterner *et al.*, 2003; Mersi *et al.*, 1992), and studies that analyzed rock powder additions to compost found higher metabolic activity and functional diversity of microorganisms (Li *et al.*, 2020). Accordingly, Carson *et al.* (2007, 2009) showed that specific minerals attract specific bacterial communities and are thus more than an inert matrix for bacterial growth. This agrees with the recently established ‘mineralosphere’ concept, which suggests that the mineral specific physico-chemical properties and its inorganic nutrient supply support selective microbial colonization (Uroz *et al.*, 2015). One factor for higher CH_4 emissions from ‘Eifelgold’ treatments could have been the substantially higher release of Na, which is known to have effects on methanogenic bacteria (Perski *et al.*, 1982; Thauer *et al.*, 2008). Additionally, CH_4 producing microorganisms are strictly anaerobic (Willey *et al.*, 2017), and the decline of aerobic bacteria in Eifelgold (Table 8) could have been linked to a potential increase of anaerobic bacteria. Furthermore, emission curves equalized towards the end of the trial. Further research is needed to analyse if emission curves would further adjust or even decrease for Eifelgold.

In contrast to CH_4, CO_2 emissions did not differ significantly for the treatments, even though the stronger decomposition of organic matter in the rock powder treated slurries would have suggested a concomitant increase in CO_2. Possible reasons for less pronounced differences in CO_2 emissions are that CO_2 is better buffered than CH_4. The bicarbonate buffer system as well as carbonation with other cations like Ca^+ and Mg^+ can buffer CO_2 emissions, whereas such pathways do not exist for CH_4 (Sommer and Husted, 1995; Sommer *et al.*, 2013). Peaks in CO_2 emission on the first day were likely due to the stirring and a concomitant oxygenation, resulting in higher aerobic microbial respiration. The very low N_2O emissions can be related to the absence of a slurry crust during most of the storage period. During the storage period of livestock slurry, N_2O may be emitted either as a by-product of incomplete ammonium oxidation or as a by-product of incomplete denitrification (Oenema *et al.*, 2001). Since the condition in liquid manure is strictly anaerobic, neither process occurs. Our findings that increased N_2O emissions correlated with the formation of a slurry crust agree with earlier studies (Sommer *et al.*, 2000; Dinuccio *et al.*, 2008). Dinuccio et al. (2008) argues that N_2O emission occurred since the slurry crust may contain a mosaic of anaerobic and aerobic micro-sites that are favourable for N_2O production. This agrees with Wood et al. (2012), who equally found increased N_2O emissions when slurry crusts formed.

The mixing of the rock powder treatments before the trial started could have had an additional effect on slurry properties and emissions. However, the slurry used for all treatments was mixed for 40min with a tractor-powered rotor in the slurry underground storage prior to collection, and so the 1.30min mixing of the rock powder slurries with a hand-mixer likely did not substantially influence slurry properties and emissions.

4.7.3 Physicochemical properties

The slurry pH increase over the experiment was consistent with recent findings by Overmeyer et al. (2020), and is related to the decomposition of organic matter and organic acids in the slurry, and the release of CO_2 (Sommer *et al.*, 2013; Overmeyer *et al.*, 2020). A slightly higher slurry pH was found for the two rock powders than for the control, which was expected due to the H^+ buffering capacity of the rock powders (Harley and Gilkes, 2000). The higher Ca and Mg contents (Table 6) of Eifelgold could be related to the slightly higher pH ('liming') effect. The lower organic matter content of the rock powder slurries correlated with their lower crust formation and could potentially be related to increased microbiological activity indicated by the higher CH_4 emissions. Despite higher NH_3 emissions, and for unknown reasons, total N and NH_4^+ were higher in the rock powder treated slurries.

The substantial nutrient release of the rock powders in the slurry is a relevant finding, since their dissolution rates are typically very low and are a major bottleneck to their usage (Harley and Gilkes, 2000). The fine particle size of the rock powders (Table 6), organic acids, and microorganism activity in the slurry likely contributed to the high nutrient release (Basak *et al.*, 2020).
The nutrient release of the rock powders agreed with their mineralogy (Table 6). For the release of elements from a rock powder, not only the content of the respective element is of importance, but particularly the weathering rate of the mineral with which the element is associated (Harley and Gilkes, 2000). Overall, the higher nutrient release of Eifelgold agreed with its higher content of fast weathering minerals such as Pyroxene, Olivine and Leucite (Deer *et al.*, 2013; Zhang *et al.*, 2018). The importance of the mineralogy was particularly evident for sodium (Na), for which the bulk content was higher in Biolit, although the Na release into the slurry was substantially higher in Eifelgold. This likely occurred since Na in Biolit was associated with the slow-weathering mineral albite (Na-endmember of the plagioclase series), whereas Na in Eifelgold was richer in the mineral anorthite (Ca-endmember of the plagioclase series), which has very high weathering rates (Palandri and Kharaka, 2004). Furthermore, traces of Na in Eifelgold could have occurred in the minerals pyroxene and leucite (Harley and Gilkes, 2000), both of which have higher dissolution rates than albite.
The substantial release of nutrients in the slurry could have important implications for future practices, since it constitutes a practical way to improve the rock powders solubility, that could be employed across various farming scales and regions. Agreeing with our findings, mixtures with other organic materials like compost or manure have shown to equally increase nutrient release from rock powders (Basak *et al.*, 2020; Li *et al.*, 2020), yet they did not measure NH_3 and GHG emissions, which are a crucial aspect for overall sustainability.

4.7.4 Microbiological properties

The decrease of *E.coli* and Enterococci over the 46 days agreed with a time and temperature dependent hygienisation during slurry storage (Skowron *et al.*, 2013). The stronger *E.coli* and Enterococci decline in our study compared to Skowron *et al*. (2013) likely occurred since we used smaller slurry volumes and higher temperatures prevailed during the storage periods. Overall, our results agree with recent findings that rock powders affect microorganism community structure (Carson *et al.*, 2009; Carson *et al.*, 2007; Uroz *et al.*, 2015).

4.7.5 Measurement design

Our alteration of the standard chamber measurement design yielded reliable relative emission data, although future trials should incorporate larger vessels so that the emitting surface to box headspace ratios becomes smaller. The measurement design has the potential to be further developed with e.g. the inclusion of various soils and grass swards, for which field analysis are difficult due to various climatic conditions. During the experiment, it turned out that 12 boxes are not necessary, and that the same experiment could have been conducted with 1-3 euro-boxes, since the residual concentration in the opened box after a measurement quickly returned to background air concentrations again after several minutes.

4.7.6 Limitations

A limitation of the study is that the physiochemical and microbiological analyses of the slurry were conducted without repetition. This limits the degree to which the unexpected and unresolved findings of higher residual N contents in the rock powder can be interpretated. Also, a more comprehensive macro- and micronutrient analysis of the rock powder amended slurry should be conducted, particularly to include silicon (Si) and heavy metals.

4.7.7 Implications

For real-farm settings, our results revealed a goal conflict of rock powder treatments, since the reduction of the floating crust and the improved flowability are major goals for farmers, whereby associated increases in NH_3 emissions are clearly an agronomic and environmental drawback. Furthermore, the considerable release of macro- and micronutrients from the rock powders could indirectly explain the claim that treatments improve plant yields and fodder quality, although the substantial Na release from 'Eifelgold' might lead to soil dependent ionic imbalances. Additionally, the significant release of CH_4 must be further tested, not only because it is a potent GHG gas, but also since, when substantiated by further trials, it would be an interesting catalyst for biogas production. The higher temperatures and thus higher microbiological activity in biogas reactors would likely promote additional macro- and micronutrient release from the rock powders, which could be a potential co-benefit.

4.7.8 Practical remarks

Discussions with farmers who treat their slurry revealed a pertinent point: If one would merely judge from the scientific literature, the impression arises that NH_3 and GHG emissions are the major problems of livestock management, which they are not. Many farmers are aware that stirring or reducing the floating crust of the slurry increases NH_3 emissions yet stirring and homogenizing the slurry is practically necessary and not a yes or no question, but one of degree. Accordingly, such conflicting outcomes also exist for practices that reduce NH_3 emissions like slurry injection into the soil, which can, compared to slurry surface application, increase N_2O emissions (Flessa and Beese, 2000), reduce yields (Misselbrook *et al.*, 1996), increase the survival rates of *E. coli* and enterococci (Hodgson *et al.*, 2016) and their leaching (Fangueiro *et al.*, 2014).

Overall effects of slurry treatments (often farmer individual mixtures of rock powders, effective microorganisms, charcoal etc.) are complex to comprehensively evaluate, since they have numerous effects that are difficult to measure, are often delayed in time, and multi-factorially confounded when field trials are concerned. It is apparent that many claimed benefits of SRP treatments can be related to merely a better handling of the slurry or to subjective perception. For some of the oftentimes anecdotal claims, contradictory evidence can be found in the literature. For example, the claim that a more balanced macro- and micronutrient supply from SRPs leads to increased legume proportions on pastures agrees with early findings by Chittenden *et al.* (1967), who found increased white clover (*Trifolium repens)* and *Lotus* major Scop. compositions after rock powder application, and with Dahlin *et al.* (2015) who report increased red clover (*Trifolium pratense*) growth. However, no significant effects on clover growth were found by Ramezanian *et al.* (2015), who used the same rock powder with the same particle size as Dahlin *et al.* (2015), likely due to differences in soil properties.

Another anecdotal claim is that SRPs improve the quality of the pasture and thus animal health. Assessing animal health in agriculture is complex since it is hard to measure, many mechanisms are interconnected (Vieweger and Döring, 2015), and mineral nutrient deficiency symptoms often just appear gradually over several years (Suttle, 2010). The claim of improved animal health after rock powder additions could stem from a more balanced supply of the basic cations Na, Ca, and Mg, as well as of micronutrients, for which forage deficiencies have been repeatedly reported (Dove *et al.*, 2016; Masters *et al.*, 2019; Brennan *et al.*, 2019), and a recent study showed that for 72 grassland sites Fe and Zn were among the most important predictors for aboveground biomass (Radujković *et al.*, 2021). A well-balanced nutrient supply is often impaired by fertilization regimes focusing on yield and NPK, since e.g. Mg fertilization does oftentimes not increase pasture yield, whereas it is essential to raise pasture Mg concentrations to adequate levels (Suttle, 2010; Chittenden *et al.*, 1967).

Importantly, our analysis confirmed the increasing evidence that slurry can be a carrier of pathogens (Scheinemann *et al.*, 2015; Blaiotta *et al.*, 2016; Kudva *et al.*, 1998; Martinez *et al.*, 2009). This is an emergent threat, and because there is limited evidence about environmentally feasible hygienisation methods, farmers experiment themselves with various slurry treatments which are rarely scientifically substantiated. Our results showed that rock powders had effects on the microbiology of the slurry, although the directionality (beneficial /detrimental) remains inconclusive.

4.8 Conclusion

We analyzed some of the major and hitherto unexamined claims regarding the mixture of rock powders with cattle slurry and found agronomically and environmentally conflicting results. NH_3 and

N_2O emissions did not differ significantly between the treatments up until the end of the trial, when rock powders led to a practically desired reduction of the floating crust that however coincided with increased NH_3 emissions and decreased N_2O emissions. We found that rock powders significantly increased previously neglected CH_4 emissions while CO_2 emissions were unaffected. Macro- and micronutrients were released from the rock powders into the slurry, which could substantially increase their efficiency as a soil amendment. Mixing globally abundant rock powders from the mining industry with organic materials could be a practical and low-cost multi-nutrient fertilizer, which bears particular potential for tropical countries with highly weathered soils, where commercial fertilizers are often not affordable and accessible. Overall, however, it remains a challenge to conclude whether rock powders should be mixed with slurry, because effects are diverse, and our experiment is to the best of our knowledge the first peer-reviewed study in this field. Necessarily, the next steps must be additional studies with various slurries to substantiate or challenge our findings, to inform discussions about slurry treatments, and to better understand the involved biogeochemical mechanisms.

In turn, if the significantly higher CH_4 emissions are confirmed, rock powder additions could be an additive for biogas production from livestock slurry (Amon *et al.*, 2007), with the potential co-benefit that elevated temperatures in the biogas reactor likely further stimulate rock weathering and thus nutrient release (Harley and Gilkes, 2000). Eventually, slurry management is at the core for overall farm health and must therefore not, regardless of its importance, be reduced to NH_3 emission abatement. Therefore, it is proposed that slurry treatments must be holistically evaluated in a transdisciplinary dialogue between science and farmers.

5 Synoptic conclusion and outlook

The aim of this thesis was to review the agricultural usage of silicate rock powders (SRPs) in the context of One Health. Although there is broad agreement about the inextricably linked health of soils, plants, animals, humans, and their environment, it is rarely made explicit that health is an ill-defined concept. There are numerous and conflicting philosophical approaches to health and there is currently no consensus about a clear definition or an operationalization scheme for any domain. Irrespective of growing efforts to holistically approach health, the scientific pursuit to do so continues to be challenging and contested, which is particularly the case for soil health. Even though there is increasing evidence about the various links between soil health and the other health domains, these links are oftentimes abstract and methodologically inconsistent. Therefore, various examples were provided of how soil health is connected to plant, animal, and human health via nutritional, toxicological, and microbial links.

However, the quantitative assessment of these links remains a major difficulty, which is also the case for the assessment of soil health itself. A common approach is to quantitatively assess soil health through various indicators, which are often further converted into soil health indices. Attempts to create such soil health indices are increasingly complex and appear to be impractical since they are often created without any reference to real-world agronomic limitations. In other words, the gap between what scientists want to measure and what is feasible at the farm level is growing. In practice, as for human health, money, time, and resource constraints do not permit the oftentimes aimed for "measure everything" approaches. The operationalization of soil health must therefore become more context-dependent and adapted to a joint problem prioritization with the farmer.

Despite these operational difficulties, the concept of soil health is capable to forward a better understanding of the multifunctionality of soils and provides an umbrella term under which necessary inter- and transdisciplinary discourses can take place. Generally, for any soil health operation, one of the most important aspects is a definition of the objective from the very beginning, i.e. is the objective (1) a management recommendation for the land manager, (2) a tool for communication and education, or (3) a monitoring program.

It is likely that the trend of exponentially increasing soil health publications and the ubiquity of soil health within agronomic conferences, political agendas, and public debates will continue, and the concept might develop in a similar fashion as an even more ubiquitous concept: sustainability. While the equally vague-defined concept of sustainability has arguably been capable to globally render the importance of operating in alignment with the capacity of the earth´s biophysical system, it similarly has become a positively connotated catch-phrase for almost any domain and tempts authors "to hide behind the non-literal language" (Ross *et al.*, 1997). With sustainability, One Health, or soil health, it thus appears essential to become more specific and ask more critically: what do we actually want to achieve with these terms, what specific challenges do we want to tackle?

For soils, one omnipresent challenge is to increase yields while maintaining and improving the soils biophysicochemical properties in economically and environmentally feasible ways. One potential way to tackle this challenge it the longstanding yet contradictory practice of amending soils with multi-nutrient silicate rock powders (SRPs). It was thus reviewed how and under which circumstances SRPs can improve soil health. The contradictions of prior studies were confirmed, and the inherent inconsistency of trials limits the degree to which they can be interpreted. However, new findings nonetheless challenge the notion that SRPs are at best slow-release soil amendments. Several studies have shown that SRPs can not only provide macro- and micronutrients on agronomically relevant timescales, but can also improve various soil biophysicochemical properties essential for soil health, especially for highly weathered tropical soils. For these soils, pedogenic theory as well as increasing empirical evidence outlines significant agronomic potential for mafic and ultramafic SRPs, which gains additional importance regarding the economic and infrastructural barriers to fertilizers in many tropical regions.

SRPs potential as an affordable, locally available, and – given a prior geochemical screening - environmentally benign K and micronutrient fertilizers must hereby be stressed. Regarding One Health, widespread soil micronutrient deficiencies are a threat for which there is currently no soil amendment on the agronomic horizon that appears to be capable of tackling this challenge. The need to further explore rock powder modifications must also be emphasized, since physical, chemical, or biological modifications showed great potential to overcome the major obstacle of SRPs low dissolution rates. The economic and environmental feasibility of SRPs is questionable if the distance between production- and application site is too long, and if the rocks are not obtained as a waste product but mined and crushed with the sole intent of application.

Future SRP research faces the challenge that the mechanisms and biophysicochemical properties that need to be understood are more complex than those properties and mechanisms typically analyzed in agronomic trials with soluble fertilizers. Regarding SRPs, this includes assessments aiming to capture the full scope of potential soil and plant health benefits, CO_2 sequestration, or the environmental and economic benefits of re-using rock waste. The individual measurements of each of these aspects is already laborious and costly, whilst efforts to comprehensively evaluate SRPs context-dependent agronomic efficiency and/or LCAs would quickly reach tremendous complexities, and it thus remains questionable if such assessments will be possible in the near future. Therefore, one determining aspect will be to gather, synthesize, and harness the dispersed information of farmers who already use SRPs and further promote participatory research. Although such research is not always appreciated in the scientific world (Döring, 2018), it is crucial since it for example reveals the practical unfeasibility of high SRP application amounts used in many scientific experiments. Nevertheless, despite the labor and cost requirements, rigorous long-term experiments that include a set of minimum geochemical indicators will be crucial for advancing the usage of SRPs. Likewise, more research is needed that analyzes the oftentimes anecdotal claims from rock powder providers and farmers regarding the effects of various SRP practices.

One such practice is the longstanding yet scientifically unexamined mixture of SRPs with cattle slurry. It is claimed that SRP reduce the slurry´s crust and NH_3 emissions, and improve the biophysicochemical properties of the slurry. These claims were analyzed, together with a concomitant measurement of previously not considered CO_2, N_2O and CH_4 emissions. The major claim that SRPs reduce NH_3 emissions had to be refuted since non-significant differences were found for the daily emission rates as well as for the cumulative emissions over the course of 46 days. However, at the end of the trial, the rock powders led to a practically desired reduction of the floating crust that coincided with increased NH_3 emissions and decreased N_2O emissions, although N_2O emissions were still very low for all treatments. Previously neglected significant increases in CH_4 emissions were found, whereas no significant differences were found for CO_2 emissions. Importantly, macro- and micronutrients were released from the rock powders and their nutrient release rate agreed with the mineralogy of the respective SRP. Higher total NH_4^+ contents in the rock powder slurries could be explained by a microbial stimulation and thus higher organic matter mineralization rates. For unknown reasons, total N was also higher in the SRP slurries at the end of the trial, despite the higher NH_3 emissions. One explanation could have been the inaccuracy of the slurry analysis, for which one limitation was that it was conducted without replicates. Furthermore, SRPs stimulated the microbiology in the slurry, although the directionality (beneficial /detrimental) of the microbiological changes remains inconclusive.

The altered standard chamber measurement design which was used to analyze the emissions from the slurry provided reliable relative emission rates, although additional emission experiments are suggested with a larger slurry surface to box-headspace ratio. Additional experiments are particularly needed to (1) verify the effects on emissions, especially for CH_4, and to (2) better understand and quantify the biophysicochemical changes in the slurry and the weathering rates of the rock powders. Furthermore, agronomic trials are needed that assess the effects of SRP amended slurry on crop growth and nutrient content, and if its effects differ from the mere sum of applying SRPs and slurry alone to the soil. This should facilitate recommendations as to whether, or under which circumstances, SRP should be used as a slurry additive, since the current findings constitute an agronomic-environmental goal conflict.

Overall, we are far from a comprehensive mechanistic understanding of SRPs. Nevertheless, this thesis contributed new insights regarding the complex mechanisms underlying the efficiency of SRPs, and thereby helps to guide future research in this interdisciplinary and rapidly expanding area of research. As indicated above, the long-term trials and participatory research needed to advance our understanding about SRPs will require considerable investments in terms of time, money, and labor. However, such efforts are argued to be justified, since SRPs can positively impact some fields of major importance: soil health, plant biotic and abiotic stress resistance, climate change mitigation, and waste recycling. Furthermore, a rapid deployment of SRPs at large scale appears to be feasible within the coming decades, since the logistical infrastructure for application already exists in many places, owing to the common practice of agricultural liming. Considering the inertia of conventional large-scale fertilizer markets, a new paradigm of *multilocal* rather than *global* fertilizer markets could be envisioned. Herein, SRPs and especially their combination with locally available organic materials could play a significant role as a new kind of organo-mineral fertilizer that could contribute to a healthier and more sustainable agriculture.

References

Aarnio, T., Räty, M. and Martikainen, P.J. (2003), "Long-term availability of nutrients in forest soil derived from fast- and slow-release fertilizers", *Plant and Soil*, Vol. 252, pp. 227–239.

Abbott, L.K. and Manning, D.A.C. (2015), "Soil Health and Related Ecosystem Services in Organic Agriculture", *Sustainable Agriculture Research*, Vol. 4 No. 3, p. 116.

Abdel–Mouty, M.M. and El-Greadly, N.H.M. (2008), "The Productivity of Two Okra Cultivars as Affected by Gibberellic Acid, Organic N, Rock Phosphate and Feldspar Application", *Journal of Applied Sciences Research*, No. 4(6), pp. 627–636.

Abou-El-Seoud, I.I. and Abdel-Megeed, A. (2012), "Impact of rock materials and biofertilizations on P and K availability for maize (Zea Maize) under calcareous soil conditions", *Saudi journal of biological sciences*, Vol. 19 No. 1, pp. 55–63.

Abrahams, P.W. (2002), "Soils: their implications to human health", *The Science of the total environment*, Vol. 291 No. 1-3, pp. 1–32.

Abrahams, P.W. (2003), "Human Geophagy: A Review of Its Distribution, Causes, and Implications", in Abrahams, P.W. (Ed.), *Geology and Health*, Oxford University Press.

Adams, R.S. and Stevenson, F.J. (1964), "Ammonium Sorption and Release from Rocks and Minerals1", *Soil Science Society of America Journal*, Vol. 28 No. 3, p. 345.

Adhikari, K. and Hartemink, A.E. (2016), "Linking soils to ecosystem services — A global review", *Geoderma*, Vol. 262, pp. 101–111.

Adimalla, N. (2020), "Heavy metals pollution assessment and its associated human health risk evaluation of urban soils from Indian cities: a review", *Environmental geochemistry and health*, Vol. 42 No. 1, pp. 173–190.

Ahmed, T., Hossain, M. and Sanin, K.I. (2012), "Global burden of maternal and child undernutrition and micronutrient deficiencies", *Annals of nutrition & metabolism*, 61 Suppl 1, pp. 8–17.

Aktar, M.W., Sengupta, D. and Chowdhury, A. (2009), "Impact of pesticides use in agriculture: their benefits and hazards", Interdisc Toxicol; Vol. 2(1): 1–12.

Akter, M. and Akagi, T. (2005), "Effect of Fine Root Contact on Plant-Induced Weathering of Basalt", *Soil Science and Plant Nutrition*, Vol. 51 No. 6, pp. 861–871.

Albert, R. (1938), "Untersuchungen über die Verwendbarkeit von Gesteinsabfällen verschiedener Herkunft und Art zur Verbesserung geringwertiger Waldböden.", *Forstarchiv*, Vol. 14, pp. 237–240.

Ali, A.H. and Taalab, A.S. (2008), "Effect of Natural And/or Chemical Potassium Fertilizers on Growth, Bulbs Yield and Some Physical and Chemical Constituents of Onion (Allium cepa, L.)", *Research Journal of Agriculture and Biological Sciences*, No. 4(3): 228-237.

Alloway, B.J. (2008), *Micronutrient deficiencies in global crop production*, Springer, Dordrecht.

Alonso-Andicoberry, C., García-Peña, F., Pereira-Bueno, J., Costas, E. and Ortega-Mora, L. (2001), "Herd-level risk factors associated with Leptospira spp. seroprevalence in dairy and beef cattle in Spain", *Preventive veterinary medicine*, Vol. 52 No. 2, pp. 109–117.

Amann, T., Hartmann, J., Struyf, E., Oliveira Garcia, W. de, Fischer, E.K., Janssens, I., Meire, P. and Schoelynck, J. (2020), "Enhanced Weathering and related element fluxes – a cropland mesocosm approach", *Biogeosciences*, Vol. 17 No. 1, pp. 103–119.

Amon, B., Kryvoruchko, V., Amon, T. and Zechmeister-Boltenstern, S. (2006), "Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment", *Agriculture, Ecosystems & Environment*, Vol. 112 No. 2-3, pp. 153–162.

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K. and Gruber, L. (2007), “Biogas production from maize and dairy cattle manure—Influence of biomass composition on the methane yield”, *Agriculture, Ecosystems & Environment*, Vol. 118 No. 1-4, pp. 173–182.

Amsili, J.P., van Es, H.M. and Schindelbeck, R.R. (2021), “Cropping system and soil texture shape soil health outcomes and scoring functions”, *Soil Security*, Vol. 4, p. 100012.

Anda, M., Shamshuddin, J. and Fauziah, C.I. (2013), “Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions”, *Soil and Tillage Research*, Vol. 132, pp. 1–11.

Atlas, R.M. and Maloy, S.R. (2014), *One health: People, animals, and the environment / edited by Ronald M. Atlas, University of Louisville, Louisville, KY, and Stanley Maloy, San Diego State University, San Diego, CA*, ASM Press, Washington, DC.

Atungwu, J.J., Oladeji, O.A., Aiyelaagbe, I. and Olabiyi, T.I. (2014), “Influence of rock dust-based soil re-mineralisation on root-knot disease of organic watermelon plants”, *Archives Of Phytopathology And Plant Protection*, Vol. 47 No. 12, pp. 1489–1496.

Azeh Engwa, G., Udoka Ferdinand, P., Nweke Nwalo, F. and N. Unachukwu, M. (2019), “Mechanism and Health Effects of Heavy Metal Toxicity in Humans”, in Karcioglu, O. and Arslan, B. (Eds.), *Poisoning in the Modern World - New Tricks for an Old Dog?*, IntechOpen.

Badr, M.A. (2006), “Efficiency of K-feldspar Combined with Organic Materials and Silicate Dissolving Bacteria on Tomato Yield”, *Journal of Applied Sciences Research*, Vol. 12, pp. 1191–1198.

Bai, Z., Zhang, H., Li, N., Bai, Z., Zhang, L., Xue, Z., Jiang, H., Song, Y. and Zhou, D. (2016), “Impact of Environmental Microbes on the Composition of the Gut Microbiota of Adult BALB/c Mice”, *PloS one*, Vol. 11 No. 8, e0160568.

Bakken, A.K., Gautneb, H. and Myhr, K. (1997), “The potential of crushed rocks and mine tailings as slow-releasing K fertilizers assessed by intensive cropping with Italian ryegrass in different soil types”, *Nutrient Cycling in Agroecosystems*, No. 47, pp. 41–48.

Bakken, A.K., Gautneb H., Sveistrup, T. and Myhr, K. (2000), “Crushed rocks and mine tailings applied as K fertilizers on grassland”, *Nutrient Cycling in Agroecosystems*, No. 56, pp. 53–57.

Balfour, E.B. (1943), *The living soil: Evidence of the importance to human health of soil vitality, with special reference to national planning*, 8. ed., Faber and Faber, London.

Baligar, V.C. and Bennett, O.L. (1986), “Outlook on fertilizer use efficiency in the tropics”, *Nutrient Cycling in Agroecosystems*, Vol. 10 No. 1, pp. 83–96.

Bamberg, L.A., Silveira, C., Martins, E.d.S., Bergmann, M., Martinazzo, R. and Theodoro, S.H. (Eds.) (2017), *Anasi 3 Congresso Brasileiro de Rochagem*.

Barak, P., Chen, Y. and Singer, A. (1983), “Ground basalt and tuff as iron fertilizers for calcareous soils”, *Plant and Soil*, No. 73, pp. 155–158.

Basak, B.B. and Biswas, D.R. (2009), “Influence of potassium solubilizing microorganism (Bacillus mucilaginosus) and waste mica on potassium uptake dynamics by sudan grass (Sorghum vulgare Pers.) grown under two Alfisols”, *Plant and Soil*, Vol. 317 No. 1-2, pp. 235–255.

Basak, B.B., Sarkar, B., Biswas, D.R., Sarkar, S., Sanderson, P. and Naidu, R. (2017), “Bio-Intervention of Naturally Occurring Silicate Minerals for Alternative Source of Potassium”, in *Advances in Agronomy*, Vol. 141, Elsevier, pp. 115–145.

Basak, B.B., Sarkar, B. and Naidu, R. (2020), “Environmentally safe release of plant available potassium and micronutrients from organically amended rock mineral powder”, *Environmental geochemistry and health*.

Basak, B.B., Sarkar, B., Sanderson, P. and Naidu, R. (2018), “Waste mineral powder supplies plant available potassium: Evaluation of chemical and biological interventions”, *Journal of Geochemical Exploration*, Vol. 186, pp. 114–120.
Baveye, P.C. (2021a), “Bypass and hyperbole in soil research: Worrisome practices critically reviewed through examples”, *European Journal of Soil Science*, Vol. 72 No. 1, pp. 1–20.
Baveye, P.C. (2021b), “Soil health at a crossroad”, *Soil Use and Management*.
Baveye, P.C., Baveye, J. and Gowdy, J. (2016), “Soil “Ecosystem” Services and Natural Capital: Critical Appraisal of Research on Uncertain Ground”, *Frontiers in Environmental Science*, Vol. 4 No. 10, p. 609.
Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., Mercure, J.-F., Pollitt, H., Holden, P.B., Edwards, N.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I.A., Hansen, J. and Banwart, S.A. (2020), “Potential for large-scale CO2 removal via enhanced rock weathering with croplands”, *Nature*, Vol. 583 No. 7815, pp. 242–248.
Beerling, D.J., Leake, J.R., Long, S.P., Scholes, J.D., Ton, J., Nelson, P.N., Bird, M., Kantzas, E., Taylor, L.L., Sarkar, B., Kelland, M., DeLucia, E., Kantola, I., Müller, C., Rau, G. and Hansen, J. (2018), “Farming with crops and rocks to address global climate, food and soil security”, *Nature plants*, Vol. 4 No. 3, pp. 138–147.
Bennett, P.C., Rogers, J.R. and Choi, W.J. (2001), “Silicates, Silicate Weathering, and Microbial Ecology”, *Geomicrobiology Journal*, Vol. 18 No. 1, pp. 3–19.
Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M.-C.C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Corral, G.H., Kazou, M., Kinkel, L., Lange, L., Lima, N., Loy, A., Macklin, J.A., Maguin, E., Mauchline, T., McClure, R., Mitter, B., Ryan, M., Sarand, I., Smidt, H., Schelkle, B., Roume, H., Kiran, G.S., Selvin, J., Souza, R.S.C. de, van Overbeek, L., Singh, B.K., Wagner, M., Walsh, A., Sessitsch, A. and Schloter, M. (2020), “Microbiome definition re-visited: old concepts and new challenges”, *Microbiome*, Vol. 8 No. 1, p. 103.
Berg, W., Brunsch, R. and Pazsiczki, I. (2006), “Greenhouse gas emissions from covered slurry compared with uncovered during storage”, *Agriculture, Ecosystems & Environment*, Vol. 112 No. 2-3, pp. 129–134.
Beriot, N., Peek, J., Zornoza, R., Geissen, V. and Huerta Lwanga, E. (2021), “Low density-microplastics detected in sheep faeces and soil: A case study from the intensive vegetable farming in Southeast Spain”, *The Science of the total environment*, Vol. 755 No. Pt 1, p. 142653.
Berner, R.A. (2004), *The phanerozoic carbon cycle: CO2 and O2*, Oxford University Press, Oxford.
Berry, W. (1977), *The Unsettling of America: Culture & Agriculture.*, Sierra Club Books. 228 p.
Bian, Z., Miao, X., Lei, S., Chen, S., Wang, W. and Struthers, S. (2012), “The challenges of reusing mining and mineral-processing wastes”, *Science (New York, N.Y.)*, Vol. 337 No. 6095, pp. 702–703.
Bischoff, K., Thompson, B., Erb, H.N., Higgins, W.P., Ebel, J.G. and Hillebrandt, J.R. (2012), “Declines in blood lead concentrations in clinically affected and unaffected cattle accidentally exposed to lead”, *Journal of veterinary diagnostic investigation official publication of the American Association of Veterinary Laboratory Diagnosticians, Inc*, Vol. 24 No. 1, pp. 182–187.
Blaiotta, G., Di Cerbo, A., Murru, N., Coppola, R. and Aponte, M. (2016), “Persistence of bacterial indicators and zoonotic pathogens in contaminated cattle wastes”, *BMC microbiology*, Vol. 16, p. 87.
Blanc-Betes, E., Kantola, I.B., Gomez-Casanovas, N., Hartman, M.D., Parton, W.J., Lewis, A.L., Beerling, D.J. and DeLucia, E.H. (2021), “In silico assessment of the potential of basalt

amendments to reduce N 2 O emissions from bioenergy crops", *GCB Bioenergy*, Vol. 13 No. 1, pp. 224–241.

Blum, W.E.H. (1988), "Problems of soil conservation Council of Europe," *in Nature and Environment Series. Steering Committee for the Conservation and Management of the Environment and Natural Habitats (CDPE).*, Vol. 39.

Blum, W.E.H. (2005), "Functions of Soil for Society and the Environment", *Reviews in Environmental Science and Bio/Technology*, Vol. 4 No. 3, pp. 75–79.

Blum, W.E.H., Schad, P. and Nortcliff, S. (2018), *Essentials of soil science: Soil formation, functions, use and classification (World reference Base, WRB)*, Borntraeger Science Publishers, Stuttgart.

Blum, W.E.H., Zechmeister-Boltenstern, S. and Keiblinger, K.M. (2019), "Does Soil Contribute to the Human Gut Microbiome?", *Microorganisms*, Vol. 7 No. 9.

Blume, H.-P. (2000-), *Handbuch der Bodenuntersuchung*, Wiley; Berlin Beuth, Weinheim, Chichester.

BMJV (1998), *Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten (Bundes-Bodenschutzgesetz - BBodSchG)*.

Boggs, S., JR. (2009), *Petrology of Sedimentary Rocks*, Cambridge University Press, Cambridge.

Bolland, M. and Baker, M.J. (2000), "Powdered granite is not an effective fertilizer for clover and wheat in sandy soils fromWestern Australia", *Nutrient Cycling in Agroecosystems*, Vol. 56, pp. 59–68.

Bonanomi, G., Cesarano, G., Antignani, V., Di Maio, C., Filippis, F. de and Scala, F. (2018), "Conventional farming impairs Rhizoctonia solani disease suppression by disrupting soil food web", *Journal of Phytopathology*, Vol. 166 No. 9, pp. 663–673.

Bonfante, A., Terribile, F. and Bouma, J. (2019), "Refining physical aspects of soil quality and soil health when exploring the effects of soil degradation and climate change on biomass production: an Italian case study", *SOIL*, Vol. 5 No. 1, pp. 1–14.

Borken, W. and Brumme, R. (1997), "Liming practice in temperate forest ecosystems and the effects on CO 2 N 2 O and CH 4 fluxes", *Soil Use and Management*, Vol. 13 No. s4, pp. 251–257.

Bormann, B.T., Wang, D., Snyder, M.C., Bormann, F.H., Benoit, G. and April, R. (1998), "Rapid, plant-induced weathering in an aggrading experimental ecosystem", *Biogeochemistry*, Vol. 43 No. 2, pp. 129–155.

Bouma, J. (2021), "Soil challenges beyond publication issues", *European Journal of Soil Science*, Vol. 72 No. 1, pp. 29–30.

Bouwman, A.F., Beusen, A.H.W., Lassaletta, L., van Apeldoorn, D.F., van Grinsven, H.J.M., Zhang, J. and Ittersum van, M.K. (2017), "Lessons from temporal and spatial patterns in global use of N and P fertilizer on cropland", *Scientific reports*, Vol. 7, p. 40366.

Brennan, R.F., Penrose, B. and Bell, R.W. (2019), "Micronutrients limiting pasture production in Australia", *Crop and Pasture Science*, Vol. 70 No. 12, p. 1053.

Brevik, E.C. and Burgess, L.C. (2015), "Soil: Influence on Human Health", *Encyclopedia of Environmental Management*.

Brevik, E.C., Cerdà, A., Steffan, Joshua, J. and Burgess, L.C. (2017), "Links Between Soil Security and the Influence of Soil on Human Health", *Global Soil Security.*, Progress in Soil Science, pp. 261–274.

Brevik, E.C. and Sauer, T.J. (2015), "The past, present, and future of soils and human health studies", *SOIL*, Vol. 1 No. 1, pp. 35–46.

Brevik, E.C., Slaughter, L., Singh, B.R., Steffan, J.J., Collier, D., Barnhart, P. and Pereira, P. (2020), "Soil and Human Health: Current Status and Future Needs", *Air, Soil and Water Research*, Vol. 13, 117862212093444.

Brevik, E.C., Steffan, J.J., Rodrigo-Comino, J., Neubert, D., Burgess, L.C. and Cerdà, A. (2019), "Connecting the public with soil to improve human health", *European Journal of Soil Science*, Vol. 70 No. 4, pp. 898–910.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X. and Huard, F. (2010), "Why are wheat yields stagnating in Europe? A comprehensive data analysis for France", *Field Crops Research*, Vol. 119 No. 1, pp. 201–212.

Brown, T.L. (2003), *Making truth: Metaphor in science*, University of Illinois Press, Urbana.

Brümmer, G. (1978), "Funktionen des Bodens im Stoffhaushalt der Ökosphäre. Deutscher Rat für Landes pflege: Zum ökologischen Landbau, 31,13–20.".

Bryan, N.S. and van Grinsven, H. (2013), "The Role of Nitrate in Human Health", in *Advances in Agronomy*, Vol. 119, Elsevier, pp. 153–182.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., Deyn, G. de, Goede, R. de, Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W. and Brussaard, L. (2018), "Soil quality – A critical review", *Soil Biology and Biochemistry*, Vol. 120, pp. 105–125.

Burghelea, C.I., Dontsova, K., Zaharescu, D.G., Maier, R.M., Huxman, T., Amistadi, M.K., Hunt, E. and Chorover, J. (2018), "Trace element mobilization during incipient bioweathering of four rock types", *Geochimica et Cosmochimica Acta*, Vol. 234, pp. 98–114.

Cakmak, I. (2002), "Plant nutrition research: Priorities to meet human needs for food in sustainable ways", *Plant and Soil*, Vol. 247, pp. 3–24.

Calow, P. (1995), "Ecosystem health - a critical analysis of concepts. NATO ASI Series J. Global' Environmental Change. In "Evaluating and Monitoring Health of Large Scale Ecosystems", D. J. Rapport, C. L. Daudet and P. Calow, Eds,), Vol. 28, pp. 33-41, Springer, Berlin.".

Campbell, N.S. (2009), "The Use of Rockdust and Composted Materials as Soil Fertility Amendments", PhD Thesis, University of Glasgow, 2009.

Carson, J.K., Campbell, L., Rooney, D., Clipson, N. and Gleeson, D.B. (2009), "Minerals in soil select distinct bacterial communities in their microhabitats", *FEMS microbiology ecology*, Vol. 67 No. 3, pp. 381–388.

Carson, J.K., Rooney, D., Gleeson, D.B. and Clipson, N. (2007), "Altering the mineral composition of soil causes a shift in microbial community structure", *FEMS microbiology ecology*, Vol. 61 No. 3, pp. 414–423.

Castranova, V. (2000), "From Coal Mine Dust To Quartz: Mechanisms of Pulmonary Pathogenicity", *Inhalation toxicology*, 12 Suppl 3, pp. 7–14.

Castro, D. and Sharma, S. (2021), *StatPearls: Hypokalemia*, Treasure Island (FL).

Cerling, T.E. (1984), "The stable isotopic composition of modern soil carbonate and its relationship to climate", *Earth and Planetary Science Letters*, Vol. 71 No. 2, pp. 229–240.

Chebotarev, I. (1955a), "Metamorphism of natural waters in the crust of weathering—1", *Geochimica et Cosmochimica Acta*, Vol. 8 No. 1-2, pp. 22–48.

Chebotarev, I. (1955b), "Metamorphism of natural waters in the crust of weathering—2", *Geochimica et Cosmochimica Acta*, Vol. 8 No. 3, pp. 137–170.

Chen, S., Xiang, H., Zhu, X., Zhang, H., Wang, D., Liu, H., Wang, J., Yin, T., Liu, L., Kong, M., Zhang, J., Ogura, S.-I. and Zhao, X. (2018), "Free Dietary Choice and Free-Range Rearing Improve the Product Quality, Gait Score, and Microbial Richness of Chickens", *Animals an open access journal from MDPI*, Vol. 8 No. 6.

Chen, X., Yang, G., Chen, J., Wen, Z. and Ge, K. (1980), "Studies on the relations of selenium and Keshan disease", *Biological trace element research*, Vol. 2 No. 2, pp. 91–107.

Cherrier, V., Grebot, B., Kirhensteine, I., Brutus, J., Taylor, K., Berman, S. and Sarteel, M. (Eds.) (2014), *European Commission (DG Environment), Collection and analysis of Data for the Control of Emissions from spreading manure: AMEC Environment, BIO Intellegence Service*.

Chesworth, W., Magias-Vasquez, F., Acquaye, D. and Thomson, E. (1983), “Agricultural alchemy: stones into bread”, *Episodes*, Vol. 1, pp. 3–7.

Chittenden, E.T., Stanton, D.J., Watson, J. and Dodson, K.J. (1967), “Serpentine and dunite as magnesium fertiliser”, *New Zealand Journal of Agricultural Research*, Vol. 10 No. 1, pp. 160–171.

Christensen, M.L. and Sommer, S.G. (2013), “Manure Characterisation and Inorganic Chemistry”, No. In Animal Manure: Recycling, Treatment, and Management; Jensen, L.S., Christensen, M.L., Sommer, S.G., Schmidt, T., Eds; John Wiley & Sons Inc.: Chichester,West Sussex, UK, 2013; pp. 41–65. ISBN 9781118676677.

Ciceri, D. and Allanore, A. (2015), “Microfluidic Leaching of Soil Minerals: Release of K+ from K Feldspar”, *PloS one*, Vol. 10 No. 10, e0139979.

Ciceri, D. and Allanore, A. (2019), “Local fertilizers to achieve food self-sufficiency in Africa”, *The Science of the total environment*, Vol. 648, pp. 669–680.

Ciceri, D., Close, T.C., Barker, A.V. and Allanore, A. (2019), “Fertilizing properties of potassium feldspar altered hydrothermally”, *Communications in Soil Science and Plant Analysis*, Vol. 5 No. 4, pp. 1–10.

Ciceri, D., Manning, D.A.C. and Allanore, A. (2015), “Historical and technical developments of potassium resources”, *The Science of the total environment*, Vol. 502, pp. 590–601.

Ciceri, D., Oliveira, M. de and Allanore, A. (2017), “Potassium fertilizer via hydrothermal alteration of K-feldspar ore”, *Green Chem*, Vol. 19 No. 21, pp. 5187–5202.

Clemens, J., Bergmann, S. and Vandré, R. (2002), “Reduced ammonia emissions from slurry after self-acidification with organic supplements”, *Environmental technology*, Vol. 23 No. 4, pp. 429–435.

Cook, R.J. (2000), “Advances in Plant Health Management in the Twentieth Century”, *Annual review of phytopathology*, Vol. 38, pp. 95–116.

Cook, R.J. (2007), “Take-all decline: model system in the science of biological control and clue to the success of intensive cropping”, in Vincent, C., Goettel, M.S. and Lazarovits, G. (Eds.), *Biological control: a global perspective*, CABI, Wallingford, pp. 399–414.

Cook, R.J. (2014), “Plant Health Management: Pathogen Suppressive Soils”, in *Encyclopedia of Agriculture and Food Systems*, Elsevier, pp. 441–455.

Corah, L.R. and Dargatz, D. (1996), “Forage Analyses from Cow/Calf Herds in 18 States”.

Coroneos, C., Hinsinger, P. and Gilkes, R.J. (1996), “Granite powder as a source of potassium for plants: a glasshouse bioassay comparing two pasture species”, *Fertilizer Research*, Vol. 45, pp. 143–152.

Crèvecoeur, J. de (1904), *Letters from an American farmer (reprinted from the original edition), New York, NY, USA, Fox and Duffield,*, New York, Fox, Duffield & Company.

Crusciol, C.A.C., Moretti, L.G., Bossolani, J.W., Moreira, A., Micheri, P.H. and Rossi, R. (2019), “Can Dunite Promote Physiological Changes, Magnesium Nutrition and Increased Corn Grain Yield?”, *Communications in Soil Science and Plant Analysis*, Vol. 50 No. 18, pp. 2343–2353.

Cycoń, M., Mrozik, A. and Piotrowska-Seget, Z. (2019), “Antibiotics in the Soil Environment-Degradation and Their Impact on Microbial Activity and Diversity”, *Frontiers in microbiology*, Vol. 10, p. 338.

Dahlin, A.S., Ramezanian, A., Campbell, C.D., Hillier, S. and Öborn, I. (2015), "Waste recovered by-products can increase growth of grass-clover mixtures in low fertility soils and alter botanical and mineral nutrient composition", *Annals of Applied Biology*, Vol. 166 No. 1, pp. 105–117.

Dalmora, A.C., Ramos, C.G., Silva Oliveira, M.L., Silva Oliveira, L.F., Homrich Schneider, I.A. and Kautzmann, R.M. (2020), "Application of andesite rock as a clean source of fertilizer for eucalyptus crop: Evidence of sustainability", *Journal of Cleaner Production*, Vol. 256 No. 9/10, p. 120432.

Daniel, R. (2005), "The metagenomics of soil", *Nature reviews. Microbiology*, Vol. 3 No. 6, pp. 470–478.

Darwin, C. (1881), *The Formation of Vegetable Mould through the Action of Worms*, John Murray.

Deer, W.A., Howie, R.A. and Zussman, J. (2013), *An introduction to the rock-forming minerals*, 3. edition, The Minerological Society, London.

DeLucia, E.H., Kantola, I.B., Blanc-Betes, E., Masters, M.D., Val Martin, M., Bernacchi, C., Beerling, D.J. and Long, S.P. (2019), *Basalt application for carbon sequestration reduces nitrous oxide fluxes from croplands: Geophys. Res. Abstr. 21, EGU2019-EGU4500*.

Destoumieux-Garzón, D., Mavingui, P., Boetsch, G., Boissier, J., Darriet, F., Duboz, P., Fritsch, C., Giraudoux, P., Le Roux, F., Morand, S., Paillard, C., Pontier, D., Sueur, C. and Voituron, Y. (2018), "The One Health Concept: 10 Years Old and a Long Road Ahead", *Frontiers in veterinary science*, Vol. 5, p. 14.

Dias, K.G.d.L., Guimarães, P.T.G., do Carmo, D.L., Reis, T.H.P. and Lacerda, J.J.d.J. (2018), "Alternative sources of potassium in coffee plants for better soil fertility, productivity, and beverage quality", *Pesquisa Agropecuária Brasileira*, Vol. 53 No. 12, pp. 1355–1362.

Dick, R. (2018), "Soil Health: The Theory of Everything (Terrestrial) or Just Another Buzzword?", *CSA News*, Vol. 63 No. 11, pp. 12–17.

Dietzen, C., Harrison, R. and Michelsen-Correa, S. (2018), "Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment", *International Journal of Greenhouse Gas Control*, Vol. 74, pp. 251–258.

Dinuccio, E., Berg, W. and Balsari, P. (2008), "Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation", *Atmospheric Environment*, Vol. 42 No. 10, pp. 2448–2459.

Djordjevic, S.P., Stokes, H.W. and Roy Chowdhury, P. (2013), "Mobile elements, zoonotic pathogens and commensal bacteria: conduits for the delivery of resistance genes into humans, production animals and soil microbiota", *Frontiers in microbiology*, Vol. 4, p. 86.

Doran, J.W. and Jones, A.J. (1997), *Methods for Assessing Soil Quality*, Soil Science Society of America, Madison, WI, USA.

Doran, J.W., Sarrantonio, M. and Liebig, M.A. (1996), "Soil Health and Sustainability", *Advances in Agronomy*, Vol. 56, pp. 1–54.

Doran, J.W. and Werner, M.R. (1990), "Management and soil biology. In: Sustainable Agriculture in Temperate Zones, ed. C.A. Francis et al. 1990.", pp. 205–230.

Doran, J.W. and Zeiss, M.R. (2000), "Soil health and sustainability. Managing the biotic component of soil quality", *Applied Soil Ecology*, Vol. 15 No. 1, pp. 3–11.

Dordas, C. (2008), "Role of nutrients in controlling plant diseases in sustainable agriculture. A review", *Agronomy for Sustainable Development*, Vol. 28 No. 1, pp. 33–46.

Döring, T.F. (2018), "Research into Practice—Promoting Participation, Perseverance and Publications", *Organic Farming*, Vol. 4 No. 1.

Döring, T.F. (2019), "Unbiased but Not Neutral", *Organic Farming*, Vol. 5 No. 1.

Döring, T.F., Pautasso, M., Finckh, M.R. and Wolfe, M.S. (2012), “Concepts of plant health - reviewing and challenging the foundations of plant protection”, *Plant Pathology*, Vol. 61 No. 1, pp. 1–15.

Döring, T.F., Vieweger, A., Pautasso, M., Vaarst, M., Finckh, M.R. and Wolfe, M.S. (2015), “Resilience as a universal criterion of health”, *Journal of the science of food and agriculture*, Vol. 95 No. 3, pp. 455–465.

Dove, H., Masters, D.G. and Thompson, A.N. (2016), “New perspectives on the mineral nutrition of livestock grazing cereal and canola crops”, *Animal Production Science*, Vol. 56 No. 8, p. 1350.

Driciru, M., Rwego, I.B., Ndimuligo, S.A., Travis, D.A., Mwakapeje, E.R., Craft, M., Asiimwe, B., Alvarez, J., Ayebare, S. and Pelican, K. (2020), “Environmental determinants influencing anthrax distribution in Queen Elizabeth Protected Area, Western Uganda”, *PloS one*, Vol. 15 No. 8, e0237223.

Driehuis, F., Wilkinson, J.M., Jiang, Y., Ogunade, I. and Adesogan, A.T. (2018), “Silage review: Animal and human health risks from silage”, *Journal of Dairy Science*, Vol. 101 No. 5, pp. 4093–4110.

Duncan, E.W., Dell, C.J., Kleinman, P.J.A. and Beegle, D.B. (2017), “Nitrous Oxide and Ammonia Emissions from Injected and Broadcast-Applied Dairy Slurry”, *Journal of environmental quality*, Vol. 46 No. 1, pp. 36–44.

Durso, L.M. and Cook, K.L. (2019), “One Health and Antibiotic Resistance in Agroecosystems”, *EcoHealth*, Vol. 16 No. 3, pp. 414–419.

EC (2006), “European Commision (EC): Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Thematic Strategy for Soil Protection, COM 231 Final, Brussels”.

EC (2019a), “Climate Action European Environment Agency. Annual European Union greenhouse gas in-ventory 1990–2017 and inventory report 2019. In Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.”.

EC (2019b), *European Union emission inventory report 1990-2018 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), EEA report*, no 2019,08, Publications Office of the European Union, Luxembourg.

Ehrenfeld, D.W. (1988), “Why put a value on biodiversity?”, in Wilson, E.O. and Peter, F.M. (Eds.), *Biodiversity*, Washington (DC), 212–216.

EJP (2021), “Soil research. EJP - European Joint Programme Soil”.

Emsley, J. (2011), *Nature's building blocks: An A-Z guide to the elements / John Emsley*, New ed., Oxford University Press, Oxford.

Epstein, E. (1999), “SILICON”, *Annual review of plant physiology and plant molecular biology*, Vol. 50, pp. 641–664.

Epstein, E. (2009), “Silicon: its manifold roles in plants”, *Annals of Applied Biology*, Vol. 155 No. 2, pp. 155–160.

Ercumen, A., Pickering, A.J., Kwong, L.H., Arnold, B.F., Parvez, S.M., Alam, M., Sen, D., Islam, S., Kullmann, C., Chase, C., Ahmed, R., Unicomb, L., Luby, S.P. and Colford, J.M. (2017), “Animal Feces Contribute to Domestic Fecal Contamination: Evidence from E. coli Measured in Water, Hands, Food, Flies, and Soil in Bangladesh”, *Environmental science & technology*, Vol. 51 No. 15, pp. 8725–8734.

European Commission (EC) (2020), “Caring for soil is caring for life – Ensure 75% of soils are healthy by 2030 for food, people, nature and climate”, *Directorate-General for Research and Innovation*, p. 82.

Fageria, N.K. and Baligar, V.C. (2008), “Chapter 7 Ameliorating Soil Acidity of Tropical Oxisols by Liming For Sustainable Crop Production”, in *Advances in Agronomy*, Vol. 99, Elsevier, pp. 345–399.

Fan, Y. and Pedersen, O. (2021), “Gut microbiota in human metabolic health and disease”, *Nature reviews. Microbiology*, Vol. 19 No. 1, pp. 55–71.

Fangueiro, D., Coutinho, J., Chadwick, D., Moreira, N. and Trindade, H. (2008), “Effect of cattle slurry separation on greenhouse gas and ammonia emissions during storage”, *Journal of environmental quality*, Vol. 37 No. 6, pp. 2322–2331.

Fangueiro, D., Surgy, S., Napier, V., Menaia, J., Vasconcelos, E. and Coutinho, J. (2014), “Impact of slurry management strategies on potential leaching of nutrients and pathogens in a sandy soil amended with cattle slurry”, *Journal of environmental management*, Vol. 146, pp. 198–205.

FAO (2015), *Status of the World’s Soil Resources: Technical Summary*.

FAO (2017), *The future of food and agriculture: Trends and challenges*, Food and Agriculture Organization of the United Nations, Rome.

FAO and ITPS (2017), *Global Assessment of the Impact of Plant Protection Products on Soil Functions and Soil Ecosystems.*

Faraone, N., Evans, R., LeBlanc, J. and Hillier, N.K. (2020), “Soil and foliar application of rock dust as natural control agent for two-spotted spider mites on tomato plants”, *Scientific reports*, Vol. 10 No. 1, p. 12108.

Feigin, D.S. (1989), “Misconceptions regarding the pathogenicity of silicas and silicates”, *Journal of thoracic imaging*, Vol. 4 No. 1, pp. 68–80.

Fettes, D. and Desmons, J. (Eds.) (2011), *Metamorphic rocks: A classification and glossary of terms ; recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Metamorphic Rocks*, 1. paperback ed., Cambridge Univ. Press, Cambridge.

Fierer, N. and Jackson, R.B. (2006), “The diversity and biogeography of soil bacterial communities”, *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 103 No. 3, pp. 626–631.

Flandroy, L., Poutahidis, T., Berg, G., Clarke, G., Dao, M.-C., Decaestecker, E., Furman, E., Haahtela, T., Massart, S., Plovier, H., Sanz, Y. and Rook, G. (2018), “The impact of human activities and lifestyles on the interlinked microbiota and health of humans and of ecosystems”, *The Science of the total environment*, Vol. 627, pp. 1018–1038.

Fleming, A. (1942), “In-vitro tests of Penicillin potency”, *The Lancet*, Vol. 239 No. 6199, pp. 732–733.

Flessa, H. and Beese, F. (2000), “Laboratory Estimates of Trace Gas Emissions following Surface Application and Injection of Cattle Slurry”, *Journal of Environment Quality*, Vol. 29 No. 1, pp. 262–268.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. and Snyder, P.K. (2005), “Global consequences of land use”, *Science (New York, N.Y.)*, Vol. 309 No. 5734, pp. 570–574.

Foxx, C.L., Heinze, J.D., González, A., Vargas, F., Baratta, M.V., Elsayed, A.I., Stewart, J.R., Loupy, K.M., Arnold, M.R., Flux, M.C., Sago, S.A., Siebler, P.H., Milton, L.N., Lieb, M.W., Hassell, J.E., Smith, D.G., Lee, K.A.K., Appiah, S.A., Schaefer, E.J., Panitchpakdi, M., Sikora, N.C., Weldon, K.C., Stamper, C.E., Schmidt, D., Duggan, D.A., Mengesha, Y.M., Ogbaselassie, M., Nguyen, K.T., Gates, C.A., Schnabel, K., Tran, L., Jones, J.D., Vitaterna, M.H., Turek, F.W., Fleshner, M., Dorrestein, P.C., Knight, R., Wright, K.P. and Lowry, C.A. (2020), “Effects of Immunization With the Soil-Derived Bacterium Mycobacterium vaccae on Stress Coping Behaviors and Cognitive Performance in a "Two Hit" Stressor Model", *Frontiers in physiology*, Vol. 11, p. 524833.

Franks, D.M. (2020), "Reclaiming the neglected minerals of development", *The Extractive Industries and Society*, Vol. 7 No. 2, pp. 453–460.

Franzosi, C., Castro, L.N. and Celeda, A.M. (2014), "Technical Evaluation of Glauconies as Alternative Potassium Fertilizer from the Salamanca Formation, Patagonia, Southwest Argentina", *Natural Resources Research*, Vol. 23 No. 3, pp. 311–320.

Fyfe, W.S. (1989), "Soil and global change", *Episodes*, Vol. 12, pp. 249–254.

Fyfe, W.S., Leonardos, O.H. and Theodoro, S.H. (2006), "Sustainable farming with native rocks. The transition without revolution", *Annals of the Brazilian Academy of Sciences*, 78 (4), pp. 715–720.

Fyfe, W.S., Pride, C. and van Straaten, P. (1987), "Sustainable food production and agrogeology", Small Mining International, Bulletin 5–6: 4–5.

Garcia, S.N., Osburn, B.I. and Jay-Russell, M.T. (2020), "One Health for Food Safety, Food Security, and Sustainable Food Production", *Frontiers in Sustainable Food Systems*, Vol. 4, p. 540.

Garcia-Gomez, A., Szmidt, R. and Roig, A. (2002), "Enhancing of the Composting Rate of Spent Mushroom Substrate by Rock Dust", *Compost Science & Utilization*, Vol. 10 No. 2, pp. 99–104.

Gerber, S. (2003), "Gülleaufbereitung – Einsatz von Güllezusätzen in der Praxis. Auswertung und Ergebnisse der Umfrage 2000".

Gillman, G.P., Burkett, D.C. and Coventry, R.J. (2001), "A laboratory study of application of basalt dust to highly weathered soils: effect on soil cation chemistry", *Soil Research*, Vol. 39 No. 4, p. 799.

Glazner, A., Bartley, J. and Coleman, D. (2019), "A More Informative Way to Name Plutonic Rocks", *GSA Today*, Vol. 29 No. 2, pp. 4–10.

Godfray, H.C.J. and Garnett, T. (2014), "Food security and sustainable intensification", *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, Vol. 369 No. 1639, p. 20120273.

Goicoechea, N. (2009), "To what extent are soil amendments useful to control Verticillium wilt?", *Pest management science*, Vol. 65 No. 8, pp. 831–839.

Goldschmidt, V.M. (1922), "Oversikgtskart over utbredelsen av de forskjellige kalimineraler I norsk fjeldgrund.", *Norsk Landmansblad*, Vol. 41, pp. 268–269.

Gomiero, T. (2016), "Soil Degradation, Land Scarcity and Food Security: Reviewing a Complex Challenge", *Sustainability*, Vol. 8 No. 3, p. 281.

Gondal, A.S., Rauf, A. and Naz, F. (2019), "The first report of tomato foot rot caused by Rhizoctonia solani AG-3 PT from Pakistan", *Journal of Plant Pathology*, Vol. 101 No. 2, p. 425.

Goyal, D., Yadav, A., Prasad, M., Singh, T.B., Shrivastav, P., Ali, A., Dantu, P.K. and Mishra, S. (2020), "Effect of Heavy Metals on Plant Growth: An Overview", in Naeem, M., Ansari, A.A. and Gill, S.S. (Eds.), *Contaminants in Agriculture*, Springer International Publishing, Cham, pp. 79–101.

Graham, R.D. (2008), "Micronutrient Deficiencies in Crops and Their Global Significance.", in Alloway, B.J. (Ed.), *Micronutrient Deficiencies in Global Crop Production*, Springer Netherlands, Dordrecht, pp. 41–61.

Greiner, L., Keller, A., Grêt-Regamey, A. and Papritz, A. (2017), "Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services", *Land Use Policy*, Vol. 69, pp. 224–237.

Grieneisen, L.E., Charpentier, M.J.E., Alberts, S.C., Blekhman, R., Bradburd, G., Tung, J. and Archie, E.A. (2019), "Genes, geology and germs: gut microbiota across a primate hybrid zone are

explained by site soil properties, not host species", *Proceedings. Biological sciences*, Vol. 286 No. 1901, p. 20190431.
Griffiths, B., Faber, J. and Bloem, J. (2018), "Applying Soil Health Indicators to Encourage Sustainable Soil Use: The Transition from Scientific Study to Practical Application", *Sustainability*, Vol. 10 No. 9, p. 3021.
Groot Koerkamp, P., Metz, J., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O. and Wathes, C.M. (1998), "Concentrations and Emissions of Ammonia in Livestock Buildings in Northern Europe", *Journal of Agricultural Engineering Research*, Vol. 70 No. 1, pp. 79–95.
Gu, G., Cevallos-Cevallos, J.M., Vallad, G.E. and van Bruggen, A.H.C. (2013), "Organically managed soils reduce internal colonization of tomato plants by Salmonella enterica serovar Typhimurium", *Phytopathology*, Vol. 103 No. 4, pp. 381–388.
Gunnarsen, K.C., Jensen, L.S., Gómez-Muñoz, B., Rosing, M.T. and Neergaard, A. de (2019), "Glacially abraded rock flour from Greenland: Potential for macronutrient supply to plants", *Journal of Plant Nutrition and Soil Science*, Vol. 182 No. 5, pp. 846–856.
Guntzer, F., Keller, C. and Meunier, J.-D. (2012), "Benefits of plant silicon for crops. A review", *Agronomy for Sustainable Development*, Vol. 32 No. 1, pp. 201–213.
Gupta, R.C. (2007), *Veterinary toxicology: Basic and clinical principles / Ramesh C. Gupta, editor*, Academic, Amsterdam, London.
Haahtela, T., Hertzen, L. von, Mäkelä, M. and Hannuksela, M. (2008), "Finnish Allergy Programme 2008-2018--time to act and change the course", *Allergy*, Vol. 63 No. 6, pp. 634–645.
Haes, H. de, R.L. Voortman, D.W. Bussink, C.W. Rougoor and and W.J. van der Weijden (2012), *Scarcity of Micronutrients in Soil, Feed, Food and Mineral Reserves*.
Hanly, J.A., Loganathan, P. and Currie, L.D. (2005), "Effect of serpentine rock and its acidulated products as magnesium fertilisers for pasture, compared with magnesium oxide and Epsom salts, on a Pumice Soil. 1. Dry matter yield and magnesium uptake", *New Zealand Journal of Agricultural Research*, Vol. 48 No. 4, pp. 451–460.
Hanski, I., Hertzen, L. von, Fyhrquist, N., Koskinen, K., Torppa, K., Laatikainen, T., Karisola, P., Auvinen, P., Paulin, L., Mäkelä, M.J., Vartiainen, E., Kosunen, T.U., Alenius, H. and Haahtela, T. (2012), "Environmental biodiversity, human microbiota, and allergy are interrelated", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 109 No. 21, pp. 8334–8339.
Haque, F., Santos, R.M. and Chiang, Y.W. (2020), "Optimizing Inorganic Carbon Sequestration and Crop Yield With Wollastonite Soil Amendment in a Microplot Study", *Frontiers in Plant Science*, Vol. 11, p. 103.
Haque, F., Santos, R.M., Dutta, A., Thimmanagari, M. and Chiang, Y.W. (2019), "Co-Benefits of Wollastonite Weathering in Agriculture: CO2 Sequestration and Promoted Plant Growth", *ACS omega*, Vol. 4 No. 1, pp. 1425–1433.
Hari, V., Rakovec, O., Markonis, Y., Hanel, M. and Kumar, R. (2020), "Increased future occurrences of the exceptional 2018-2019 Central European drought under global warming", *Scientific reports*, Vol. 10 No. 1, p. 12207.
Harley, A.D. (2002), "The evaluation and improvement of silicate mineral fertilisers", PhD thesis, University of Western Australia, 2002.
Harley, A.D. and Gilkes, R.J. (2000), "Factors influencing the release of plant nutrient elements from silicate rock powders: a geochemical overview", *Nutrient Cycling in Agroecosystems*, Vol. 56, pp. 11–36.

Hartemink, A.E. (2002), “Soil Science in Tropical and Temperate Regions—Some Differences and Similarities”, in *Advances in Agronomy*, Vol. 77, Elsevier, pp. 269–292.
Hartemink, A.E. (2006), *The future of soil science*, International Union of Soil Sciences, Wageningen.
Hartmann, J., West, A.J., Renforth, P., Köhler, P., De La Rocha, Christina L., Wolf-Gladrow, D.A., Dürr, H.H. and Scheffran, J. (2013), “Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification”, *Reviews of Geophysics*, Vol. 51 No. 2, pp. 113–149.
Hawkes, C. and Ruel, M.T. (2006), *Understanding the links between agriculture and health*, International Food Policy Research Institute.
Haynes, R.J. (2014), “A contemporary overview of silicon availability in agricultural soils”, *Journal of Plant Nutrition and Soil Science*, Vol. 177 No. 6, pp. 831–844.
Heckman, J. (2006), “A history of organic farming: Transitions from Sir Albert Howard's War in the Soil to USDA National Organic Program”, *Renewable Agriculture and Food Systems*, Vol. 21 No. 3, pp. 143–150.
Hellal, F.A., El-Sayed, S. and Zewainy, R.M. (2013), “Effects of natural potassium source enriched with compost on nutrient uptake and yield of sugar beet grown in newly reclaimed soils”, *Middel East Journal of Agriculture Research*, 2 (3), pp. 101–107.
Hénault, C., Bourennane, H., Ayzac, A., Ratié, C., Saby, N.P.A., Cohan, J.-P., Eglin, T. and Le Gall, C. (2019), “Management of soil pH promotes nitrous oxide reduction and thus mitigates soil emissions of this greenhouse gas”, *Scientific reports*, Vol. 9 No. 1, p. 20182.
Henrard, M. and Forti, R. (Eds.) (2016), *Agriculture, forestry and fishery statistics: 2015 edition, Eurostat. Statistical books*, Vol. 2015, 2015 edition. (Reedition), Publications Office, Luxembourg.
Hiddink, G.A., van Bruggen, A.H.C., Termorshuizen, A.J., Raaijmakers, J.M. and Semenov, A.V. (2005), “Effect of Organic Management of Soils on Suppressiveness to Gaeumannomyces graminis var. tritici and its Antagonist, Pseudomonas fluorescens”, *European Journal of Plant Pathology*, Vol. 113 No. 4, pp. 417–435.
Hilf, H.H. (1938), “The manuring of poor soils with basalt grit (in German).”, *Forstarchiv*, Vol. 14, pp. 93–100.
Hinsinger, P., Barros, O.N.F., Benedetti, M.F., Noack, Y. and Callot, G. (2001), “Plant-induced weathering of a basaltic rock: Experimental evidence”, *Geochimica et Cosmochimica Acta*, Vol. 65, pp. 137–152.
Hinsinger, P., Bolland, M. and Gilkes, R.J. (1996), “Silicate rock powder: effect on selected chemical properties of a range of soils from Western Australia and on plant growth as assessed in a glasshouse experiment”, *Fertilizer Research*, No. 45, pp. 69–79.
Hirt, H. (2020), “Healthy soils for healthy plants for healthy humans: How beneficial microbes in the soil, food and gut are interconnected and how agriculture can contribute to human health”, *EMBO reports*, Vol. 21 No. 8, e51069.
Hodgson, C.J., Oliver, D.M., Fish, R.D., Bulmer, N.M., Heathwaite, A.L., Winter, M. and Chadwick, D.R. (2016), “Seasonal persistence of faecal indicator organisms in soil following dairy slurry application to land by surface broadcasting and shallow injection”, *Journal of environmental management*, Vol. 183, pp. 325–332.
Hoegh-Guldberg, O., D., Jacob, M., Taylor, M., Bindi, S., Brown, I., Camilloni, A., Diedhiou, R., Djalante, K.L., Ebi, F., Engelbrecht, J., Guiot, Y., Hijioka, S., Mehrotra, A., Payne, S.I., Seneviratne, A., Thomas, R. and Warren, a.G.Z. (2018), “Impacts of 1.5ºC Global Warming on Natural and Human Systems”, *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas*

emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
Holdren, G.R. and Speyer, P.M. (1985), “Reaction rate-surface area relationships during the early stages of weathering—I. Initial observations”, *Geochimica et Cosmochimica Acta*, Vol. 49 No. 3, pp. 675–681.
Horvath, D. and Reid, R. (1984), “Indirect effects of soil and water on animal health”, *Science of The Total Environment*, Vol. 34 No. 1-2, pp. 143–156.
Hosier, S. and Bradley, L. (1999), *Guide to Symptoms of Plant Nutrient Deficiencies*, The University of Arizona Cooperative Extension. Publication AZ1106, available at: ag.arizona.edu/pubs/.
Hossain, A., Krupnik, T.J., Timsina, J., Mahboob, M.G., Chaki, A.K., Farooq, M., Bhatt, R., Fahad, S. and Hasanuzzaman, M. (2020), “Agricultural Land Degradation: Processes and Problems Undermining Future Food Security”, in Fahad, S., Hasanuzzaman, M., Alam, M., Ullah, H., Saeed, M., Ali Khan, I. and Adnan, M. (Eds.), *Environment, Climate, Plant and Vegetation Growth*, Vol. 2, Springer International Publishing, Cham, pp. 17–61.
Hough, R.L. (2007), “Soil and human health. An epidemiological review”, *European Journal of Soil Science*, Vol. 58 No. 5, pp. 1200–1212.
Howard, A. (1947), *The soil and health: A study of organic agriculture.*, New York, NY, USA, Devin-Adair Company.
Huber, M., Knottnerus, J.A., Green, L., van der Horst, H., Jadad, A.R., Kromhout, D., Leonard, B., Lorig, K., Loureiro, M.I., van der Meer, J.W.M., Schnabel, P., Smith, R., van Weel, C. and Smid, H. (2011), “How should we define health?”, *BMJ*, Vol. 343, d4163.
Hubert, S.M., Al-Ajeeli, M., Bailey, C.A. and Athrey, G. (2019), “The Role of Housing Environment and Dietary Protein Source on the Gut Microbiota of Chicken”, *Animals an open access journal from MDPI*, Vol. 9 No. 12.
Hultman, J., Waldrop, M.P., Mackelprang, R., David, M.M., McFarland, J., Blazewicz, S.J., Harden, J., Turetsky, M.R., McGuire, A.D., Shah, M.B., VerBerkmoes, N.C., Lee, L.H., Mavrommatis, K. and Jansson, J.K. (2015), “Multi-omics of permafrost, active layer and thermokarst bog soil microbiomes”, *Nature*, Vol. 521 No. 7551, pp. 208–212.
Humboldt-Dachroeden, S., Rubin, O. and Sylvester Frid-Nielsen, S. (2020), “The state of One Health research across disciplines and sectors - a bibliometric analysis”, *One health (Amsterdam, Netherlands)*, Vol. 10, p. 100146.
Hutchings, M.R. and Harris, S. (1997), “Effects of farm management practices on cattle grazing behaviour and the potential for transmission of bovine tuberculosis from badgers to cattle”, *The Veterinary Journal*, Vol. 153 No. 2, pp. 149–162.
IAASTD (2009), “Agriculture at crossroads: Global Summary for Decision Makers”, International Assessment of Agricultural Knowledge, Science and Technology for Development. Island Press, Washington, DC. Reports agreed to at an Intergovernmental Plenary Session, Johannesburg, South Africa, April 2008.
Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Schindelbeck, R.R., Moebius-Clune, B.N. and Gugino, B.K. (2009), “Use of an integrative soil health test for evaluation of soil management impacts”, *Renewable Agriculture and Food Systems*, Vol. 24 No. 3, pp. 214–224.
IFOAM (2008), “Definition of organic agriculture”, available at: https://www.ifoam.bio/why-organic/organic-landmarks/definition-organic (accessed 25 July 2021).
IPBES (2018), *The IPBES assessment report on land degradation and restoration.: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,*
IPCC/OECD/IEA (1997), “Revised 1996 IPCC guidelines for national greenhouse gas inventories, Vol. 3.”.

Jacobsen, C.S. and Bech, T.B. (2012), "Soil survival of Salmonella and transfer to freshwater and fresh produce", *Food Research International*, Vol. 45 No. 2, pp. 557–566.

Jadad, A.R. and O'Grady, L. (2008), "How should health be defined?", *BMJ*, Vol. 337, a2900.

Janzen, H.H., Janzen, D.W. and Gregorich, E.G. (2021), "The 'soil health' metaphor: Illuminating or illusory?", *Soil Biology and Biochemistry*, Vol. 159, p. 108167.

Järup, L. (2003), "Hazards of heavy metal contamination", *British medical bulletin*, Vol. 68, pp. 167–182.

Jasanoff, S. (2007), "Technologies of humility", *Nature*, Vol. 450 No. 7166, p. 33.

Jenkins, H.E., Woodroffe, R. and Donnelly, C.A. (2008), "The effects of annual widespread badger culls on cattle tuberculosis following the cessation of culling", *International journal of infectious diseases IJID official publication of the International Society for Infectious Diseases*, Vol. 12 No. 5, pp. 457–465.

Jenny, H. (1941), *Factors of soil formation: A system of quantitative pedology*, McGraw-Hill, New York.

Jones, C. and Jacobsen, J. (2005), "Plant nutrition and soil fertility. Nutrient management module 2", Montana State University. http://landresources.montana.edu/nm/documents/NM2.pdf.

Jones, D.L., Cross, P., Withers, P.J.A., DeLuca, T.H., Robinson, D.A., Quilliam, R.S., Harris, I.M., Chadwick, D.R. and Edwards-Jones, G. (2013), "REVIEW: Nutrient stripping: the global disparity between food security and soil nutrient stocks", *Journal of Applied Ecology*, Vol. 50 No. 4, pp. 851–862.

Kahnt, G., Pfleiderer, H. and Hijazi, L.A. (1986), "Wirkungen meliorativer Gaben von Gesteinsmehlen und Gesteinssanden auf das Wachstum verschiedener landwirtschaftlicher Kulturpflanzen sowie auf physikalische Kennwerte eines Sandbodens und eines Tonbodens", *Agronomy Agronomy & Crop Science*, Vol. 157, pp. 169–180.

Kantola, I.B., Masters, M.D., Beerling, D.J., Long, S.P. and DeLucia, E.H. (2017), "Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering", *Biology letters*, Vol. 13 No. 4.

Karaca, A., Cetin, S.C., Turgay, O.C. and Kizilkaya, R. (2010), "Effects of Heavy Metals on Soil Enzyme Activities", in *Soil Heavy Metals*, *Soil Biology*, Vol. 19, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 237–262.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F. and Schuman, G.E. (1997), "Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial)", *Soil Science Society of America Journal*, Vol. 61 No. 1, pp. 4–10.

Kavanagh, I., Burchill, W., Healy, M.G., Fenton, O., Krol, D.J. and Lanigan, G.J. (2019), "Mitigation of ammonia and greenhouse gas emissions from stored cattle slurry using acidifiers and chemical amendments", *Journal of Cleaner Production*, Vol. 237, p. 117822.

Kay, A.B. (2000), "Overview of 'allergy and allergic diseases: with a view to the future'", *British medical bulletin*, Vol. 56 No. 4, pp. 843–864.

Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., van der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B. and Fresco, L.O. (2016), "The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals", *SOIL*, Vol. 2 No. 2, pp. 111–128.

Keith, A.M., Schmidt, O. and McMahon, B.J. (2016), "Soil stewardship as a nexus between Ecosystem Services and One Health", *Ecosystem Services*, Vol. 17, pp. 40–42.

Kelland, M.E., Wade, P.W., Lewis, A.L., Taylor, L.L., Sarkar, B., Andrews, M.G., Lomas, M.R., Cotton, T.E.A., Kemp, S.J., James, R.H., Pearce, C.R., Hartley, S.E., Hodson, M.E., Leake, J.R., Banwart, S.A. and Beerling, D.J. (2020), "Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil", *Global change biology*, Vol. 26 No. 6, pp. 3658–3676.

Kellogg, C.E. (1938), *Soil and society, in: Soils and Men: Yearbook of Agriculture 1938, edited by: Washington, DC, USA, United States Government Printing Office, 863–886, 1938.*

Kemper, K.J., Lakritz, J. and Lal, R. (2017), "The Soil-Animal-Human Health Nexus", Singh, B.R. McLaughlin, and M.J. Brevik, 16–20. Stuttgart: GeoEcology Essays.

Kemper, K.J., Xia, Y., Lakritz, J. and Lal, R. (2020), "Health of Soil, Plants, Animals, and People", in Lal, R. (Ed.), *The Soil–Human Health Nexus*, CRC Press, First edition. | Boca Raton, FL CRC Press, 2020. |, pp. 13–46.

Keyvanfar, A.L., SHAFAGHAT, A., TAN SZE INN and SAPURA MOHAMAD (2020), "A SUSTAINABLE URBAN FARMING INDEX ASSESSMENT MODEL FOR EVALUATING FOOD PRODUCTIVITY THAT APPLIES MULTI-CRITERIA DECISION-MAKING METHODS — A CASE STUDY IN MALAYSIA", *Journal of Sustainability Science and Management*, Vol. 15 No. 7, pp. 123–146.

Khan, S.A., Mulvaney, R.L. and Ellsworth, T.R. (2014), "The potassium paradox: Implications for soil fertility, crop production and human health", *Renewable Agriculture and Food Systems*, Vol. 29 No. 01, pp. 3–27.

Kheshgi, H.S. (1995), "Sequestering atmospheric carbon dioxide by increasing ocean alkalinity", *Energy*, Vol. 20 No. 9, pp. 915–922.

Kim, K.-H., Kabir, E. and Jahan, S.A. (2017), "Exposure to pesticides and the associated human health effects", *The Science of the total environment*, Vol. 575, pp. 525–535.

Kistner-Othmer, M. (1989), "Einstreu von Steinmehl in Hühnerställe zur Verbesserung des Hofdüngers und der Stallluft", Dissertation, Landwirtschaft, Kassel, 1989.

Klein, C. and Philpotts, A.R. (2017), *Earth materials: Introduction to mineralogy and petrology / Cornelis Klein, University of New Mexico, Emeritus, Anthony Philpotts, University of Connecticut, Emeritus*, Second edition, Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA.

Kleiv, R.A. and Thornhill, M. (2007), "Production of mechanically activated rock flour fertilizer by high intensive ultrafine grinding", *Minerals Engineering*, Vol. 20 No. 4, pp. 334–341.

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A. and Lombi, E. (2019), "Soil and the intensification of agriculture for global food security", *Environment international*, Vol. 132, p. 105078.

Korndörfer, G.H. and Lepsch, I. (2001), "Chapter 7 Effect of silicon on plant growth and crop yield", in *Silicon in Agriculture, Studies in Plant Science*, Vol. 8, Elsevier, pp. 133–147.

Kudva, I.T., Blanch, K. and Hovde, C.J. (1998), "Analysis of Escherichia coli O157:H7 survival in ovine or bovine manure and manure slurry", *Applied and environmental microbiology*, Vol. 64 No. 9, pp. 3166–3174.

Kühn, S. and van Franeker, J.A. (2020), "Quantitative overview of marine debris ingested by marine megafauna", *Marine pollution bulletin*, Vol. 151, p. 110858.

Kumar, K., Gupta, S.C., Baidoo, S.K., Chander, Y. and Rosen, C.J. (2005), "Antibiotic uptake by plants from soil fertilized with animal manure", *Journal of environmental quality*, Vol. 34 No. 6, pp. 2082–2085.

Kump, L.R., Brantley, S.L. and Arthur, M.A. (2000), "Chemical Weathering, Atmospheric CO 2 and Climate", *Annual Review of Earth and Planetary Sciences*, Vol. 28 No. 1, pp. 611–667.

Lackey, R.T. (2007), "Science, scientists, and policy advocacy", *Conservation biology the journal of the Society for Conservation Biology*, Vol. 21 No. 1, pp. 12–17.

Lal, R. (2008), “Soils and sustainable agriculture. A review”, *Agronomy for Sustainable Development*, Vol. 28 No. 1, pp. 57–64.
Lal, R. (2015), “Restoring Soil Quality to Mitigate Soil Degradation”, *Sustainability*, Vol. 7 No. 5, pp. 5875–5895.
Lal, R. (Ed.) (2020), *The Soil–Human Health Nexus*, CRC Press, First edition. | Boca Raton, FL CRC Press, 2020. |.
Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D.J., Glaser, B., Hatano, R., Hartemink, A.E., Kosaki, T., Lascelles, B., Monger, C., Muggler, C., Ndzana, G.M., Norra, S., Pan, X., Paradelo, R., Reyes-Sánchez, L.B., Sandén, T., Singh, B.R., Spiegel, H., Yanai, J. and Zhang, J. (2021), “Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective”, *Geoderma Regional*, Vol. 25, e00398.
Lancet, T. (2009), “What is health? The ability to adapt”, *The Lancet*, Vol. 373 No. 9666, p. 781.
Larson, B. (2014), *Metaphors for environmental sustainability: Redefining our relationship with nature*, Yale University Press, New Haven.
Lasaga, A.C., Soler, J.M., Ganor, J., Burch, T.E. and Nagy, K.L. (1994), “Chemical weathering rate laws and global geochemical cycles”, *Geochimica et Cosmochimica Acta*, Vol. 58 No. 10, pp. 2361–2386.
Latz, E., Eisenhauer, N., Rall, B.C., Scheu, S. and Jousset, A. (2016), “Unravelling Linkages between Plant Community Composition and the Pathogen-Suppressive Potential of Soils”, *Scientific reports*, Vol. 6, p. 23584.
Lavie, C.J., Crocker, E.F., Key, K.J. and Ferguson, T.G. (1986), “Marked hypochloremic metabolic alkalosis with severe compensatory hypoventilation”, *Southern medical journal*, Vol. 79 No. 10, pp. 1296–1299.
Le Maitre, R.W., Streckeisen, A., Zanettin, B., Le Bas, M.J., Bonin, B. and Bateman, P. (2002), *Igneous Rocks*, Cambridge University Press, Cambridge.
Lee, W.-J. and Hase, K. (2014), “Gut microbiota-generated metabolites in animal health and disease”, *Nature chemical biology*, Vol. 10 No. 6, pp. 416–424.
Lefebvre, D., Goglio, P., Williams, A., Manning, D.A., Azevedo, A.C. de, Bergmann, M., Meersmans, J. and Smith, P. (2019), “Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil”, *Journal of Cleaner Production*, Vol. 233, pp. 468–481.
Lehmann, J., Bossio, D.A., Kögel-Knabner, I. and Rillig, M.C. (2020), “The concept and future prospects of soil health”, *Nature reviews. Earth & environment*, Vol. 1 No. 10, pp. 544–553.
Leonardos, O.H., Fyfe, W.S. and Kronberg, B.I. (1987), “The use of ground rocks in laterite systems: an improvement to the use of conventional soluble fertilizers?”, *Chemical Geology*, No. 60, pp. 361–370.
Leonardos, O.H., Theodoro, S.H. and Assad, M.L. (2000), “Remineralization for sustainable agriculture: A tropical perspective from a Brazilian viewpoint”, *Nutrient Cycling in Agroecosystems*, No. 56, pp. 3–9.
Leopold, A. (1939), “A Biotic View of Land”, *Journal of Forestry*, Vol. 37, pp. 727–730.
Leopold, A. (1949), *A Sand County Almanac with Essays on Conservation from Round River*, New York: Random House. 1966.
Letey, J., R. Sojka, D. R. Upchurch, D. Cassel, K. Olson, W. Payne, S. Petrie, G. Price, R. J. Reginato, H. D. Scott, P. Smethurst and G. Triplett (2003), “Deficiencies in the soil quality concept and its application”, *Journal ofSoif andWater Conservation*, Volume 58, Number 4.
Li, G., Sun, G.-X., Ren, Y., Luo, X.-S. and Zhu, Y.-G. (2018), “Urban soil and human health: a review”, *European Journal of Soil Science*, Vol. 69 No. 1, pp. 196–215.

Li, J., Mavrodi, D.V. and Dong, Y. (2020), “Effect of rock dust-amended compost on the soil properties, soil microbial activity, and fruit production in an apple orchard from the Jiangsu province of China”, *Archives of Agronomy and Soil Science*, Vol. 16, pp. 1–14.

Li, J.-G. and Dong, Y.-H. (2013), “Effect of a rock dust amendment on disease severity of tomato bacterial wilt”, *Antonie van Leeuwenhoek*, Vol. 103 No. 1, pp. 11–22.

Li, Z., Xie, X., Zhang, S. and Liang, Y. (2011), “Negative Effects of Oxytetracycline on Wheat (Triticum aestivum L.) Growth, Root Activity, Photosynthesis, and Chlorophyll Contents”, *Agricultural Sciences in China*, Vol. 10 No. 10, pp. 1545–1553.

Liang, Y., Nikolic, M., Bélanger, R., Gong, H. and Song, A. (2015), *Silicon in Agriculture*, Springer Netherlands, Dordrecht.

Liddicoat, C., Sydnor, H., Cando-Dumancela, C., Dresken, R., Liu, J., Gellie, N.J.C., Mills, J.G., Young, J.M., Weyrich, L.S., Hutchinson, M.R., Weinstein, P. and Breed, M.F. (2020), “Naturally-diverse airborne environmental microbial exposures modulate the gut microbiome and may provide anxiolytic benefits in mice”, *The Science of the total environment*, Vol. 701, p. 134684.

Liu, D., Lian, B., Wang, B. and Jiang, G. (2011), “Degradation of potassium rock by earthworms and responses of bacterial communities in its gut and surrounding substrates after being fed with mineral”, *PloS one*, Vol. 6 No. 12, e28803.

Liu, S., Qi, X., Han, C., Liu, J., Sheng, X., Li, H., Luo, A. and Li, J. (2017), “Novel nano-submicron mineral-based soil conditioner for sustainable agricultural development”, *Journal of Cleaner Production*, Vol. 149, pp. 896–903.

Liu, S.K., Han, C., Liu, J.M. and Li, H. (2015), “Hydrothermal decomposition of potassium feldspar under alkaline conditions”, *RSC Advances*, Vol. 5 No. 113, pp. 93301–93309.

Lobry de Bruyn, L. and Andrews, S. (2016), “Are Australian and United States Farmers Using Soil Information for Soil Health Management?”, *Sustainability*, Vol. 8 No. 4, p. 304.

Logan, W.B. (1995), *Dirt: The ecstatic skin of the earth / William Bryant Logan*, New ed., W. W. Norton. p.62.

Long, R.P., Bailey, S.W., Horsley, S.B., Hall, T.J., Swistock, B.R. and DeWalle, D.R. (2015), “Long-Term Effects of Forest Liming on Soil, Soil Leachate, and Foliage Chemistry in Northern Pennsylvania”, *Soil Science Society of America Journal*, Vol. 79 No. 4, pp. 1223–1236.

Luangtongkum, T., Morishita, T.Y., Ison, A.J., Huang, S., McDermott, P.F. and Zhang, Q. (2006), “Effect of conventional and organic production practices on the prevalence and antimicrobial resistance of Campylobacter spp. in poultry”, *Applied and environmental microbiology*, Vol. 72 No. 5, pp. 3600–3607.

LumaSense (2007), “Photoacoustic Field Gas-Monitor – INNOVA 1412. Device description”, pp. 1–4.

MacNeill, A.J., McGain, F. and Sherman, J.D. (2021), “Planetary health care: a framework for sustainable health systems”, *The Lancet Planetary Health*, Vol. 5 No. 2, e66-e68.

Madaras, M., Mayerová, M., Kulhánek, M., Koubová, M. and Faltus, M. (2012), “Waste silicate minerals as potassium sources. A greenhouse study on spring barley”, *Archives of Agronomy and Soil Science*, Vol. 59 No. 5, pp. 671–683.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P. and Niggli, U. (2002), “Soil fertility and biodiversity in organic farming”, *Science (New York, N.Y.)*, Vol. 296 No. 5573, pp. 1694–1697.

Mahadappa, P., Krishnaswamy, N., Karunanidhi, M., Bhanuprakash, A.G., Bindhuja, B.V. and Dey, S. (2020), “Effect of plastic foreign body impaction on rumen function and heavy metal concentrations in various body fluids and tissues of buffaloes”, *Ecotoxicology and environmental safety*, Vol. 189, p. 109972.

Maher, K. (2010), “The dependence of chemical weathering rates on fluid residence time”, *Earth and Planetary Science Letters*, Vol. 294 No. 1-2, pp. 101–110.

Main, A.R., Webb, E.B., Goyne, K.W. and Mengel, D. (2020), “Reduced species richness of native bees in field margins associated with neonicotinoid concentrations in non-target soils”, *Agriculture, Ecosystems & Environment*, Vol. 287, p. 106693.

Mallee, H. (2017), “The evolution of health as an ecological concept”, *Current Opinion in Environmental Sustainability*, Vol. 25, pp. 28–32.

Mancuso, M.A.C., Soratto, R.P., Crusciol, C.A.C. and Castro, G.S.A. (2014), “Effect of potassium sources and rates on arabica coffee yield, nutrition, and macronutrient export”, *Revista Brasileira de Ciência do Solo*, Vol. 38 No. 5.

Manning, D.A. (2010), “Mineral sources of potassium for plant nutrition. A review”, *Agronomy for Sustainable Development*, Vol. 30 No. 2, pp. 281–294.

Manning, D.A. (2015), “How will minerals feed the world in 2050?”, *Proceedings of the Geologists' Association*, Vol. 126 No. 1, pp. 14–17.

Manning, D.A. and Theodoro, S.H. (2020), “Enabling food security through use of local rocks and minerals”, *The Extractive Industries and Society*, Vol. 7 No. 2, pp. 480–487.

Manning, D.A.C. (2018), “Innovation in Resourcing Geological Materials as Crop Nutrients”, *Natural Resources Research*, Vol. 27 No. 2, pp. 217–227.

Manning, D.A.C., Baptista, J., Sanchez Limon, M. and Brandt, K. (2017), “Testing the ability of plants to access potassium from framework silicate minerals”, *The Science of the total environment*, Vol. 574, pp. 476–481.

Marschner, H. (2002), *Mineral nutrition of higher plants*, 2nd ed., Academic Press, Amsterdam.

Martin, F.N. and Loper, J.E. (1999), “Soilborne Plant Diseases Caused by Pythium spp.: Ecology, Epidemiology, and Prospects for Biological Control”, *Critical Reviews in Plant Sciences*, Vol. 18 No. 2, pp. 111–181.

Martin, J.B. (2017), “Carbonate minerals in the global carbon cycle”, *Chemical Geology*, Vol. 449, pp. 58–72.

Martinez, J., Dabert, P., Barrington, S. and Burton, C. (2009), “Livestock waste treatment systems for environmental quality, food safety, and sustainability”, *Bioresource Technology*, Vol. 100 No. 22, pp. 5527–5536.

Masters, D.G., Norman, H.C. and Thomas, D.T. (2019), “Minerals in pastures—are we meeting the needs of livestock?”, *Crop and Pasture Science*, Vol. 70 No. 12, p. 1184.

Matricardi, P.M. and Bonini, S. (2000), “High microbial turnover rate preventing atopy: a solution to inconsistencies impinging on the Hygiene hypothesis?”, *Clinical and experimental allergy journal of the British Society for Allergy and Clinical Immunology*, Vol. 30 No. 11, pp. 1506–1510.

Matthews, D.M. and Jenks, S.M. (2013), “Ingestion of Mycobacterium vaccae decreases anxiety-related behavior and improves learning in mice”, *Behavioural processes*, Vol. 96, pp. 27–35.

Mavangira, V., Evans, T.J., Villamil, J.A., Hahn, A.W., Chigerwe, M. and Tyler, J.W. (2008), “Relationships between demographic variables and lead toxicosis in cattle evaluated at North American veterinary teaching hospitals”, *Journal of the American Veterinary Medical Association*, Vol. 233 No. 6, pp. 955–959.

Mbissik, A., Elghali, A., Ouabid, M., Raji, O., Bodinier, J.-L. and El Messbahi, H. (2021), “Alkali-Hydrothermal Treatment of K-Rich Igneous Rocks for Their Direct Use as Potassic Fertilizers”, *Minerals*, Vol. 11 No. 2, p. 140.

McCarrison, R. (1921), *Studies in deficiency disease*, London, UK, Hazell, Watson and Viney Ltd.

McMahon, B.J., Wall, P.G., Fanning, S. and Fahey, A.G. (2015), “Targets to increase food production: One Health implications”, *Infection ecology & epidemiology*, Vol. 5, p. 27708.

Meadows, D.H. and Wright, D. (2009), *Thinking in systems: A primer / Donella H. Meadows ; edited by Diana Wright*, Earthscan, London.

Meena, V.D., Dotaniya, M.L., Coumar, V., Rajendiran, S., Ajay, Kundu, S. and Subba Rao, A. (2014), “A Case for Silicon Fertilization to Improve Crop Yields in Tropical Soils”, *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, Vol. 84 No. 3, pp. 505–518.

Meena, V.S., Maurya, B.R., Verma, J.P. and Meena, R.S. (Eds.) (2016), *Potassium Solubilizing Microorganisms for Sustainable Agriculture*, Springer India, New Delhi, s.l.

Mendes, R., Kruijt, M., Bruijn, I. de, Dekkers, E., van der Voort, M., Schneider, J.H.M., Piceno, Y.M., DeSantis, T.Z., Andersen, G.L., Bakker, P.A.H.M. and Raaijmakers, J.M. (2011), “Deciphering the rhizosphere microbiome for disease-suppressive bacteria”, *Science (New York, N.Y.)*, Vol. 332 No. 6033, pp. 1097–1100.

Mersi, W.V., Kuhnert-Finkernagel, R. and Schinner, F. (1992), “The influence of rock powders on microbial activity of three forest soils”, *Zeitschrift für Pflanzenernährung und Bodenkunde*, Vol. 155 No. 1, pp. 29–33.

Meyer, M.C., Bueno, C.J., Souza, N.L. de and Yorinori, J.T. (2006), “Effect of doses of fungicides and plant resistance activators on the control of Rhizoctonia foliar blight of soybean, and on Rhizoctonia solani AG1–IA in vitro development”, *Crop Protection*, Vol. 25 No. 8, pp. 848–854.

Michelini, L., Gallina, G., Capolongo, F. and Ghisi, R. (2014), “Accumulation and response of willow plants exposed to environmental relevant sulfonamide concentrations”, *International journal of phytoremediation*, Vol. 16 No. 7-12, pp. 947–961.

Migliore, L., Civitareale, C., Brambilla, G., Cozzolino, S., Casoria, P. and Gaudio, L. (1997), “Effects of sulphadimethoxine on cosmopolitan weeds (Amaranthus retroflexus L., Plantago major L. and Rumex acetosella L.)”, *Agriculture, Ecosystems & Environment*, Vol. 65 No. 2, pp. 163–168.

Misselbrook, T.H., Brookman, S.K.E., Smith, K.A., Cumby, T., Williams, A.G. and McCrory, D.F. (2005), “Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies”, *Journal of environmental quality*, Vol. 34 No. 2, pp. 411–419.

Misselbrook, T.H., LAWS, J.A. and PAIN, B.F. (1996), “Surface application and shallow injection of cattle slurry on grassland: nitrogen losses, herbage yields and nitrogen recoveries”, *Grass and Forage Science*, Vol. 51 No. 3, pp. 270–277.

Moebius-Clune, B.N., Moebius-Clune, D.J., Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., Ristow, A.J., van Es, H.M., Thies, J.E., Shayler, H.A., McBride, M.B., Kurtz, K., Wolfe, D.W. and Abawi, G.S. (2016), *Comprehensive assessment of soil health: The Cornell framework manual*, Third edition, Cornell University, Ithaca, NY.

Mohammed, S.M.O., Brandt, K., Gray, N.D., White, M.L. and Manning, D.A.C. (2014), “Comparison of silicate minerals as sources of potassium for plant nutrition in sandy soil”, *European Journal of Soil Science*, Vol. 65 No. 5, pp. 653–662.

Montgomery, S.L. (2003), *The Chicago guide to communicating science, Chicago guides to writing, editing, and publishing*, Univ. of Chicago Press, Chicago.

Moretti, L.G., Bossolani, J.W., Crusciol, C.A.C., Moreira, A., Micheri, P.H., Rossi, R. and Imaizumi, C. (2019), “Dunite in Agriculture: Physiological Changes, Nutritional Status and Soybean Yield”, *Communications in Soil Science and Plant Analysis*, Vol. 50 No. 14, pp. 1775–1784.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N. and Foley, J.A. (2012), “Closing yield gaps through nutrient and water management”, *Nature*, Vol. 490 No. 7419, pp. 254–257.

Musoke, D., Ndejjo, R., Atusingwize, E. and Halage, A.A. (2016), “The role of environmental health in One Health. A Uganda perspective”, *One health (Amsterdam, Netherlands)*, Vol. 2, pp. 157–160.

Nagajyoti, P.C., Lee, K.D. and Sreekanth, T.V.M. (2010), “Heavy metals, occurrence and toxicity for plants: a review”, *Environmental Chemistry Letters*, Vol. 8 No. 3, pp. 199–216.

Ndegwa, P.M., Hristov, A.N., Arogo, J. and Sheffield, R.E. (2008), “A review of ammonia emission mitigation techniques for concentrated animal feeding operations”, *Biosystems Engineering*, Vol. 100 No. 4, pp. 453–469.

Ng, E.L. and Zhang, J. (2019), “The Search for the Meaning of Soil Health: Lessons from Human Health and Ecosystem Health”, *Sustainability*, Vol. 11 No. 13, p. 3697.

Nieder, R., Benbi, D.K. and Reichl, F.X. (2018), *Soil Components and Human Health*, Springer Netherlands, Dordrecht.

Nielsen, N.O. (1999), “The Meaning of Health”, *Ecosystem Health*, Vol. 5 No. 2, pp. 65–66.

Niwas, J.M., Dissanayake, C.B. and Keerthisinghe, G. (1987), “Rocks as fertilizers: preliminary studies on potassium availability of some common rocks in Sri Lanka”, *Applied Geochemistry*, Vol. 2 No. 2, pp. 243–246.

Norris, C.E. and Congreves, K.A. (2018), “Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review”, *Frontiers in Environmental Science*, Vol. 6.

NRC (2005), *Mineral tolerance of animals*.

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J. and Ryan, M. (2018), “No-till and cropping system diversification improve soil health and crop yield”, *Geoderma*, Vol. 328, pp. 30–43.

Oenema, O., Bannink, A., Sommer, S.G. and Velthof, G.L. (2001), “Gaseous Nitrogen Emissions from Livestock Farming Systems”, *in: Nitrogen in the Environment: Sources, Problems, and Management. R.F. Follett and J.L. Hatfield (Eds)*.

Ohno, T. and Hettiarachchi, G.M. (2018), “Soil Chemistry and the One Health Initiative: Introduction to the Special Section”, *Journal of environmental quality*, Vol. 47 No. 6, pp. 1305–1309.

OIE (2011), *TERRESTRIAL ANIMAL HEALTH CODE, Terrestrial animal health code*, / World Organisation for Animal Health ; 1, 20th ed., OIE, Paris.

Oliver, M.A. and Gregory, P.J. (2015), “Soil, food security and human health. A review”, *European Journal of Soil Science*, Vol. 66 No. 2, pp. 257–276.

Olson, M.E., Arroyo-Santos, A. and Vergara-Silva, F. (2019), “A User's Guide to Metaphors In Ecology and Evolution”, *Trends in ecology & evolution*, Vol. 34 No. 7, pp. 605–615.

Otranto, D. and Deplazes, P. (2019), “Zoonotic nematodes of wild carnivores”, *International journal for parasitology. Parasites and wildlife*, Vol. 9, pp. 370–383.

Overmeyer, V., Holtkamp, F., Clemens, J., Büscher, W. and Trimborn, M. (2020), “Dynamics of Different Buffer Systems in Slurries Based on Time and Temperature of Storage and Their Visualization by a New Mathematical Tool”, *Animals an open access journal from MDPI*, Vol. 10 No. 4.

Palandri, J.L. and Kharaka, Y.K. (2004), *A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling: U.S. geological survey, open file report 2004-1068*.

Palmer, J.S., Hough, R.L., West, H.M. and Avery, L.M. (2019), “A review of the abundance, behaviour and detection of clostridial pathogens in agricultural soils”, *European Journal of Soil Science*, Vol. 70 No. 4, pp. 911–929.

Park, J.J.H., Grais, R.F., Taljaard, M., Nakimuli-Mpungu, E., Jehan, F., Nachega, J.B., Ford, N., Xavier, D., Kengne, A.P., Ashorn, P., Socias, M.E., Bhutta, Z.A. and Mills, E.J. (2021), “Urgently seeking efficiency and sustainability of clinical trials in global health”, *The Lancet Global Health*, Vol. 9 No. 5, e681-e690.

Parker, D.B., Casey, K.D., Todd, R.W., Waldrip, H.M., Marek, G.M., Auvermann, B.W., Marek, T.H., Webb, K., Willis, W.M., Pemberton, B. and Meyer, B. (2017), "Improved Chamber Systems for Rapid, Real-Time Nitrous Oxide Emissions from Manure and Soil", *Transactions of the ASABE*, Vol. 60 No. 4, pp. 1235–1258.

Paulot, F., Jacob, D.J., Pinder, R.W., Bash, J.O., Travis, K. and Henze, D.K. (2014), "Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH3)", *Journal of Geophysical Research: Atmospheres*, Vol. 119 No. 7, pp. 4343–4364.

Pepper, I.L. (2013), "The Soil Health-Human Health Nexus", *Critical Reviews in Environmental Science and Technology*, Vol. 43 No. 24, pp. 2617–2652.

Pepper, I.L. and Brooks, J.P. (2021), "Soil microbial influences on "One Health"", in *Principles and Applications of Soil Microbiology*, Vol. 98, Elsevier, pp. 681–700.

Pepper, I.L., Gerba, C.P., Newby, D.T. and Rice, C.W. (2009), "Soil: A Public Health Threat or Savior?", *Critical Reviews in Environmental Science and Technology*, Vol. 39 No. 5, pp. 416–432.

Peralta, J.R., Gardea-Torresdey, J.L., Tiemann, K.J., Gomez, E., Arteaga, S., Rascon, E. and Parsons, J.G. (2001), "Uptake and Effects of Five Heavy Metals on Seed Germination and Plant Growth in Alfalfa (L.)", *Bulletin of Environmental Contamination and Toxicology*, Vol. 66 No. 6, pp. 727–734.

Pereira, P., Bogunovic, I., Muñoz-Rojas, M. and Brevik, E.C. (2018), "Soil ecosystem services, sustainability, valuation and management", *Current Opinion in Environmental Science & Health*, Vol. 5, pp. 7–13.

Perski, H.J., Schönheit, P. and Thauer, R.K. (1982), "Sodium dependence of methane formation in methanogenic bacteria", *FEBS Letters*, Vol. 143 No. 2, pp. 323–326.

Powlson, D.S. (2020), "Soil health—useful terminology for communication or meaningless concept? Or both?", *Front. Agr. Sci. Eng. 2020, 7(3): 246–250*.

Powlson, D.S. (2021), "Is 'soil health' meaningful as a scientific concept or as terminology?", *Soil Use and Management*, Vol. 37 No. 3, pp. 403–405.

Pretty, J., Sutherland, W.J., Ashby, J., Auburn, J., Baulcombe, D., Bell, M., Bentley, J., Bickersteth, S., Brown, K., Burke, J., Campbell, H., Chen, K., Crowley, E., Crute, I., Dobbelaere, D., Edwards-Jones, G., Funes-Monzote, F., Godfray, H.C.J., Griffon, M., Gypmantisiri, P., Haddad, L., Halavatau, S., Herren, H., Holderness, M., Izac, A.-M., Jones, M., Koohafkan, P., Lal, R., Lang, T., McNeely, J., Mueller, A., Nisbett, N., Noble, A., Pingali, P., Pinto, Y., Rabbinge, R., Ravindranath, N.H., Rola, A., Roling, N., Sage, C., Settle, W., Sha, J.M., Shiming, L., Simons, T., Smith, P., Strzepeck, K., Swaine, H., Terry, E., Tomich, T.P., Toulmin, C., Trigo, E., Twomlow, S., Vis, J.K., Wilson, J. and Pilgrim, S. (2010), "The top 100 questions of importance to the future of global agriculture", *International Journal of Agricultural Sustainability*, Vol. 8 No. 4, pp. 219–236.

Priyanka, M. and Dey, S. (2018), "Ruminal impaction due to plastic materials - An increasing threat to ruminants and its impact on human health in developing countries", *Veterinary world*, Vol. 11 No. 9, pp. 1307–1315.

Priyono, J. and Gilkes, R.J. (2004), "Dissolution of milled-silicate rock fertilisers in the soil", *Soil Research*, Vol. 42 No. 4, p. 441.

Priyono, J. and Gilkes, R.J. (2008), "High-Energy Milling Improves the Effectiveness of Silicate Rock Fertilizers. A Glasshouse Assessment", *Communications in Soil Science and Plant Analysis*, Vol. 39 No. 3-4, pp. 358–369.

Proctor, J. and Larson, B. (2005), “Ecology, Complexity, and Metaphor”, *BioScience*, Vol. 55 No. 12, p. 1065.
Raaijmakers, J.M. and Mazzola, M. (2016), “ECOLOGY. Soil immune responses”, *Science (New York, N.Y.)*, Vol. 352 No. 6292, pp. 1392–1393.
Raaijmakers, J.M. and Weller, D.M. (1998), “Natural Plant Protection by 2,4-Diacetylphloroglucinol-Producing Pseudomonas spp. in Take-All Decline Soils”, *Molecular Plant-Microbe Interactions®*, Vol. 11 No. 2, pp. 144–152.
Radujković, D., Verbruggen, E., Seabloom, E.W., Bahn, M., Biederman, L.A., Borer, E.T., Boughton, E.H., Catford, J.A., Campioli, M., Donohue, I., Ebeling, A., Eskelinen, A., Fay, P.A., Hansart, A., Knops, J.M.H., MacDougall, A.S., Ohlert, T., Olde Venterink, H., Raynaud, X., Risch, A.C., Roscher, C., Schütz, M., Silveira, M.L., Stevens, C.J., van Sundert, K., Virtanen, R., Wardle, G.M., Wragg, P.D. and Vicca, S. (2021), “Soil properties as key predictors of global grassland production: Have we overlooked micronutrients?”, *Ecology letters*.
Ramezanian, A., Dahlin, A.S., Campbell, C.D., Hillier, S., Mannerstedt-Fogelfors, B. and Öborn, I. (2013), “Addition of a volcanic rockdust to soils has no observable effects on plant yield and nutrient status or on soil microbial activity”, *Plant and Soil*, Vol. 367 No. 1-2, pp. 419–436.
Ramezanian, A., Dahlin, A.S., Campbell, C.D., Hillier, S. and Öborn, I. (2015), “Assessing biogas digestate, pot ale, wood ash and rockdust as soil amendments. Effects on soil chemistry and microbial community composition”, *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, Vol. 65 No. 5, pp. 383–399.
Ramos, C.G., dos Santos de Medeiros, D., Gomez, L., Oliveira, L.F.S., Schneider, I.A.H. and Kautzmann, R.M. (2019), “Evaluation of Soil Re-mineralizer from By-Product of Volcanic Rock Mining: Experimental Proof Using Black Oats and Maize Crops”, *Natural Resources Research*, Vol. 56 No. 1, p. 53.
Ramos, C.G., Hower, J.C., Blanco, E., Oliveira, M.L.S. and Theodoro, S.H. (2021), “Possibilities of using silicate rock powder: An overview”, *Geoscience Frontiers*, Vol. 4 No. 2, p. 101185.
Ray, D.K., West, P.C., Clark, M., Gerber, J.S., Prishchepov, A.V. and Chatterjee, S. (2019), “Climate change has likely already affected global food production”, *PloS one*, Vol. 14 No. 5, e0217148.
Raymo, M.E. and Ruddiman, W.F. (1992), “Tectonic forcing of late Cenozoic climate”, *Nature*, Vol. 359 No. 6391, pp. 117–122.
Rayne, N. and Aula, L. (2020), “Livestock Manure and the Impacts on Soil Health: A Review”, *Soil Systems*, Vol. 4 No. 4, p. 64.
Reber, S.O., Siebler, P.H., Donner, N.C., Morton, J.T., Smith, D.G., Kopelman, J.M., Lowe, K.R., Wheeler, K.J., Fox, J.H., Hassell, J.E., Greenwood, B.N., Jansch, C., Lechner, A., Schmidt, D., Uschold-Schmidt, N., Füchsl, A.M., Langgartner, D., Walker, F.R., Hale, M.W., Lopez Perez, G., van Treuren, W., González, A., Halweg-Edwards, A.L., Fleshner, M., Raison, C.L., Rook, G.A., Peddada, S.D., Knight, R. and Lowry, C.A. (2016), “Immunization with a heat-killed preparation of the environmental bacterium Mycobacterium vaccae promotes stress resilience in mice”, *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 113 No. 22, E3130-9.
Reeve, J.R., Hoagland, L.A., Villalba, J.J., Carr, P.M., Atucha, A., Cambardella, C., Davis, D.R. and Delate, K. (2016), “Organic Farming, Soil Health, and Food Quality: Considering Possible Links”, in *Advances in Agronomy*, Vol. 137, Elsevier, pp. 319–367.
Renforth, P. and Henderson, G. (2017), “Assessing ocean alkalinity for carbon sequestration”, *Reviews of Geophysics*, Vol. 55 No. 3, pp. 636–674.

Renforth, P., Washbourne, C.-L., Taylder, J. and Manning, D.A.C. (2011), “Silicate production and availability for mineral carbonation”, *Environmental science & technology*, Vol. 45 No. 6, pp. 2035–2041.

Ribeiro, I.D.A., Volpiano, C.G., Vargas, L.K., Granada, C.E., Lisboa, B.B. and Passaglia, L.M.P. (2020), “Use of Mineral Weathering Bacteria to Enhance Nutrient Availability in Crops: A Review”, *Frontiers in Plant Science*, Vol. 11, p. 590774.

Rietz, D. and Haynes, R. (2003), “Effects of irrigation-induced salinity and sodicity on soil microbial activity”, *Soil Biology and Biochemistry*, Vol. 35 No. 6, pp. 845–854.

Rinot, O., Levy, G.J., Steinberger, Y., Svoray, T. and Eshel, G. (2019), “Soil health assessment: A critical review of current methodologies and a proposed new approach”, *The Science of the total environment*, Vol. 648, pp. 1484–1491.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A. de, Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. and Foley, J.A. (2009), “A safe operating space for humanity”, *Nature*, Vol. 461 No. 7263, pp. 472–475.

Rodale, J.I. (1945), *Pay dirt: Farming and gardening with composts*, New York, NY, USA, Devin-Adair Company.

Römheld, V. and Kirkby, E.A. (2010), “Research on potassium in agriculture: needs and prospects”, *Plant and Soil*, Vol. 335 No. 1-2, pp. 155–180.

Römheld, V. and Marschner, H. (1990), “Genotypical differences among graminaceous species in release of phytosiderophores and uptake of iron phytosiderophores”, *Plant and Soil*, Vol. 123 No. 2, pp. 147–153.

Rook, G.A.W., Raison, C.L. and Lowry, C.A. (2014), “Microbial 'old friends', immunoregulation and socioeconomic status”, *Clinical and experimental immunology*, Vol. 177 No. 1, pp. 1–12.

Roser, M., Ritchie, H. and Ortiz-Ospina, E. (2013), “World Population Growth”.

Roslund, M.I., Puhakka, R., Grönroos, M., Nurminen, N., Oikarinen, S., Gazali, A.M., Cinek, O., Kramná, L., Siter, N., Vari, H.K., Soininen, L., Parajuli, A., Rajaniemi, J., Kinnunen, T., Laitinen, O.H., Hyöty, H. and Sinkkonen, A. (2020), “Biodiversity intervention enhances immune regulation and health-associated commensal microbiota among daycare children”, *Science advances*, Vol. 6 No. 42.

Rosolem, C.A., Almeida, D.S., Rocha, K.F. and Bacco, G.H.M. (2018), “Potassium fertilisation with humic acid coated KCl in a sandy clay loam tropical soil”, *Soil Research*, Vol. 56 No. 3, p. 244.

Rosolem, C.A., Sgariboldi, T., Garcia, R.A. and Calonego, J.C. (2010), “Potassium Leaching as Affected by Soil Texture and Residual Fertilization in Tropical Soils”, *Communications in Soil Science and Plant Analysis*, Vol. 41 No. 16, pp. 1934–1943.

Ross, N., Eyles, J., Cole, D. and Iannantuono, A. (1997), “THE ECOSYSTEM HEALTH METAPHOR IN SCIENCE AND POLICY”, *Canadian Geographer / Le Géographe canadien*, Vol. 41 No. 2, pp. 114–127.

Rudmin, M., Banerjee, S. and Makarov, B. (2020), “Evaluation of the Effects of the Application of Glauconitic Fertilizer on Oat Development: A Two-Year Field-Based Investigation”, *Agronomy*, Vol. 10 No. 6, p. 872.

Rudmin, M., Banerjee, S., Makarov, B., Mazurov, A., Ruban, A., Oskina, Y., Tolkachev, O., Buyakov, A. and Shaldybin, M. (2019), “An investigation of plant growth by the addition of glauconitic fertilizer”, *Applied Clay Science*, Vol. 180, p. 105178.

Rutherford, K.M.D., Langford, F.M., Jack, M.C., Sherwood, L., Lawrence, A.B. and Haskell, M.J. (2009), “Lameness prevalence and risk factors in organic and non-organic dairy herds in the United Kingdom”, *The Veterinary Journal*, Vol. 180 No. 1, pp. 95–105.

Sajeev, E.P., Winiwarter, W. and Amon, B. (2018), “Greenhouse Gas and Ammonia Emissions from Different Stages of Liquid Manure Management Chains: Abatement Options and Emission Interactions”, *Journal of environmental quality*, Vol. 47 No. 1, pp. 30–41.

Samad, M.S., Bakken, L.R., Nadeem, S., Clough, T.J., Klein, C.A.M. de, Richards, K.G., Lanigan, G.J. and Morales, S.E. (2016), “High-Resolution Denitrification Kinetics in Pasture Soils Link N2O Emissions to pH, and Denitrification to C Mineralization”, *PloS one*, Vol. 11 No. 3, e0151713.

Sanchez, P.A. (2002), “Ecology. Soil fertility and hunger in Africa”, *Science (New York, N.Y.)*, Vol. 295 No. 5562, pp. 2019–2020.

Sanchez, P.A. (2015), “En route to plentiful food production in Africa”, *Nature plants*, Vol. 1, p. 14014.

Sanchez, P.A. (2019), *Properties and Management of Soils in the Tropics*, Cambridge University Press.

Sanchez, P.A., Palm, C.A. and Buol, S.W. (2003), “Fertility capability soil classification: a tool to help assess soil quality in the tropics”, *Geoderma*, Vol. 114 No. 3-4, pp. 157–185.

Santos, W.O., Mattiello, E.M., da Costa, L.M., Abrahão, W.A.P., Novais, R.F. de and Cantarutti, R.B. (2015), “Thermal and chemical solubilization of verdete for use as potassium fertilizer”, *International Journal of Mineral Processing*, Vol. 140, pp. 72–78.

Santos, W.O., Mattiello, E.M., Vergutz, L. and Costa, R.F. (2016), “Production and evaluation of potassium fertilizers from silicate rock”, *Journal of Plant Nutrition and Soil Science*, Vol. 179 No. 4, pp. 547–556.

Saunders, S.E., Bartz, J.C. and Bartelt-Hunt, S.L. (2012), “Soil-mediated prion transmission: is local soil-type a key determinant of prion disease incidence?”, *Chemosphere*, Vol. 87 No. 7, pp. 661–667.

Scantlebury, M., Hutchings, M.R., Allcroft, D.J. and Harris, S. (2004), “Risk of Disease from Wildlife Reservoirs: Badgers, Cattle, and Bovine Tuberculosis”, *Journal of Dairy Science*, Vol. 87 No. 2, pp. 330–339.

Scheinemann, H.A., Dittmar, K., Stöckel, F.S., Müller, H. and Krüger, M.E. (2015), “Hygienisation and nutrient conservation of sewage sludge or cattle manure by lactic acid fermentation”, *PloS one*, Vol. 10 No. 3, e0118230.

Scherr, S.J. (1999), *Soil degradation: A threat to developing-country food security by 2020?, Food, agriculture, and the environment discussion paper*, Vol. 27, Internat. Food Policy Research Inst, Washington, DC.

Schimel, J. (2012), *Writing science: How to write papers that get cited and proposals that get funded / Joshua Schimel*, Oxford University Press, Oxford.

Schlatter, D., Kinkel, L., Thomashow, L., Weller, D. and Paulitz, T. (2017), “Disease Suppressive Soils: New Insights from the Soil Microbiome”, *Phytopathology*, Vol. 107 No. 11, pp. 1284–1297.

Schlesinger, W.H. and Bernhardt, E.S. (2013), *Biogeochemistry: An analysis of global change*, 3rd ed., Academic Press, Waltham, Mass.

Schleyer, C., Lux, A., Mehring, M. and Görg, C. (2017), “Ecosystem Services as a Boundary Concept: Arguments from Social Ecology”, *Sustainability*, Vol. 9 No. 7, p. 1107.

Schneidemesser, E.v., Kutzner, R., Münster, A., Staudt, E. and Saar, D. (2016), “Landwirtschaft, Ammoniak und Luftverschmutzung”, *IASS fact sheet*, No. 1.

Schnorr, S.L. (2020), "The soil in our microbial DNA informs about environmental interfaces across host and subsistence modalities", *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, Vol. 375 No. 1812, p. 20190577.

Schreuder, J., Velkers, F.C., Bouwstra, R.J., Beerens, N., Stegeman, J.A., Boer, W.F. de, van Hooft, P., Elbers, A.R.W., Bossers, A. and Jurburg, S.D. (2020), "An observational field study of the cloacal microbiota in adult laying hens with and without access to an outdoor range", *Animal microbiome*, Vol. 2 No. 1, p. 28.

Schroder, J.L., Zhang, H., Girma, K., Raun, W.R., Penn, C.J. and Payton, M.E. (2011), "Soil Acidification from Long-Term Use of Nitrogen Fertilizers on Winter Wheat", *Soil Science Society of America Journal*, Vol. 75 No. 3, pp. 957–964.

Schuiling, R.D. and Krijgsman, P. (2006), "Enhanced Weathering. An Effective and Cheap Tool to Sequester Co2", *Climatic Change*, Vol. 74 No. 1-3, pp. 349–354.

Scovino, S.J. and Rowell, D.L. (1988), "The use of feldspars as potassium fertilizers in the savannah of Colombia", *Fertilizer Research*, No. 17, pp. 71–83.

Seaton, F.M., Barrett, G., Burden, A., Creer, S., Fitos, E., Garbutt, A., Griffiths, R.I., Henrys, P., Jones, D.L., Keenan, P., Keith, A., Lebron, I., Maskell, L., Pereira, M.G., Reinsch, S., Smart, S.M., Williams, B., Emmett, B.A. and Robinson, D.A. (2020), "Soil health cluster analysis based on national monitoring of soil indicators", *European Journal of Soil Science*, Vol. 348 No. 6235, p. 1261071.

Seifritz, W. (1990), "CO2 disposal by means of silicates", *Nature*, Vol. 345 No. 6275, p. 486.

Shade, A., Hogan, C.S., Klimowicz, A.K., Linske, M., McManus, P.S. and Handelsman, J. (2012), "Culturing captures members of the soil rare biosphere", *Environmental microbiology*, Vol. 14 No. 9, pp. 2247–2252.

Shah, G.A., Shah, G.M., Rashid, M.I., Groot, J.C.J., Traore, B. and Lantinga, E.A. (2018), "Bedding additives reduce ammonia emission and improve crop N uptake after soil application of solid cattle manure", *Journal of environmental management*, Vol. 209, pp. 195–204.

Shah, G.M., Shah, G.A., Groot, J., Oenema, O. and Lantinga, E.A. (2012), "Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland", *Agriculture, Ecosystems & Environment*, Vol. 160, pp. 59–65.

Sheldrick, W.F. and Lingard, J. (2004), "The use of nutrient audits to determine nutrient balances in Africa", *Food Policy*, Vol. 29 No. 1, pp. 61–98.

Sheldrick, W.F., Syers, J. and Lingard, J. (2003), "Soil nutrient audits for China to estimate nutrient balances and output/input relationships", *Agriculture, Ecosystems & Environment*, Vol. 94 No. 3, pp. 341–354.

Sheldrick, W.F., Syers, J.K. and Lingard, J. (2002), "A conceptual model for conducting nutrient audits at national, regional, and global scales", *Nutrient Cycling in Agroecosystems*, Vol. 62 No. 1, pp. 61–72.

Sillanpaeae, M. (1990), "Micronutrient assessment at the country level: an international study".

Silva, B., Paradelo, R., Vázquez, N., García-Rodeja, E. and Barral, M.T. (2013), "Effect of the addition of granitic powder to an acidic soil from Galicia (NW Spain) in comparison with lime", *Environmental Earth Sciences*, Vol. 68 No. 2, pp. 429–437.

Silva, D.R.G., Carlos, R.S., Giuliano, M., Danilo, d.A.S., Eduardo, L.C. and der, S.M. de (2014), "Yield, nutrient uptake and potassium use efficiency in rice fertilized with crushed rocks", *African Journal of Agricultural Research*, Vol. 9 No. 4, pp. 455–464.

Silva, V., Mol, H.G.J., Zomer, P., Tienstra, M., Ritsema, C.J. and Geissen, V. (2019), "Pesticide residues in European agricultural soils - A hidden reality unfolded", *The Science of the total environment*, Vol. 653, pp. 1532–1545.

Sinclair, A.H. and Edwards, A.C. (2008), “Micronutrient Deficiency Problems in Agricultural Crops in Europe”, in Alloway, B.J. (Ed.), *Micronutrient Deficiencies in Global Crop Production*, Springer Netherlands, Dordrecht, pp. 225–244.

Singh, B.R., McLaughlin, M.J. and Brevik, E.C. (2017), *The nexus of soils, plants, animals and human health, GeoEcology essays*.

Singh, S., Parihar, P., Singh, R., Singh, V.P. and Prasad, S.M. (2015), “Heavy Metal Tolerance in Plants: Role of Transcriptomics, Proteomics, Metabolomics, and Ionomics”, *Frontiers in Plant Science*, Vol. 6, p. 1143.

Sivertsen, T. and Bernhoft, A. (2017), *Mineral balances in animal nutrition*, pp. 99–104.

Skowron, K., Olszewska, H., Skowron, K.J., Paluszak, P. and Breza-Boruta, B. (2013), “Hygienic Aspects of Cattle Slurry Storage as the Most Popular and Cheapest Method of Handling Liquid Animal Excrements / Higieniczne aspekty składowania gnojowicy bydlęcej jako najpopularniejszej i najtańszej metody postępowania z płynnymi odchodami zwierzęcymi”, *Annals of Animal Science*, Vol. 13 No. 3, pp. 597–609.

Smith, D.G., Martinelli, R., Besra, G.S., Illarionov, P.A., Szatmari, I., Brazda, P., Allen, M.A., Xu, W., Wang, X., Nagy, L., Dowell, R.D., Rook, G.A.W., Rosa Brunet, L. and Lowry, C.A. (2019), “Identification and characterization of a novel anti-inflammatory lipid isolated from Mycobacterium vaccae, a soil-derived bacterium with immunoregulatory and stress resilience properties”, *Psychopharmacology*, Vol. 236 No. 5, pp. 1653–1670.

Smith, E.A. and Oehme, F.W. (1992), “The biological activity of glyphosate to plants and animals: a literature review”, *Veterinary and Human Toxicology*.

Smith, K., Cumby, T., Lapworth, J., Misselbrook, T. and Williams, A. (2007), “Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms”, *Biosystems Engineering*, Vol. 97 No. 4, pp. 464–471.

Smith, L.A., Marion, G., Swain, D.L., White, P.C.L. and Hutchings, M.R. (2009), “The effect of grazing management on livestock exposure to parasites via the faecal-oral route”, *Preventive veterinary medicine*, Vol. 91 No. 2-4, pp. 95–106.

Smith, P., Cotrufo, M.F., Rumpel, C., Paustian, K., Kuikman, P.J., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bustamante, M., House, J.I., Sobocká, J., Harper, R., Pan, G., West, P.C., Gerber, J.S., Clark, J.M., Adhya, T., Scholes, R.J. and Scholes, M.C. (2015), “Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils”, *SOIL*, Vol. 1 No. 2, pp. 665–685.

Smolińska, U. and Kowalska, B. (2018), “Biological control of the soil-borne fungal pathogen Sclerotinia sclerotiorum — a review”, *Journal of Plant Pathology*, Vol. 100 No. 1, pp. 1–12.

Smout, F.A., Skerratt, L.F., Butler, J.R.A., Johnson, C.N., Congdon, B.C. and Thompson, R.C.A. (2017), “The hookworm Ancylostoma ceylanicum: An emerging public health risk in Australian tropical rainforests and Indigenous communities”, *One health (Amsterdam, Netherlands)*, Vol. 3, pp. 66–69.

Snoek, H. and Wülfrath, H. (1983), *Das Buch vom Steinmehl: Entstehung, Verwendung und Bedeutung im Land- und Gartenbau*, Orac, Wien.

Soil Health Institute (2021), “National Soil Health Measurements to Accelerate Agricultural Transformation”, available at: https://soilhealthinstitute.org/national-soil-health-measurements-accelerate-agricultural-transformation/ (accessed 9 August 2021).

Sojka, R.E. and Upchurch, D.R. (1999), “Reservations Regarding the Soil Quality Concept”, *Soil Science Society of America Journal*, Vol. 63 No. 5, pp. 1039–1054.

Sojka, R.E., Upchurch, D.R. and Borlaug, N.E. (2003), “QUALITY SOIL MANAGEMENT OR SOIL QUALITY MANAGEMENT: PERFORMANCE VERSUS SEMANTICS”, *Advances in Agronomy*, Vol. 79, p. 68.

Sommer, S.G. and Husted, S. (1995), “The chemical buffer system in raw and digested animal slurry”, *The Journal of Agricultural Science*, Vol. 124 No. 1, pp. 45–53.

Sommer, S.G., Jensen, L.S., Christensen, M.L. and Schmidt, T. (2013), *Animal manure recycling: Treatment and management / edited by Sven G. Sommer, Morten L. Christensen, Thomas Schmidt, Lars S. Jensen*, Wiley, Chichester.

Sommer, S.G., Petersen, S.O. and Søgaard, H.T. (2000), “Greenhouse Gas Emission from Stored Livestock Slurry”, *Journal of Environment Quality*, Vol. 29 No. 3, pp. 744–751.

Song, Q. and Li, J. (2015), “A review on human health consequences of metals exposure to e-waste in China”, *Environmental pollution (Barking, Essex 1987)*, Vol. 196, pp. 450–461.

Sonneveld, M.P.W., Schröder, J.J., Vos, J.A. de, Monteny, G.J., Mosquera, J., Hol, J.M.G., Lantinga, E.A., Verhoeven, F.P.M. and Bouma, J. (2008), “A whole-farm strategy to reduce environmental impacts of nitrogen”, *Journal of environmental quality*, Vol. 37 No. 1, pp. 186–195.

Souza, M.E.P. de, Cardoso, I.M., Carvalho, A.M.X. de, Lopes, A.P. and Jucksch, I. (2019), “Gneiss and steatite vermicomposted with organic residues: release of nutrients and heavy metals”, *International Journal of Recycling of Organic Waste in Agriculture*, Vol. 10, p. 183.

Souza, M.E.P. de, Cardoso, I.M., Carvalho, A.M.X. de, Lopes, A.P., Jucksch, I. and Janssen, A. (2018), “Rock Powder Can Improve Vermicompost Chemical Properties and Plant Nutrition: an On-farm Experiment”, *Communications in Soil Science and Plant Analysis*, Vol. 49 No. 1, pp. 1–12.

Souza, M.E.P. de, Carvalho, A.M.X. de, Deliberali, D.C. de, Jucksch, I., Brown, G.G., Mendonça, E.S. and Cardoso, I.M. (2013), “Vermicomposting with rock powder increases plant growth”, *Applied Soil Ecology*, Vol. 69, pp. 56–60.

Sparling, G.P., B.G., O. and D. Vaughan (1981), “Microbial biomass and activity in soils amended with glucose”, *Soil Biology and Biochemistry*, Vol. 13, pp. 301–307.

Spears, J.W. (2000), “Micronutrients and immune function in cattle”, Proceedings of the Nutrition Society, 59, 587–594.

Stavi, I., Bel, G. and Zaady, E. (2016), “Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review”, *Agronomy for Sustainable Development*, Vol. 36 No. 2.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B. and Sörlin, S. (2015), “Sustainability. Planetary boundaries: guiding human development on a changing planet”, *Science (New York, N.Y.)*, Vol. 347 No. 6223, p. 1259855.

Stein, A.J. (2010), “Global impacts of human mineral malnutrition”, *Plant and Soil*, Vol. 335 No. 1-2, pp. 133–154.

Sterner, R.W., Elser, J.J. and Vitousek, P.M. (2003), *Ecological Stoichiometry*, Princeton University Press.

Stevens, A.W. (2018), “Review: The economics of soil health”, *Food Policy*, Vol. 80, pp. 1–9.

Stocker, T. (2014), *Climate change 2013: The physical science basis Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change / edited by Thomas F. Stocker, Working Group I co-chair, University of Bern [and nine others]*, Cambridge University Press, New York.

Stolte, J., Tesfai, M., Lillian Øygarden, Sigrun Kværnø, Jacob, K., Frank, V. and Panos, P. (Eds.) (2016), *Soil threats in Europe*.

Strefler, J., Amann, T., Bauer, N., Kriegler, E. and Hartmann, J. (2018), "Potential and costs of carbon dioxide removal by enhanced weathering of rocks", *Environmental Research Letters*, Vol. 13 No. 3, p. 34010.

Sturrock, C.J., Woodhall, J., Brown, M., Walker, C., Mooney, S.J. and Ray, R.V. (2015), "Effects of damping-off caused by Rhizoctonia solani anastomosis group 2-1 on roots of wheat and oil seed rape quantified using X-ray Computed Tomography and real-time PCR", *Frontiers in Plant Science*, Vol. 6, p. 461.

Summerell, B.A., Laurence, M.H., Liew, E.C.Y. and Leslie, J.F. (2010), "Biogeography and phylogeography of Fusarium: a review", *Fungal Diversity*, Vol. 44 No. 1, pp. 3–13.

Sutherland, M.A., Webster, J. and Sutherland, I. (2013), "Animal Health and Welfare Issues Facing Organic Production Systems", *Animals an open access journal from MDPI*, Vol. 3 No. 4, pp. 1021–1035.

Suttle, N.F. (2010), *Mineral nutrition of livestock*, 4th ed., CABI, Wallingford, Cambridge, Mass.

Takeda, E., Yamamoto, H., Yamanaka-Okumura, H. and Taketani, Y. (2012), "Dietary phosphorus in bone health and quality of life", *Nutrition reviews*, Vol. 70 No. 6, pp. 311–321.

Tan, Z.X., Lal, R. and Wiebe, K.D. (2005), "Global Soil Nutrient Depletion and Yield Reduction", *Journal of Sustainable Agriculture*, Vol. 26 No. 1, pp. 123–146.

Tasho, R.P. and Cho, J.Y. (2016), "Veterinary antibiotics in animal waste, its distribution in soil and uptake by plants: A review", *Science of The Total Environment*, 563-564, pp. 366–376.

Tavares, L.d.F., Carvalho, A.M.X. de, Camargo, L.G.B., Pereira, S.G.d.F. and Cardoso, I.M. (2018), "Nutrients release from powder phonolite mediated by bioweathering actions", *International Journal of Recycling of Organic Waste in Agriculture*, Vol. 7 No. 2, pp. 89–98.

Taylor, L.L., Driscoll, C.T., Groffman, P.M., Rau, G.H., Blum, J.D. and Beerling, D.J. (2021), "Increased carbon capture by a silicate-treated forested watershed affected by acid deposition", *Biogeosciences*, Vol. 18 No. 1, pp. 169–188.

tenBerge, H.F.M., van der Meer, H.G., Steenhuizen, J.W., Goedhart, P.W., Knops, P. and Verhagen, J. (2012), "Olivine Weathering in Soil, and Its Effects on Growth and Nutrient Uptake in Ryegrass (Lolium perenne L.): A Pot Experiment", *PloS one*, Vol. 7 No. 8, e42098.

Thauer, R.K., Kaster, A.-K., Seedorf, H., Buckel, W. and Hedderich, R. (2008), "Methanogenic archaea: ecologically relevant differences in energy conservation", *Nature reviews. Microbiology*, Vol. 6 No. 8, pp. 579–591.

Theodoro, S.H. and Leonardos, O.H. (2006), "The use of rocks to improve family agriculture in Brazil", *Anais da Academia Brasileira de Ciências*, No. 78, pp. 721–730.

Tilman, D., Balzer, C., Hill, J. and Befort, B.L. (2011), "Global food demand and the sustainable intensification of agriculture", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 108 No. 50, pp. 20260–20264.

Tista, M., Gager, M., Gaisbauer, S. and Ullrich, B. (2019), "European Union Emission Inventory Report 1990-2017 under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP)".

Torqueti, S.T.d.S., Boldrin, K.V.F., Nascimento, Â.M.P.d., Paiva, P.D.d.O., Furtini Neto, A.E. and Luz, I.C.A. (2016), "Alternative potassium source for the cultivation of ornamental sunflower", *Ciência e Agrotecnologia*, Vol. 40 No. 3, pp. 257–264.

Tóth, G., Gardi, C., Bódis, K., Ivits, É., Aksoy, E., Jones, A., Jeffrey, S., Petursdottir, T. and Montanarella, L. (2013), "Continental-scale assessment of provisioning soil functions in Europe", *Ecological Processes*, Vol. 2 No. 1.

Traub, R.J., Hobbs, R.P., Adams, P.J., Behnke, J.M., Harris, P.D. and Thompson, R.C.A. (2007), "A case of mistaken identity--reappraisal of the species of canid and felid hookworms (Ancylostoma) present in Australia and India", *Parasitology*, Vol. 134 No. Pt 1, pp. 113–119.
Tyrrell, C., Burgess, C.M., Brennan, F.P. and Walsh, F. (2019), "Antibiotic resistance in grass and soil", *Biochemical Society transactions*, Vol. 47 No. 1, pp. 477–486.
Uroz, S., Kelly, L.C., Turpault, M.-P., Lepleux, C. and Frey-Klett, P. (2015), "The Mineralosphere Concept: Mineralogical Control of the Distribution and Function of Mineral-associated Bacterial Communities", *Trends in microbiology*, Vol. 23 No. 12, pp. 751–762.
van Bockhaven, J., Vleesschauwer, D. de and Höfte, M. (2013), "Towards establishing broad-spectrum disease resistance in plants. Silicon leads the way", *Journal of experimental botany*, Vol. 64 No. 5, pp. 1281–1293.
van Bruggen, A.H.C., Francis, I.M. and Krag, R. (2015), "The vicious cycle of lettuce corky root disease: effects of farming system, nitrogen fertilizer and herbicide", *Plant and Soil*, Vol. 388 No. 1-2, pp. 119–132.
van Bruggen, A.H.C., Goss, E.M., Havelaar, A., van Diepeningen, A.D., Finckh, M.R. and Morris, J.G. (2019), "One Health - Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health", *The Science of the total environment*, Vol. 664, pp. 927–937.
van Bruggen, A.H.C. and Termorshuizen, A.J. (2003), "Integrated approaches to root disease management in organic farming systems", *Australasian Plant Pathology*, Vol. 32 No. 2, p. 141.
van Elsas, J.D., Chiurazzi, M., Mallon, C.A., Elhottova, D., Kristufek, V. and Salles, J.F. (2012), "Microbial diversity determines the invasion of soil by a bacterial pathogen", *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 109 No. 4, pp. 1159–1164.
van Immerseel, F., Buck, J. de, Pasmans, F., Huyghebaert, G., Haesebrouck, F. and Ducatelle, R. (2004), "Clostridium perfringens in poultry: an emerging threat for animal and public health", *Avian pathology journal of the W.V.P.A*, Vol. 33 No. 6, pp. 537–549.
van Ness, G.B. (1971), "Ecology of anthrax", *Science (New York, N.Y.)*, Vol. 172 No. 3990, pp. 1303–1307.
van Straaten, P. (2002), *Rocks for crops: Agrominerals of sub-saharan Africa*, ICRAF, Nairobi. 338 p.
van Straaten, P. (2006), "Farming with rocks and minerals: challenges and opportunities", *Anais da Academia Brasileira de Ciências*, No. 78(4), pp. 731–747.
van Straaten, P. (2007), *Agrogeology: The use of rocks for crops*, Enviroquest Ltd., Cambridge, Ontario Canada. 440 p.
van Wagenberg, C.P.A., Haas, Y. de, Hogeveen, H., van Krimpen, M.M., Meuwissen, M.P.M., van Middelaar, C.E. and Rodenburg, T.B. (2017), "Animal Board Invited Review: Comparing conventional and organic livestock production systems on different aspects of sustainability", *Animal an international journal of animal bioscience*, Vol. 11 No. 10, pp. 1839–1851.
Verbruggen, E., Struyf, E. and Vicca, S. (2021), "Can arbuscular mycorrhizal fungi speed up carbon sequestration by enhanced weathering?", *PLANTS, PEOPLE, PLANET*, Vol. 3 No. 5, pp. 445–453.
Vieira Megda, M.X., Mariano, E., Leite, J.M., Megda, M.M. and Ocheuze Trivelin, P.C. (2014), "Chloride ion as nitrification inhibitor and its biocidal potential in soils", *Soil Biology and Biochemistry*, Vol. 72, pp. 84–87.
Vieweger, A. and Döring, T.F. (2015), "Assessing health in agriculture--towards a common research framework for soils, plants, animals, humans and ecosystems", *Journal of the science of food and agriculture*, Vol. 95 No. 3, pp. 438–446.
Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L.E., Holland, E., Johnes, P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A.,

Robertson, G.P., Sanchez, P.A., Townsend, A.R. and Zhang, F.S. (2009), "Agriculture. Nutrient imbalances in agricultural development", *Science (New York, N.Y.)*, Vol. 324 No. 5934, pp. 1519–1520.

Voisin, A. (1959), *Soil, grass, and cancer*, New York, NY, USA, Philosophical.

Wagner, K., Brinkmann, J., Bergschmidt, A., Renziehausen, C. and March, S. (2021), "The effects of farming systems (organic vs. conventional) on dairy cow welfare, based on the Welfare Quality® protocol", *Animal an international journal of animal bioscience*, Vol. 15 No. 8, p. 100301.

Walker, J.C.G., Hays, P.B. and Kasting, J.F. (1981), "A negative feedback mechanism for the long-term stabilization of Earth's surface temperature", *Journal of Geophysical Research*, Vol. 86 No. C10, p. 9776.

Wall, D.H., Nielsen, U.N. and Six, J. (2015), "Soil biodiversity and human health", *Nature*, Vol. 528 No. 7580, pp. 69–76.

Wallander, H. and Wickman, T. (1999), "Biotite and microcline as potassium sources in ectomycorrhizal and non-mycorrhizal Pinus sylvestris seedlings", *Mycorrhiza*, Vol. 9 No. 1, pp. 25–32.

Walsh, E.M., Sweet, S., Knap, A., Ing, N. and Rangel, J. (2020), "Queen honey bee (Apis mellifera) pheromone and reproductive behavior are affected by pesticide exposure during development", *Behavioral ecology and sociobiology*, Vol. 74 No. 3, pp. 1–14.

Walter, W.D., Walsh, D.P., Farnsworth, M.L., Winkelman, D.L. and Miller, M.W. (2011), "Soil clay content underlies prion infection odds", *Nature communications*, Vol. 2, p. 200.

Wang, F., Fu, Y.-H., Sheng, H.-J., Topp, E., Jiang, X., Zhu, Y.-G. and Tiedje, J.M. (2021), "Antibiotic resistance in the soil ecosystem: A One Health perspective", *Current Opinion in Environmental Science & Health*, Vol. 20, p. 100230.

Wang, J.G., Zhang, F.S., Cao, Y. and Zhang, X.L. (2000), "Effect of plant types on release of mineral potassium from gneiss", *Nutrient Cycling in Agroecosystems*, No. 56, pp. 37–44.

Watson, C.A., Öborn, I., Edwards, A.C., Dahlin, A.S., Eriksson, J., Lindström, B., Linse, L., Owens, K., Topp, C. and Walker, R.L. (2012), "Using soil and plant properties and farm management practices to improve the micronutrient composition of food and feed", *Journal of Geochemical Exploration*, Vol. 121, pp. 15–24.

Webb, J., Pain, B., Bittman, S. and Morgan, J. (2010), "The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—A review", *Agriculture, Ecosystems & Environment*, Vol. 137 No. 1-2, pp. 39–46.

Weerasuriya, T.J., Pushpakumara, S. and Cooray, P.I. (1993), "Acidulated pegmatitic mica: A promising new multi-nutrient mineral fertilizer", *Fertilizer Research*, No. 34, pp. 67–77.

Wei, X., Wu, S.C., Nie, X.P., Yediler, A. and Wong, M.H. (2009), "The effects of residual tetracycline on soil enzymatic activities and plant growth", *Journal of environmental science and health. Part. B, Pesticides, food contaminants, and agricultural wastes*, Vol. 44 No. 5, pp. 461–471.

Wei, Z., Gu, Y., Friman, V.-P., Kowalchuk, G.A., Xu, Y., Shen, Q. and Jousset, A. (2019), "Initial soil microbiome composition and functioning predetermine future plant health", *Science advances*, Vol. 5 No. 9, eaaw0759.

Weil, R.R. and Brady, N.C. (2017), *The nature and properties of soils*, Fifteenth edition, global edition, Pearson Prentice Hall, Harlow, London, New York NY.

Welbaum, G.E., Sturz, A.V., Dong, Z. and Nowak, J. (2004), "Managing Soil Microorganisms to Improve Productivity of Agro-Ecosystems", *Critical Reviews in Plant Sciences*, Vol. 23 No. 2, pp. 175–193.

Weller, D.M., Raaijmakers, J.M., Gardener, B.B.M. and Thomashow, L.S. (2002), “Microbial populations responsible for specific soil suppressiveness to plant pathogens”, *Annual review of phytopathology*, Vol. 40, pp. 309–348.

Werle, R., Garcia, R.A. and Rosolem, C.A. (2008), “Lixiviação de potássio em função da textura e da disponibilidade do nutriente no solo”, *Revista Brasileira de Ciência do Solo*, Vol. 32 No. 6, pp. 2297–2305.

White, A.F. (2003), “Natural Weathering Rates of Silicate Minerals”, in *Treatise on Geochemistry*, Vol. 49, Elsevier, pp. 133–168.

White, A.F., Blum, A.E., Bullen, T.D., Vivit, D.V., Schulz, M. and Fitzpatrick, J. (1999), “The effect of temperature on experimental and natural chemical weathering rates of granitoid rocks”, *Geochimica et Cosmochimica Acta*, Vol. 63 No. 19-20, pp. 3277–3291.

White, A.F. and Brantley, S.L. (1995), *Chemical weathering rates of silicate minerals, Reviews in mineralogy, 0275-0279*, vol. 31, Mineralogical Society of America, Washington, D.C.

White, A.F. and Brantley, S.L. (2003), “The effect of time on the weathering of silicate minerals: why do weathering rates differ in the laboratory and field?”, *Chemical Geology*, Vol. 202 No. 3-4, pp. 479–506.

White, J.G. and Zasoski, R.J. (1999), “Mapping soil micronutrients”, *Field Crops Research*, Vol. 1999 No. 60, pp. 11–26.

Whitehead, D.C. (2000), *Nutrient elements in grassland. Soil-plant-animal relationships. CABI International, Wallingford. UK.*

Whitney, D.L. and Evans, B.W. (2010), “Abbreviations for names of rock-forming minerals”, *American Mineralogist*, Vol. 95 No. 1, pp. 185–187.

WHO (1958), “The First ten years of the World Health Organization.”, 538 p.

WHO (1984), “World Health Organization. Regional Office for Europe. Health promotion a discussion document on the concept and principles summary report of the Working Group on Concept and Principles of Health Promotion. Copenhagen, 9-13 July 1984. Copenhagen”.

WHO (2008), *Anthrax in humans and animals,* 4th ed., World Health Organization, Geneva, Switzerland.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W. de, Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S. and Murray, C.J.L. (2019), “Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems”, *The Lancet*, Vol. 393 No. 10170, pp. 447–492.

Willey, J.M., Sherwood, L. and Woolverton, C.J. (2017), *Prescott's microbiology*, Tenth edition, McGraw-Hill, New York NY.

Williams, H., Colombi, T. and Keller, T. (2020), “The influence of soil management on soil health: An on-farm study in southern Sweden”, *Geoderma*, Vol. 360, p. 114010.

Wilpert, K. and Lukes, M. (2003), “Ecochemical effects of phonolite rock powder, dolomite and potassium sulfate in a spruce stand on an acidified glacial loam”, *Nutrient Cycling in Agroecosystems*, p. 65.

Winiwarter, V. (2006), “Soils and Society. An environmental history of challenge and response”, *Die Bodenkultur*, Vol. 57 No. 4, pp. 231–242.

Winiwarter, V. and Blum, W.E.H. (2008), “From marl to rock powder. On the history of soil fertility management by rock materials”, *Journal of Plant Nutrition and Soil Science*, Vol. 171 No. 3, pp. 316–324.

Witter, E. and Kirchmann, H. (1989), “Peat, zeolite and basalt as adsorbents of ammoniacal nitrogen during manure decomposition”, *Plant and Soil*, Vol. 115 No. 1, pp. 43–52.

Wood, J.D., Gordon, R.J., Wagner-Riddle, C., Dunfield, K.E. and Madani, A. (2012), “Relationships between dairy slurry total solids, gas emissions, and surface crusts”, *Journal of environmental quality*, Vol. 41 No. 3, pp. 694–704.

Workneh, F. and van Bruggen, A. (1994), “Microbial density, composition, and diversity in organically and conventionally managed rhizosphere soil in relation to suppression of corky root of tomatoes”, *Applied Soil Ecology*, Vol. 1 No. 3, pp. 219–230.

Xu, Y., Li, H., Shi, R., Lv, J., Li, B., Yang, F., Zheng, X. and Xu, J. (2020), “Antibiotic resistance genes in different animal manures and their derived organic fertilizer”, *Environmental Sciences Europe*, Vol. 32 No. 1.

Xu, Y., Yang, H., Zhang, L., Su, Y., Shi, D., Xiao, H. and Tian, Y. (2016), “High-throughput sequencing technology to reveal the composition and function of cecal microbiota in Dagu chicken”, *BMC microbiology*, Vol. 16 No. 1, p. 259.

Xue, R., Wang, C., Liu, M., Zhang, D., Li, K. and Li, N. (2019), “A new method for soil health assessment based on Analytic Hierarchy Process and meta-analysis”, *The Science of the total environment*, Vol. 650 No. Pt 2, pp. 2771–2777.

Zaied, H. (1999), “Untersuchungen zum Einfluß verschiedener Zusätze auf den Rotteverlauf, die Stickstoffdynamik und die Kompostqualität bei der Kompostierung von Reststoffen aus der Legehennenhaltung.”, Forschungs- und Studienzentrum fürr Veredelungswirtschaft Weser-Ems, Vol. 344, 203., Göttingen, 1999.

Zhang, C., Feng, Y., Liu, Y.-W., Chang, H., Li, Z. and Xue, J.-M. (2017), “Uptake and translocation of organic pollutants in plants: A review”, *Journal of Integrative Agriculture*, Vol. 16 No. 8, pp. 1659–1668.

Zhang, G., Kang, J., Wang, T. and Zhu, C. (2018), “Review and outlook for agromineral research in agriculture and climate mitigation”, *Soil Research*, Vol. 56 No. 2, p. 113.

Zhou, D., Bai, Z., Zhang, H., Li, N., Bai, Z., Cheng, F., Jiang, H., Mao, C., Sun, X. and Lu, Z. (2018), “Soil is a key factor influencing gut microbiota and its effect is comparable to that exerted by diet for mice”, *F1000Research*, Vol. 7, pp. 2–16.

Zhou, D., Zhang, H., Bai, Z., Zhang, A., Bai, F., Luo, X., Hou, Y., Ding, X., Sun, B., Sun, X., Ma, N., Wang, C., Dai, X. and Lu, Z. (2016), “Exposure to soil, house dust and decaying plants increases gut microbial diversity and decreases serum immunoglobulin E levels in BALB/c mice”, *Environmental microbiology*, Vol. 18 No. 5, pp. 1326–1337.

Zhu, D., An, X.-L., Chen, Q.-L., Yang, X.-R., Christie, P., Ke, X., Wu, L.-H. and Zhu, Y.-G. (2018), “Antibiotics Disturb the Microbiome and Increase the Incidence of Resistance Genes in the Gut of a Common Soil Collembolan”, *Environmental science & technology*, Vol. 52 No. 5, pp. 3081–3090.

Zimnicki, T., Boring, T., Evenson, G., Kalcic, M., Karlen, D.L., Wilson, R.S., Zhang, Y. and Blesh, J. (2020), “On Quantifying Water Quality Benefits of Healthy Soils”, *BioScience*, Vol. 70 No. 4, pp. 343–352.

Zinsstag, J. (2015), *One Health: The Theory and Practice of Integrated Health Approaches*, CABI, Wallingford.

Zuba, S.N., Nogueira, W.C., Fernandes, L.A., Sampaio, R.A. and da Costa, C.A. (2011), “Yield and nutrition of tomato using different nutrient sources”, *Horticultura Brasileira*, Vol. 29, pp. 50–56.

6 Appendix

6.1 Appendix to chapter 2

Table 9: Effects of rock powders on yield and soil properties. Studies without statistical significance tests are excluded. Abbreviations: sig p = significant positive, sig n = significant negative, ins = insignificant, nm = not measured, bio = biological indicator, phy = physical indicator.

	Yield				pH			CEC			K			P				Ca				Mg				Na			Fe			Mn			Zn				Si			Heavy metals				Bio			Phy			Cu		
	sig p	ins	sig n	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	sig n	nm	sig p	ins	sig n	nm	sig p	ins	sig n	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	sig n	nm	sig p	ins	nm	sig p	sig n	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm
Source																																																						
(Anda et al., 2013)	1				1			1			1						1	1				1				1					1			1				1	1			1						1			1			1
(Bakken et al., 1997)	1	1			1	1				2	1	1					2				2				2			2			2			2				2			2				2			2			2			2
(Bakken et al., 2000)	1	1				2				2			2				2				2				2			2			2			2				2			2				2			2			2			2
(Barak et al., 1983)				1			1			1			1				1				1				1			1	2					1				1			1				1			1			1			1
(Basak and Biswas, 2009)	1						1			1	1						1				1				1			1	1			1			1				1						1			1			1			1
(Bolland and Baker, 2000)			1				1			1		1					1				1				1			1			1			1				1			1				1			1						1
(Campbell, 2009)		1				1			1			1			1				1				1				1			1			1			1				1					1		1				1			1
(Ciceri et al., 2019)	1				1					1	1						1	1							1			1			1			1				1			1				1			1			1			1
(Coroneos et al., 1996)	2	1				1				1	1						1				1				1			1			1			1				1			1				1			1			1			1
(Crusciol et al., 2019)	2				2					2			2				2				2	2						2			2			2				2	2						2			2			2			2
(Dahlin et al., 2015)	1	1				1				1		1			1				1				1				1			1			1			1					1				1			1			1			1
(Dalmora et al., 2020)	1	1					1			1	1			1	1						1				1			1			1			1				1			1				1			1			1			1
(Dias et al., 2018	2				1	1		1	1		1	1		1	1			1	1				2					2	1	1				2	1	1					2				2			2			2		1	
(Gunnarsen et al., 2019)		2					1			1			1				1				1	1						1			1			1				1			1				1			1			1			1
(Hanly et al., 2005)		1					1			1			1				1				1	1						1			1			1				1			1				1			1			1			1
(Hinsinger et al., 1996)	1	1					1			1	1	1					1		2				2				2				2			2				2			2				2			2			2			2
(Kahnt et al., 1986)	1		1				2			2			2				2				2				2			2			2			2				2			2				2			2	1	1				2
(Li and Dong, 2013)	1				1				1			1			1			1				1						1		1			1					1			1				1	1					1			1
(Li et al., 2020)	1						1			1			1				1	1				1						1	1			1			1						1				1	1					1			1

Table 9 continued: Soil Health matrix. Studies without statistical significance tests are excluded. Abbreviations: sig = significant, ins = insignificant, nm = not measured, bio = biological indicator, phy = physical indicator.

	Yield				pH			CEC			K			P				Ca				Mg			
	sig p	ins	sig n	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	sig n	nm	sig p	ins	sig n	nm	sig p	ins	sig n	nm
Source																									
(Anda et al., 2013)	1				1			1			1						1	1				1			
(Bakken et al., 1997)	1	1			1	1				2	1	1					2				2				2
(Bakken et al., 2000)	1	1				2				2			2				2				2				2
(Barak et al., 1983)				1			1			1			1				1				1				1
(Basak and Biswas, 2009)	1						1			1	1						1				1				1
(Bolland and Baker, 2000)			1				1			1		1					1				1				1
(Campbell, 2009)		1				1			1			1			1				1				1		
(Ciceri et al., 2019)	1				1					1	1						1	1							1
(Coroneos et al., 1996)	2	1				1				1	1						1				1				1
(Crusciol et al., 2019)	2				2					2			2				2				2	2			
(Dahlin et al., 2015)	1	1				1				1		1			1				1				1		
(Dalmora et al., 2020)	1	1					1			1	1			1	1						1				1
(Dias et al., 2018	2				1	1		1	1		1	1		1	1			1	1				2		
(Gunnarsen et al., 2019)		2					1			1			1				1				1	1			
(Hanly et al., 2005)		1					1			1			1				1				1	1			
(Hinsinger et al., 1996)	1	1					1			1	1	1					1		2				2		
(Kahnt et al., 1986)	1		1				2			2			2				2				2				2
(Li and Dong, 2013)	1				1				1			1			1			1				1			
(Li et al., 2020)	1						1			1			1				1	1				1			

	Na			Fe			Mn			Zn				Si			Heavy metals				Bio			Phy			Cu		
	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	sig n	nm	sig p	ins	nm	sig p	sig n	ins	nm	sig p	ins	nm	sig p	ins	nm	sig p	ins	nm
Source																													
(Anda et al., 2013)	1					1			1				1	1			1						1			1			1
(Bakken et al., 1997)			2			2			2				2			2				2			2			2			2
(Bakken et al., 2000)			2			2			2				2			2				2			2			2			2
(Barak et al., 1983)			1	2					1				1			1				1			1			1			1
(Basak and Biswas, 2009)			1	1			1			1				1						1			1			1			1
(Bolland and Baker, 2000)			1			1			1				1			1				1			1						1
(Campbell, 2009)		1			1			1			1				1					1	1					1			1
(Ciceri et al., 2019)			1			1			1				1			1				1			1			1			1
(Coroneos et al., 1996)			1			1			1				1			1				1			1			1			1
(Crusciol et al., 2019)			2			2			2				2	2						2			2			2			2
(Dahlin et al., 2015)		1			1			1			1					1				1			1			1			1
(Dalmora et al., 2020)			1			1			1				1			1				1			1			1			1
(Dias et al., 2018			2	1	1				2	1	1					2				2			2			2		1	
(Gunnarsen et al., 2019)			1			1			1				1			1				1			1			1			1
(Hanly et al., 2005)			1			1			1				1			1				1			1			1			1
(Hinsinger et al., 1996)		2				2			2				2			2				2			2			2			2
(Kahnt et al., 1986)			2			2			2				2			2				2			2	1	1				2
(Li and Dong, 2013)			1		1			1					1			1				1	1					1			1
(Li et al., 2020)			1	1			1			1						1				1	1					1			1

6.2 Appendix chapter 3

6.2.1 Temperature, humidity, and dew point

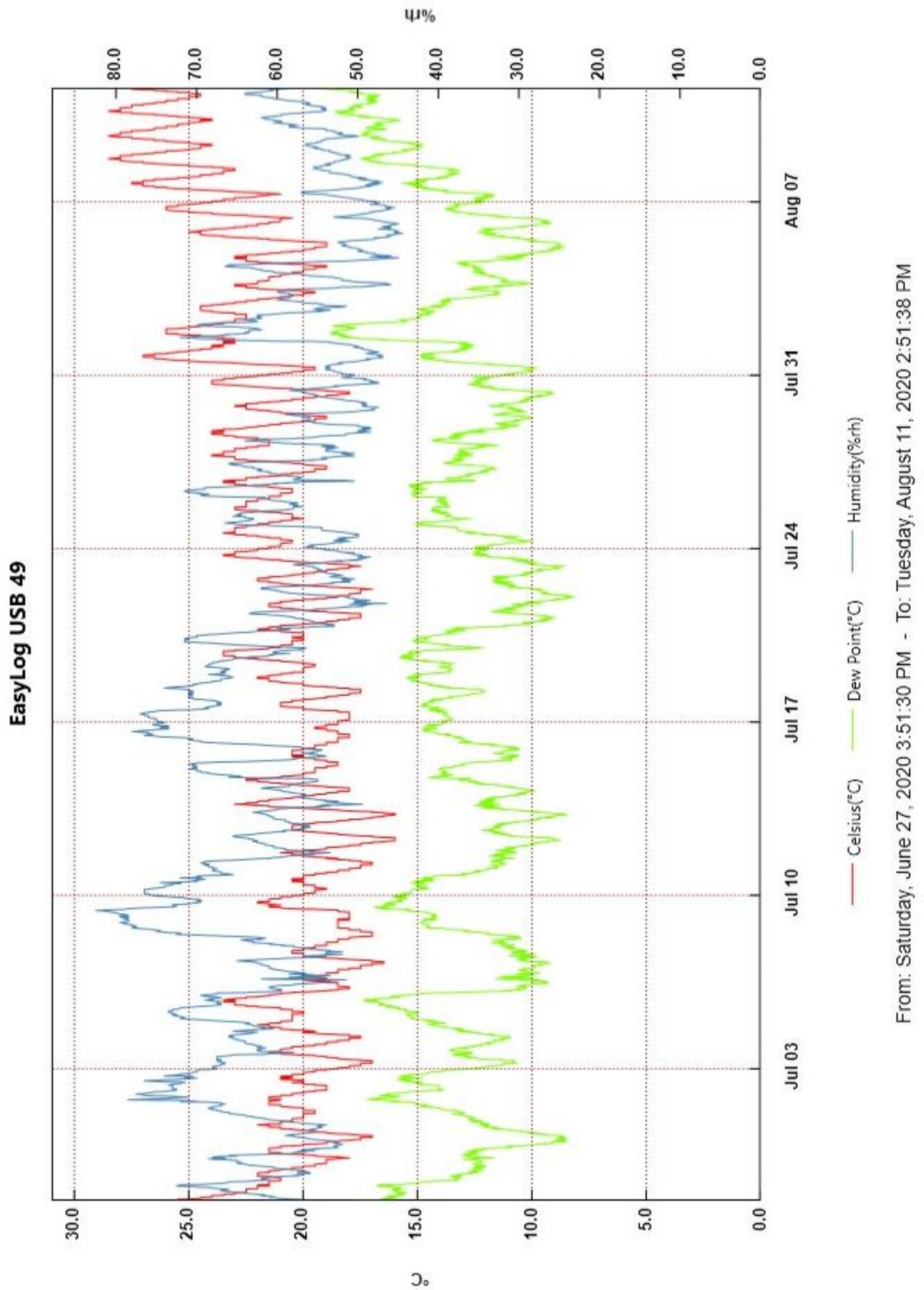


Figure 10: Temperature, Dew Point, and humidity over the 46 days of the trial.

6.2.2 Trial schedule

Table 10: Timetable of all the slurry emission measurements. “Time” denotes the starting time of the measurement of the respective slurry vessel.

27.6.2020	
Slurry Vessel	time
Biolit 1	14:01
Normal 1	14:13
Eifel 1	14:45
Eifel 2	14:57
Biolit 2	15:21
Normal 2	15:33
Biolit 3	15:45
Normal 3	16:08
Eifel 3	16:21
Eifel 4	16:45
Biolit 4	16:57
normal 4	17:09
28.6.2020	
Normal 1	13:24
Eifel 1	13:51
Biolit 1	14:03
Biolit 2	14:27
Normal 2	14:40
Eifel 2	14:51
Biolit 3	15:03
Normal 3	15:15
Eifel 3	15:27
Eifel 4	15:52
Biolit 4	16:16
Normal 4	16:28
29.6.2020	
Eifel 1	12:03
Biolit 1	12:15
Normal 1	12:27
Eifel 2	12:39
Biolit 2	13:07
Normal 2	13:19
Biolit 3	13:31
Normal 3	13:44
Eifel 3	13:58
Normal 4	14:22
Eifel 4	14:34
Biolit 4	14:59
30.6.2020	
Eifel 1	14:16
Biolit 1	14:28
Normal 1	14:40
Biolit 2	15:16
Normal 2	15:29
Eifel 2	15:41
Biolit 3	15:53
Normal 3	16:06
Eifel 3	16:17
Normal 4	16:39
Eifel 4	16:51
Biolit 4	17:03
1.7.2020	
Biolit 1	15:59
Normal 1	16:11
Eifel 1	16:23
Eifel 2	16:36
Normal 2	16:48
Biolit 2	17:01
Normal 3	17:13
Eifel 3	17:24
Biolit 3	17:36
Normal 4	17:49
Biolit 4	18:01
Eifel 4	18:13

2.7.2020	
Slurry Vessel	time
Normal 1	16:39
Eifel 1	16:52
Biolit 1	17:04
Biolit 2	17:16
Eifel 2	17:28
Normal 2	17:40
Eifel 3	17:52
Biolit 3	18:04
Normal 3	18:16
Normal 4	18:28
Biolit 4	18:40
Eifel 4	18:52
3.7.2020	
Eifel 1	13:44
Biolit 1	13:56
Normal 1	14:08
Normal 2	14:20
Eifel 2	14:32
Biolit 2	14:44
Biolit 3	14:57
Normal 3	15:09
Eifel 3	15:21
Biolit 4	15:34
Eifel 4	15:53
Normal 4	16:05
4.7.2020	
Biolit 1	14:10
Normal 1	14:22
Eifel 1	14:47
Eifel 2	14:59
Biolit 2	15:11
Normal 2	15:23
Normal 3	15:35
Eifel 3	15:47
Biolit 3	15:59
Eifel 4	16:11
Normal 4	16:23
Biolit 4	16:36
5.7.2020	
Normal 1	16:36
Eifel 1	16:48
Biolit 1	17:00
Biolit 2	17:12
Normal 2	17:24
Eifel 2	17:36
Eifel 3	17:48
Biolit 3	18:00
Normal 3	18:12
Normal 4	18:25
Biolit 4	18:36
Eifel 4	18:49
6.7.2020	
Eifel 1	15:06
Biolit 1	15:19
Normal 1	15:31
Normal 2	15:44
Eifel 2	15:57
Biolit 2	16:10
Biolit 3	16:22
Normal 3	16:34
Eifel 3	16:46
Biolit 4	16:58
Eifel 4	17:10
Normal 4	17:22

7.7.2020	
Slurry Vessel	time
Biolit 1	14:41
Normal 1	14:53
Eifel 1	15:05
Eifel 2	15:17
Normal 2	15:29
Biolit 2	15:40
Normal 3	15:52
Eifel 3	16:04
Biolit 3	16:18
Eifel 4	16:29
Normal 4	17:00
Biolit 4	16:48
9.7.2020	
Normal 1	10:28
Eifel 1	10:40
Biolit 1	10:52
Eifel 2	11:04
Biolit 2	11:16
Normal 2	11:28
Biolit 3	11:40
Eifel 3	11:52
Normal 3	12:04
Normal 4	12:16
Biolit 4	12:27
Eifel 4	12:40
11.7.2020	
Eifel 1	14:57
Biolit 1	15:10
Normal 1	15:22
Biolit 2	15:34
Normal 2	15:46
Eifel 2	15:58
Normal 3	16:10
Eifel 3	16:22
Biolit 3	16:34
Biolit 4	16:46
Eifel 4	16:58
Normal 4	17:10
13.7.2020	
Normal 1	13:15
Eifel 1	13:28
Biolit 1	13:49
Eifel 2	14:01
Biolit 2	14:14
Normal 2	14:26
Biolit 3	14:38
Normal 3	14:50
Eifel 3	15:02
Normal 4	15:14
Eifel 4	15:26
Biolit 4	15:38
15.7.2020	
Eifel 1	13:15
Biolit 1	13:28
Normal 1	13:40
Biolit 2	13:52
Normal 2	14:04
Eifel 2	14:16
Normal 3	14:28
Eifel 3	14:40
Biolit 3	14:52
Eifel 4	15:04
Biolit 4	15:16
Normal 4	15:28

17.7.2020	
Slurry Vessel	time
Biolit 1	10:33
Normal 1	10:45
Eifel 1	10:57
Normal 2	11:10
Eifel 2	11:22
Biolit 2	11:34
Eifel 3	11:46
Biolit 3	11:58
Normal 3	12:10
Biolit 4	12:22
Normal 4	12:34
Eifel 4	12:46
20.7.2020	
Normal 1	14:53
Eifel 1	15:05
Biolit 1	15:17
Eifel 2	15:29
Biolit 2	15:41
Normal 2	15:53
Normal 3	16:05
Biolit 3	16:17
Eifel 3	16:29
Normal 4	16:42
Eifel 4	16:55
Biolit 4	17:07
23.7.2020	
Biolit 4	14:12
Normal 3	14:24
Eifel 4	14:36
Normal 4	14:48
Biolit 3	15:00
Eifel 3	15:12
Eifel 2	15:25
Biolit 2	15:37
Normal 2	15:49
Eifel 1	16:01
Biolit 1	16:13
Normal 1	16:25
26.7.2020	
Normal 3	15:24
Eifel 4	15:36
Biolit 4	15:48
Biolit 3	16:03
Eifel 3	16:15
Normal 1	16:27
Biolit 2	16:39
Normal 2	16:51
Eifel 2	17:03
Biolit 1	17:15
Normal 1	17:27
Eifel 1	17:39
30.7.2020	
Eifel 4	13:53
Biolit 4	14:06
Normal 4	14:18
Eifel 3	14:30
Normal 3	14:42
Biolit 3	14:54
Normal 2	15:06
Eifel 2	15:18
Biolit 2	15:30
Normal 1	15:42
Eifel 1	15:54
Biolit 1	16:06

3.8.2020	
Slurry Vessel	time
Biolit 4	14:48
Normal 4	15:00
Eifel 4	15:12
Normal 3	15:38
Biolit 3	15:50
Eifel 3	16:07
Eifel 2	16:20
Biolit 2	16:32
Normal 2	16:44
Eifel 1	17:04
Biolit 1	17:16
Normal 1	17:28
7.8.2020	
Normal 4	14:49
Eifel 4	15:02
Biolit 4	15:14
Biolit 3	15:26
Eifel 3	15:38
Normal 3	15:50
Biolit 2	16:03
Normal 2	16:15
Eifel 2	16:28
Biolit 1	16:42
Normal 1	16:54
Eifel 1	17:06
11.8.2020	
Eifel 4	14:14
Biolit 4	14:26
Normal 4	14:38
Eifel 3	14:50
Normal 3	15:02
Biolit 3	15:17
Normal 2	15:29
Eifel 2	15:41
Biolit 2	15:53
Normal 1	16:05
Eifel 1	16:17
Biolit 1	16:29

6.2.3 Rock powder analysis

6.2.3.1 Elemental and mineralogical analysis

Table 11: Full mineralogical and elemental analysis of the two rock powders "Biolit" and "Eifelgold".

XRD: Mineral identification and quantification of sample serie 2019-582

Lab. No.	Sample name	Quartz	K feldspar	Plagioclase	Amphibole	Pyroxene	Olivin	Leucite	Illite/Muskovite	Chlorite	Iron oxides	Titanium oxides	Sum
		%	%	%	%	%	%	%	%	%	%	%	%
2019-582-001	Biolit	18,97	13,37	43,50	2,14				8,74	10,55		2,73	100,00
2019-582-002	Eifelgold		9,17	13,81		44,59	7,46	10,63	3,45		10,89		100,00

Note: Quantification was done with Rietveld method (Program Profex 3.14.0)

Sample	Name	Total sum	L.O.I.	Sum	SiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	SO3
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
2019-582-001	Biolit	101,04	5,04	96,00	57,07	14,59	8,01	0,13	3,99	3,00	3,86	2,91	1,58	0,35	0,25
2019-582-002	Eifelgold	100,25	0,58	99,67	43,37	14,36	11,22	0,18	9,06	11,06	3,16	3,38	2,77	0,51	0,21

Labornummer	Probenname	Sc	V	Cr	Mn	Co	Ni	Cu	Zn	Ga	As	Rb	Sr			
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)			
2019-582-001	Biolit	18	91	50	1059	15	20	20	83	22	7,6	55	238			
2019-582-002	Eifelgold	27	316	154	1433	46	97	52	78	16	3,1	83	765			
Labornummer	Probenname	*Y*	*Zr*	Nb	Mo	Cs	Ba	La	Ce	Nd	Sm	Hf	W	Pb	Th	U
		(ppm)	*(ppm)*	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
2019-582-001	Biolit	*47*	*604*	60	2	4	670	108	134	64	9	6	24	19	12	3,2
2019-582-002	Eifelgold	*25*	*300*	67	<NWG	<NWG	1072	169	131	51	5	4	30	17	6	6,2

6.2.3.2 Particle analysis – Biolit

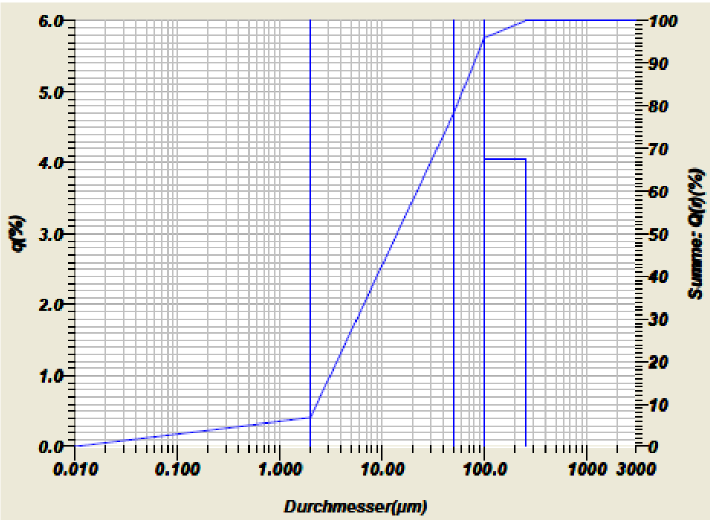
Table 12: Rock particle size distribution and grain size variation of the rock powder "Biolit".

universitätbonn Rheinische Friedrich-Wilhelms-Universität Bonn   steinmanninstitut

Universität Bonn

Sequenzname	: Geologie niedrig	2019.02.04 15:20:47
Konditionen	: Fraunhofer	
Transmission (R)	: 87.5(%)	
Transmission (B)	: 83.7(%)	
Datenbezeichnung	: MW für Probe 1	

Median	: 14.08115(µn	Q(x)-Wert	: (1)2000 (µm)- 100.000(%	x(Q)-Wert	: (1)5.000 (%)- 0.4926(µm)
Modalwert	: 12.8476(µm		: (2)1000 (µm)- 100.000(%		: (2)10.00 (%)- 2.3113(µm)
D10	: 2.31130(µm		: (3)630.0 (µm)- 100.000(%		: (3)20.00 (%)- 3.6312(µm)
D90	: 79.43922(µn		: (4)200.0 (µm)- 99.012(%		: (4)30.00 (%)- 5.7049(µm)
D(v,0.5)	: 14.08115(µn		: (5)63.00 (µm)- 84.015(%		: (5)50.00 (%)- 14.0812(µm
Schiefe	: 2.2496		: (6)20.00 (µm)- 57.767(%		: (6)60.00 (%)- 22.1225(µm
Kurtosis	: 7.8078		: (7)6.300 (µm)- 32.196(%		: (7)70.00 (%)- 34.7560(µm
Durchschnittswert	: 26.20325(µn		: (8)2.000 (µm)- 6.798(%		: (8)80.00 (%)- 53.9234(µm
Varianz	: 1293.9(µm²)		: (9)0.630 (µm)- 5.316(%		: (9)90.00 (%)- 79.4392(µm
Standardabweichung	: 35.9708(µm		: (10)0.200 (µm)- 3.844(%		: (10)95.00 (%)- 96.4192(µr
Geometr. Varianz	: 2.5964(µm²)				
Geometr. Standardabweichung	: 4.4026(µm)				
Geometr. Mittelwert	: 11.8829(µm				



Datenbezeichnung	Darstellung	Datum
MW für Probe 1 (Biolit) Fraunh.		Montag, 4. Februar 2019 15:20:47

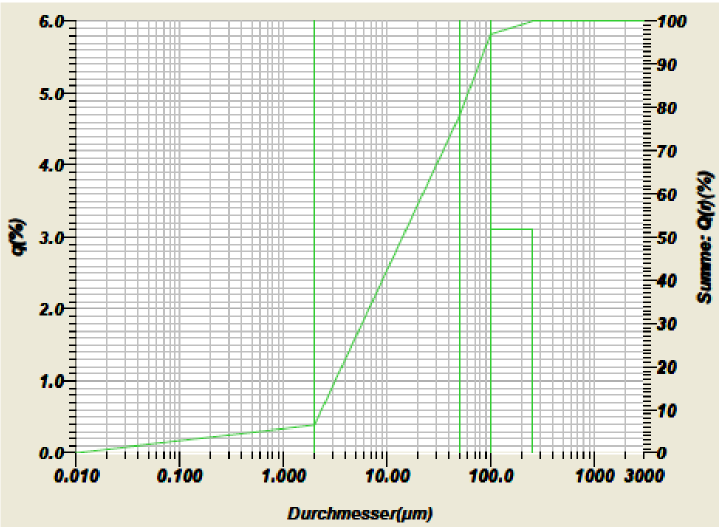
Particle analysis – Eifelgold

Table 13: Rock particle size distribution and grain size variation of the rock powder "Eifelgold".

universitätbonn Rheinische Friedrich-Wilhelms-Universität Bonn — steinmanninstitut — Universität Bonn

Sequenzname	: Geologie niedrig	2019.02.04 15:46:47
Konditionen	: Fraunhofer	
Transmission (R)	: 74.8(%)	
Transmission (B)	: 70.9(%)	
Datenbezeichnung	: MW für Probe	

Median	: 14.22653(µn	Q(x)-Wert	: (1)2000 (µm)- 100.000(%	x(Q)-Wert	: (1)5.000 (%)- 0.6309(µm)
Modalwert	: 13.2635(µm		: (2)1000 (µm)- 100.000(%		: (2)10.00 (%)- 2.3525(µm)
D10	: 2.35251(µm		: (3)630.0 (µm)- 100.000(%		: (3)20.00 (%)- 3.6891(µm)
D90	: 77.73641(µn		: (4)200.0 (µm)- 99.241(%		: (4)30.00 (%)- 5.7852(µm)
D(v,0.5)	: 14.22653(µn		: (5)63.00 (µm)- 84.255(%		: (5)50.00 (%)- 14.2265(µm
Schiefe	: 2.2235		: (6)20.00 (µm)- 57.571(%		: (6)60.00 (%)- 22.3096(µm
Kurtosis	: 7.9642		: (7)6.300 (µm)- 31.895(%		: (7)70.00 (%)- 34.9851(µm
Durchschnittswert	: 25.48770(µn		: (8)2.000 (µm)- 6.392(%		: (8)80.00 (%)- 53.9192(µm
Varianz	: 1148.2(µm²)		: (9)0.630 (µm)- 4.998(%		: (9)90.00 (%)- 77.7364(µm
Standardabweichung	: 33.8857(µm		: (10)0.200 (µm)- 3.614(%		: (10)95.00 (%)- 93.3394(µr
Geometr. Varianz	: 2.4759(µm²)				
Geometr. Standardabweichung	: 4.2412(µm)				
Geometr. Mittelwert	: 12.0253(µm				



Datenbezeichnung	Darstellung	Datum
MW für Probe 2 (Eifelgold) Fraunh.		Montag, 4. Februar 2019 15:46:47

6.2.4 Slurry

6.2.4.1 Crust formation

Figure 11: Crust formation on control slurry on day 38.

Figure 12: No crust formation on Eifelgold slurry on day 38.

6.2.4.2 Slurry physiochemical analysis before the trial

AGROLAB Agrar und Umwelt GmbH

Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum	01.07.2020
Kundennr.	10123216

PRÜFBERICHT 952371 - 816556

Auftrag	**952371**
Analysennr.	**816556 Wirtschaftsdünger**
Probeneingang	**24.06.2020**
Probenahme	**20.06.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**Gülle Ockenfels**

	Einheit	Wert i.d.TS		Einheit	Wert i.d.OS	Methode
Physikalisch-chemische Parameter						
Trockenrückstand	%			%	**7,5**	DIN EN 15934 : 2012-11
Wassergehalt	%			%	**92,5**	DIN EN 15934 : 2012-11
pH-Wert					**7**	DIN EN 12176 (S5) : 1998-06
Glühverlust (org.Substanz)	%	**75,2**		kg/cbm	**56,3**	DIN EN 15935 : 2012-11
Makronährstoffe						
Gesamtstickstoff (N)	%	**4,43**		kg/cbm	**3,32**	DIN EN 16168 : 2012-11
Ammoniumstickstoff (NH4-N)	%	**2,34**		kg/cbm	**1,75**	DIN 38406-5-2 : 1983-10
Phosphat ges. (als P2O5)	%	**1,71**		kg/cbm	**1,28**	DIN EN ISO 11885 : 2009-09
Kalium ges. (als K2O)	%	**5,25**		kg/cbm	**3,93**	DIN EN ISO 11885 : 2009-09
Magnesium ges. (als MgO)	%	**1,02**		kg/cbm	**0,77**	DIN EN ISO 11885 : 2009-09
Calcium ges. (als CaO)	%	**2,00**		kg/cbm	**1,5**	DIN EN ISO 11885 : 2009-09
Schwefel (S)	%	**0,467**		kg/cbm	**0,35**	DIN EN ISO 11885 : 2009-09
Mikronährstoffe						
Kupfer (Cu)	mg/kg	**23,8**		g/cbm	**1,78**	DIN EN ISO 11885 : 2009-09
Zink (Zn)	mg/kg	**131**		g/cbm	**9,83**	DIN EN ISO 11885 : 2009-09
Natrium (Na)	mg/kg	**1550**		g/cbm	**116**	DIN EN ISO 11885 : 2009-09
Mangan (Mn) gesamt	mg/kg	**210**		g/cbm	**16**	DIN EN ISO 11885 : 2009-09
Berechnete Werte						
C/N-Verhältnis		**9,8**				Berechnung aus Messwerten der Einzelparameter

Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz

Beginn der Prüfungen: 25.06.2020
Ende der Prüfungen: 01.07.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

Figure 13: Cattle slurry physiochemical analysis before the trial.

6.2.4.3 Slurry physiochemical analysis Control – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

AGROLAB GROUP
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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 26.08.2020
Kundennr. 10123216

PRÜFBERICHT 956841 - 817015

Auftrag	**956841**
Analysennr.	**817015 Wirtschaftsdünger**
Probeneingang	**13.08.2020**
Probenahme	**11.08.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**NORM**

	Einheit	Wert i.d.TS		Einheit	Wert i.d.OS	Methode
Physikalisch-chemische Parameter						
Trockenrückstand	%			%	**7,4**	DIN EN 15934 : 2012-11
Wassergehalt	%			%	**92,7**	DIN EN 15934 : 2012-11
pH-Wert					**7,4**	DIN EN 12176 (S5) : 1998-06
Glühverlust (org.Substanz)	%	**68,1**		kg/cbm	**50,1**	DIN EN 15935 : 2012-11
Makronährstoffe						
Gesamtstickstoff (N)	%	**2,93**		kg/cbm	**2,15**	DIN EN 16168 : 2012-11
Ammoniumstickstoff (NH4-N)	%	**0,773**		kg/cbm	**0,568**	DIN 38406-5-2 : 1983-10
Phosphat ges. (als P2O5)	%	**1,97**		kg/cbm	**1,45**	DIN EN ISO 11885 : 2009-09
Kalium ges. (als K2O)	%	**6,11**		kg/cbm	**4,49**	DIN EN ISO 11885 : 2009-09
Magnesium ges. (als MgO)	%	**1,21**		kg/cbm	**0,89**	DIN EN ISO 11885 : 2009-09
Calcium ges. (als CaO)	%	**2,35**		kg/cbm	**1,73**	DIN EN ISO 11885 : 2009-09
Schwefel (S)	%	**0,541**		kg/cbm	**0,398**	DIN EN ISO 11885 : 2009-09
Mikronährstoffe						
Kupfer (Cu)	mg/kg	**28,3**		g/cbm	**2,08**	DIN EN ISO 11885 : 2009-09
Zink (Zn)	mg/kg	**156**		g/cbm	**11,5**	DIN EN ISO 11885 : 2009-09
Natrium (Na)	mg/kg	**1990**		g/cbm	**146**	DIN EN ISO 11885 : 2009-09
Mangan (Mn) gesamt	mg/kg	**260**		g/cbm	**19**	DIN EN ISO 11885 : 2009-09
Berechnete Werte						
C/N-Verhältnis		**13,5**				Berechnung aus Messwerten der Einzelparameter

Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 19.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

Figure 14: Control cattle slurry physiochemical analysis at the end of the trial (day 46).

6.2.4.4 Slurry physiochemical analysis Biolit – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 26.08.2020
Kundennr. 10123216

PRÜFBERICHT 956841 - 817013

Auftrag **956841**
Analysennr. **817013 Wirtschaftsdünger**

Probeneingang **13.08.2020**
Probenahme **11.08.2020**
Probenehmer **Auftraggeber**
Kunden-Probenbezeichnung **BIO**

	Einheit	Wert i.d.TS		Einheit	Wert i.d.OS	Methode
Physikalisch-chemische Parameter						
Trockenrückstand	%			%	**11,8**	DIN EN 15934 : 2012-11
Wassergehalt	%			%	**88,2**	DIN EN 15934 : 2012-11
pH-Wert					**7,5**	DIN EN 12176 (S5) : 1998-06
Glühverlust (org.Substanz)	%	**40,8**		kg/cbm	**48,1**	DIN EN 15935 : 2012-11
Makronährstoffe						
Gesamtstickstoff (N)	%	**1,91**		kg/cbm	**2,25**	DIN EN 16168 : 2012-11
Ammoniumstickstoff (NH4-N)	%	**0,603**		kg/cbm	**0,712**	DIN 38406-5-2 : 1983-10
Phosphat ges. (als P2O5)	%	**1,35**		kg/cbm	**1,59**	DIN EN ISO 11885 : 2009-09
Kalium ges. (als K2O)	%	**3,87**		kg/cbm	**4,57**	DIN EN ISO 11885 : 2009-09
Magnesium ges. (als MgO)	%	**2,26**		kg/cbm	**2,67**	DIN EN ISO 11885 : 2009-09
Calcium ges. (als CaO)	%	**2,53**		kg/cbm	**2,98**	DIN EN ISO 11885 : 2009-09
Schwefel (S)	%	**0,348**		kg/cbm	**0,411**	DIN EN ISO 11885 : 2009-09
Mikronährstoffe						
Kupfer (Cu)	mg/kg	**24,5**		g/cbm	**2,89**	DIN EN ISO 11885 : 2009-09
Zink (Zn)	mg/kg	**126**		g/cbm	**14,9**	DIN EN ISO 11885 : 2009-09
Natrium (Na)	mg/kg	**1530**		g/cbm	**181**	DIN EN ISO 11885 : 2009-09
Mangan (Mn) gesamt	mg/kg	**560**		g/cbm	**66**	DIN EN ISO 11885 : 2009-09
Berechnete Werte						
C/N-Verhältnis		**12,4**				Berechnung aus Messwerten der Einzelparameter

Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 19.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

Figure 15: Biolit amended cattle slurry physiochemical analysis at the end of the trial (day 46).

6.2.4.5 Slurry physiochemical analysis Eifelgold – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 26.08.2020
Kundennr. 10123216

PRÜFBERICHT 956841 - 817014

Auftrag	**956841**
Analysennr.	**817014 Wirtschaftsdünger**
Probeneingang	**13.08.2020**
Probenahme	**11.08.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**EIFEL**

	Einheit	Wert i.d.TS		Einheit	Wert i.d.OS	Methode
Physikalisch-chemische Parameter						
Trockenrückstand	%			%	**12,2**	DIN EN 15934 : 2012-11
Wassergehalt	%			%	**87,8**	DIN EN 15934 : 2012-11
pH-Wert					**7,6**	DIN EN 12176 (S5) : 1998-06
Glühverlust (org.Substanz)	%	**39,8**		kg/cbm	**48,6**	DIN EN 15935 : 2012-11
Makronährstoffe						
Gesamtstickstoff (N)	%	**2,10**		kg/cbm	**2,56**	DIN EN 16168 : 2012-11
Ammoniumstickstoff (NH4-N)	%	**0,713**		kg/cbm	**0,87**	DIN 38406-5-2 : 1983-10
Phosphat ges. (als P2O5)	%	**1,38**		kg/cbm	**1,68**	DIN EN ISO 11885 : 2009-09
Kalium ges. (als K2O)	%	**5,02**		kg/cbm	**6,12**	DIN EN ISO 11885 : 2009-09
Magnesium ges. (als MgO)	%	**2,59**		kg/cbm	**3,16**	DIN EN ISO 11885 : 2009-09
Calcium ges. (als CaO)	%	**2,89**		kg/cbm	**3,52**	DIN EN ISO 11885 : 2009-09
Schwefel (S)	%	**0,346**		kg/cbm	**0,422**	DIN EN ISO 11885 : 2009-09
Mikronährstoffe						
Kupfer (Cu)	mg/kg	**36,3**		g/cbm	**4,43**	DIN EN ISO 11885 : 2009-09
Zink (Zn)	mg/kg	**117**		g/cbm	**14,3**	DIN EN ISO 11885 : 2009-09
Natrium (Na)	mg/kg	**7580**		g/cbm	**925**	DIN EN ISO 11885 : 2009-09
Mangan (Mn) gesamt	mg/kg	**550**		g/cbm	**67**	DIN EN ISO 11885 : 2009-09
Berechnete Werte						
C/N-Verhältnis		**11,0**				Berechnung aus Messwerten der Einzelparameter

Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 19.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

Figure 16: Eifelgold amended cattle slurry physiochemical analysis at the end of the trial (day 46).

6.2.4.6 Slurry microbiological analysis before the trial

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 06.07.2020
Kundennr. 10123216

PRÜFBERICHT 952372 - 767305

Auftrag **952372**
Analysennr. **767305 Gärprodukt**

Probeneingang **24.06.2020**
Probenahme **20.06.2020**
Probenehmer **Auftraggeber**
Kunden-Probenbezeichnung **Gülle Ockenfels**

Hygiene

	Einheit	Wert i.d.OS	Wert i.d.TS	Grenzwert		Methode
Salmonellen	in 50 g	**nicht nachgewiesen**				Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)
Aerobe Gesamtkeimzahl (37°C)	KBE/g	**6400000**				ISO 4833-1 : 2013-09(BB) u)
Fäkalcoliforme Bakterien (E.coli) (MPN)	KBE/g	**4000**				DIN EN ISO 16649-3 : 2018-01(BB) u)
Enterokokken (MPN)	KBE/g	**46000**				Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)

Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz
u) Vergabe an ein akkreditiertes Agrolab-Gruppen-Labor

Agrolab-Gruppen-Labore
Untersuchung durch
(BB) AGROLAB Standort Eching / Ammersee, Moosstrasse 6 a, 82279 Eching / Ammersee, für die zitierte Methode akkreditiert nach ISO/IEC 17025:2005, Akkreditierungsurkunde: D-PL-14289_01_00
Methoden
DIN EN ISO 16649-3 : 2018-01; ISO 4833-1 : 2013-09; Methodenbuch der BGK, Kapitel IV C : 2006-09

Nachfolgende Parameter sind grenzwertüberschreitend bzw. liegen ausserhalb des geforderten Bereichs

Analysenparameter	*Wert*	*Einheit*	
Enterokokken (MPN)	**46000**	**KBE/g**	**Höchstwert überschritten**

Beginn der Prüfungen: 25.06.2020
Ende der Prüfungen: 06.07.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

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7/6/20 1:05 PM AG Hildesheim
HRB 200557 Ust/VAT-
ID-Nr.: DE 198 696 523

Figure 17: Slurry microbiological analysis before the trial.

6.2.4.7 Slurry microbiological analysis Control – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 28.08.2020
Kundennr. 10123216

PRÜFBERICHT 956842 - 769935

Auftrag	**956842**
Analysennr.	**769935 Gärprodukt**
Probeneingang	**13.08.2020**
Probenahme	**11.08.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**NORM**

	Einheit	Wert i.d.OS	Wert i.d.TS	Vollzugshinweise zur BioAbfV	Bewertung	Methode
Hygiene						
Aerobe Gesamtkeimzahl (37°C)	KBE/g	**8600000**		<=500000000		ISO 4833-1 : 2013-09(BB) u)
Enterokokken (MPN)	KBE/g	**930**		<=5000		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)
Fäkalcoliforme Bakterien (E.coli) (MPN)	KBE/g	**<3,0**		<=5000		DIN EN ISO 16649-3 : 2018-01(BB) u)
Salmonellen	in 50 g	**nicht nachgewiesen**		nn		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)

Erläuterung: Das Zeichen "<" oder n.b. in der Spalte Ergebnis bedeutet, der betreffende Stoff ist bei nebenstehender Bestimmungsgrenze nicht quantifizierbar.
Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz
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Methoden
DIN EN ISO 16649-3 : 2018-01; ISO 4833-1 : 2013-09; Methodenbuch der BGK, Kapitel IV C : 2006-09

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 24.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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Customer Relation Manager

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AG Hildesheim
HRB 200557
Ust/VAT-ID-Nr.:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke
Dr. Carlo C. Peich

Figure 18: Control Slurry microbiological analysis after the trial.

6.2.4.8 Slurry microbiological analysis Biolit – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 28.08.2020
Kundennr. 10123216

PRÜFBERICHT 956842 - 769933

Auftrag	**956842**
Analysennr.	**769933 Gärprodukt**
Probeneingang	**13.08.2020**
Probenahme	**11.08.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**BIO**

Hygiene

	Einheit	Wert i.d.OS	Wert i.d.TS	Vollzugshinweise zur BioAbfV	Bewertung	Methode
Aerobe Gesamtkeimzahl (37°C)	KBE/g	**7000000**		<=500000000		ISO 4833-1 : 2013-09(BB) u)
Enterokokken (MPN)	KBE/g	**930**		<=5000		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)
Fäkalcoliforme Bakterien (E.coli) (MPN)	KBE/g	**<3,0**		<=5000		DIN EN ISO 16649-3 : 2018-01(BB) u)
Salmonellen	in 50 g	**nicht nachgewiesen**		nn		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)

Erläuterung: Das Zeichen "<" oder n.b. in der Spalte Ergebnis bedeutet, der betreffende Stoff ist bei nebenstehender Bestimmungsgrenze nicht quantifizierbar.
Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

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Methoden
DIN EN ISO 16649-3 : 2018-01; ISO 4833-1 : 2013-09; Methodenbuch der BGK, Kapitel IV C : 2006-09

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 27.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

AGROLAB Agrar/Umwelt Eleonore Marciniszyn, Tel. 05066/90193-61
Customer Relation Manager

DOC-7-2457204-DE-P1
AG Hildesheim HRB 200557
Ust/VAT-ID-Nr.: DE 198 696 523
Geschäftsführer Dr. Paul Wimmer

Figure 19: Biolit amended slurry microbiological analysis after the trial.

6.2.4.9 Slurry microbiological analysis Eifelgold – day 46

AGROLAB Agrar und Umwelt GmbH
Breslauer Str. 60, 31157 Sarstedt, Germany
Tel.: +49 (05066) 90193-0, Fax: +49 (05066) 90193-35
eMail: sarstedt@agrolab.de www.agrolab.de

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AGROLAB Agrar/Umwelt Breslauer Str. 60, 31157 Sarstedt

Philipp Swoboda
Reuterstr. 2a
53113 Bonn

Datum 28.08.2020
Kundennr. 10123216

PRÜFBERICHT 956842 - 769934

Auftrag	**956842**
Analysennr.	**769934 Gärprodukt**
Probeneingang	**13.08.2020**
Probenahme	**11.08.2020**
Probenehmer	**Auftraggeber**
Kunden-Probenbezeichnung	**EIFEL**

Hygiene

	Einheit	Wert i.d.OS	Wert i.d.TS	Vollzugshinweise zur BioAbfV	Bewertung	Methode
Aerobe Gesamtkeimzahl (37°C)	KBE/g	**4100000**		<=500000000		ISO 4833-1 : 2013-09(BB) u)
Enterokokken (MPN)	KBE/g	**7500**		<=5000		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)
Fäkalcoliforme Bakterien (E.coli) (MPN)	KBE/g	**<3,0**		<=5000		DIN EN ISO 16649-3 : 2018-01(BB) u)
Salmonellen	in 50 g	**nicht nachgewiesen**		nn		Methodenbuch der BGK, Kapitel IV C : 2006-09(BB) u)

Erläuterung: Das Zeichen "<" oder n.b. in der Spalte Ergebnis bedeutet, der betreffende Stoff ist bei nebenstehender Bestimmungsgrenze nicht quantifizierbar.
Die parameterspezifischen Messunsicherheiten sowie Informationen zum Berechnungsverfahren sind auf Anfrage verfügbar, sofern die berichteten Ergebnisse oberhalb der parameterspezifischen Bestimmungsgrenze liegen.

Erläuterung: Substanz: OS=Originalsubstanz, TS=Trockensubstanz
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Methoden
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Nachfolgende Parameter sind grenzwertüberschreitend bzw. liegen ausserhalb des geforderten Bereichs

Analysenparameter	*Wert*	*Einheit*	
Enterokokken (MPN)	**7500**	**KBE/g**	**Höchstwert überschritten**

Beginn der Prüfungen: 13.08.2020
Ende der Prüfungen: 24.08.2020

Die Ergebnisse beziehen sich ausschließlich auf die geprüften Gegenstände. In Fällen, wo das Prüflabor nicht für die Probenahme verantwortlich war, gelten die berichteten Ergebnisse für die Proben wie erhalten. Die auszugsweise Vervielfältigung des Berichts ohne unsere schriftliche Genehmigung ist nicht zulässig. Die Ergebnisse in diesem Prüfbericht werden gemäß der mit Ihnen schriftlich gemäß Auftragsbestätigung getroffenen Vereinbarung in vereinfachter Weise i.S. der DIN EN ISO/IEC 17025:2018, Abs. 7.8.1.3 berichtet.

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AG Hildesheim
HRB 200557
Ust/VAT-ID-Nr.:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke
Dr. Carlo C. Peich

Figure 20: Eifelgold amended slurry microbiological analysis after the trial.