UNIVERSITY
OF ICELAND

**M.S. Thesis**
**in Environment and Natural Resources**

# Restoring soils with organic soil amendments
## A case study in Geitasandur, South Iceland

**Parnika Gupta**

February 2024

**FACULTY OF LIFE AND ENVIRONMENTAL SCIENCES**
**UNIVERSITY OF ICELAND**
**2024**

# Restoring soils with organic soil amendments
## A case study in Geitasandur, South Iceland

Parnika Gupta

60 ECTS Dissertation submitted in partial fulfilment of a
*Magister Scientiarum* degree in Environment and Natural Resources

M.S. Committee
Dr. Mariana Lucia Tamayo
Dr. Magnús H. Jóhannsson
Dr. Utra Mankasingh

Master’s Examiner
Úlfur Óskarsson

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, February 2024

Restoring soils with organic soil amendments; A case study in Geitasandur, South Iceland.
Dissertation submitted in partial fulfilment of a *Magister Scientiarum (M.S.)* degree in Environment and Natural Resources

Faculty of Life and Environmental Sciences
School of Engineering and Natural Sciences
University of Iceland
Askja - Sturlugata 7
102 Reykjavík
Iceland

Telephone: +354 525 4700

Bibliographic information:
Parnika Gupta, 2024, Restoring soils with organic soil amendments; A case study in Geitasandur, South Iceland. Master’s thesis, Faculty of Life and Environmental Sciences, University of Iceland, 102 pp.

Printing: Háskólaprent
Reykjavik, Iceland, February 2024

# Abstract

Soil is a limited global resource, and it is threatened by anthropogenic activities like erosion, infertility from excessive use of chemical fertilizers and desertification that is amplified by climate change. This research analysed soils and subsequent data from a revegetation study by the Soil Conservation Service of Iceland and aimed to address the effects of various soil amendments on soil properties and vegetation cover. Four organic soil amendments including municipal waste, bokashi, chicken manure, and bonemeal were compared to two application rates of chemical fertilizers and a control. Methods involved i) analysis of soil samples for pH, soil organic matter, C/N, and available carbon; ii) vegetation surveys measuring vegetation height and vegetation cover in 2021 and 2022; and iii) a tea-bag index study to investigate decomposition rates in soil. Soil pH was significantly higher in bonemeal plots than in plots where higher dose of chemical fertilizer was applied. For 2021, grass cover and vegetation height were significantly greater in chemical fertilizer plots than the control. Two years post application (2022), vegetation cover was significantly higher for plots with chemical fertilizer, bonemeal, and chicken manure than the control. Decomposition rates did not vary among the treatments, but the litter stabilisation factor was significantly higher for chicken manure than in the control and bokashi plots. Organic soil amendments like chicken manure and bonemeal can be alternatives to chemical fertilizers. This study is an important step for reducing waste and achieving circular economy by restoring soils using locally sourced organic soil amendments.

# Útdráttur

Jarðvegur er takmörkuð auðlind sem er ógnað með margvíslegum hætti s.s. rofi, ófrjósemi vegna óhóflegrar notkunar á tilbúnum áburði og eyðimerkurmyndun tengd loftslagsbreytingum. Í rannsókninni sem hér er lýst eru skoðuð áhrif mismunandi gerða lífræns áburðar á framvindu gróðurs og jarðvegs, en hún er hluti af uppgræðslutilraunum á vegum Landgræðslunnar. Fjórar gerðir lífræns áburðar áburðar voru prófaðar: molta, bokashi molta, kjúklingaskítur og kjötmjöl og bornar saman við tvo mis-stóra skammta tilbúins áburðar og viðmið þar sem ekkert var borið á. Mælingar sem voru gerðar: i) greining á jarðvegi: mælingar á sýrustigi, kolefnisinnihaldi, C/N hlutfalli og auðleysanlegu kolefni; ii) mælingar á gróðurþekju og gróðurhæð 2021 og 2022; iii) mælingar á niðurbroti örvera með s.k. tepokaaðferð (tea bag index: TBI). Sýrustig reyndist marktækt hærra þar sem kjötmjöl var notað, en marktækt lægra þar sem tilbúnum áburði var dreift. Þekja grasa og gróðurhæð voru marktækt meiri en í viðmiði árið 2021 þar sem stærri skammtur tilbúins áburðar var notaður , en 2022 jókst þekjan þar sem notað var kjötmjöl og kjúklingaskítur og varð, ásamt tilbúna áburðinum, hærri en viðmið það árið. Örveruvirkni var svipuð í öllum meðferðum, en “stabilisation factor” var marktækt hærri þar sem notaður var kjúklingaskítur heldur en í viðmið og bokashi meðferðum. Ljóst er að kjötmjöl og kjúklingaskítur geta hæglega komið í stað tilbúins áburðar í uppgræðslu. Rannsóknir af þessu tagi skipta mjög miklu máli í þeirri viðleitni að draga úr sóun lífrænna efna í anda hringrásarhagkerfisins og nýta lífræn staðbundin áburðarefni.

*Dedication*

*This thesis is dedicated to the people closest to me, both from India and Iceland, who have shown unconditional love, kindness, and support.*

# Table of Contents

**List of Figures ........ viii**

**List of Tables ........ ix**

**List of Appendices ........ x**

**Abbreviations and Symbols ........ xi**

**Acknowledgements ........ xiii**

**1 Chapter 1 - Literature Review ........ 15**
- 1.1 Introduction ........ 15
- 1.2 Soil degradation and use of synthetic fertilizers ........ 16
- 1.3 Soil restoration through organic soil amendments ........ 18
- 1.4 Status of soils in Iceland ........ 19
- 1.5 Current research on efficacy of organic soil amendments ........ 23
- 1.6 Research gaps and challenges ........ 33

**2 Chapter 2 – Effects of soil amendments on Icelandic soil properties and vegetation growth ........ 35**
- 2.1 Introduction ........ 35
- 2.2 Methodology ........ 38
  - 2.2.1 Study site description ........ 38
  - 2.2.1.1 Study site ........ 38
  - 2.2.1.2 Experimental Design ........ 40
  - 2.2.2 Measurements ........ 43
  - 2.2.2.1 Tea-Bag Index Study (TBI) ........ 43
  - 2.2.2.2 Soil sampling and analysis ........ 45
  - 2.2.2.3 Vegetation measurements ........ 50
  - 2.2.3 Statistical Analysis ........ 51
- 2.3 Results ........ 53
  - 2.3.1 Litter decomposition and stabilisation ........ 53
  - 2.3.2 Soil properties ........ 55
  - 2.3.3 Vegetation Growth Parameters ........ 59
  - 2.3.4 Correlations between parameters for 2022 ........ 67
- 2.4 Discussion and recommendations ........ 69
  - 2.4.1 Soil properties ........ 69
  - 2.4.2 Vegetation growth parameters ........ 70
  - 2.4.3 Litter decomposition and stabilisation ........ 72
  - 2.4.4 Relation between soil properties and vegetation ........ 73
- 2.5 Conclusion ........ 74

**References ........ 75**

**Appendices ........ 95**

# List of Figures

| | | |
|---|---|---|
| Figure 1.1 | Icelandic soils and their types | 20 |
| Figure 2.1 | Study site in Geitasandur, Iceland | 39 |
| Figure 2.2 | Experimental design of the study site | 40 |
| Figure 2.3 | Bokashi treatment application in May 2022 | 41 |
| Figure 2.4 | Teabag study | 44 |
| Figure 2.5 | Soil sample collection from the study site at Geitasandur | 45 |
| Figure 2.6 | Soil sample preparation | 46 |
| Figure 2.7 | Soil organic matter measurement setup | 47 |
| Figure 2.8 | Soil pH(water) measurement setup | 48 |
| Figure 2.9 | Vegetation data sampling from the study site at Geitasandur | 50 |
| Figure 2.10 | Litter decomposition rate (k) and Stabilization factor (S) from TBI study for eight soil amendments | 54 |
| Figure 2.11 | Soil pH(water) for eight soils amendments | 58 |
| Figure 2.12 | Vegetation survey data for five soil amendments in 2021 | 61 |
| Figure 2.13 | Vegetation survey data for eight soil amendments in 2022 | 64 |
| Figure 2.14 | Vegetation survey data for five soil amendments in 2021 and 2022 | 66 |

# List of Tables

Table 1.1 Number of publications based on keyword searches via Web of Science and Google Scholar 23

Table 1.2 Summary of key findings of literature review on effects of soil amendments on Andosols 27

Table 1.3 Key findings of literature review on the effects of soil amendments on subarctic vegetation 29

Table 1.4 Key findings of publications found on the portals of GróLind, GRÓ-LRT, SCSI and Skemman, focusing on changes in Andosols and subarctic vegetation in Iceland due to the application of organic soil amendments 30

Table 2.1 Description of applied soil amendments 42

Table 2.2 Modified Braun-Blanquet cover scale and recorded vegetation parameters 50

Table 2.3 Litter decomposition rate and stabilisation factor from TBI study for eight soil amendments in 2022 53

Table 2.4 Soil properties of soil samples collected from Geitasandur study for eight soil amendments in 2022 56

Table 2.5 Soil available carbon (POXC) 57

Table 2.6 Vegetation parameters for five soil amendments in 2021 60

Table 2.7 Vegetation parameters for eight soil amendments in 2022 63

Table 2.8 Spearman correlation coefficients between soil properties and vegetation parameters for the year 2022 68

# List of Appendices

Appendix A Soil properties for eight soil amendments. 97

Appendix B Vegetation survey data for five soil amendments in 2021 98

Appendix C Vegetation survey data for eight soil amendments in 2022 99

Appendix D Vegetation survey data for five soil amendments in 2021 and 2022 100

# Abbreviations and Symbols

| | |
|---|---|
| C | Carbon |
| C/N | Carbon to Nitrogen |
| CEC | Cation Exchange capacity |
| $CO_2$ | Carbon dioxide |
| $CH_4$ | Methane |
| °C | degree Celsius |
| EC | European Commission |
| EU | European Union |
| FAO | Food and Agriculture Organization of the United Nations |
| g | gram |
| GHGs | Greenhouse gases |
| $H_2S$ | Hydrogen sulphide |
| ITPS | Intergovernmental Technical Panel on Soils |
| kg | kilogram |
| kg/ha | kilogram per hectare |
| kg N/ha | kilogram of Nitrogen per hectare |
| L | Litre |
| LOI | Loss on ignition |
| M | Mean |
| mg | milligram |
| ml | millilitre |
| mm | millimeter |
| N | Nitrogen |

| | |
|---|---|
| $NH_3$ | Ammonia |
| nm | nanometer |
| $N_2O$ | Nitrous Oxide |
| OM | Organic Matter |
| % | Percentage |
| P | Phosphorus |
| POXC | Permanganate-Oxidizable Carbon |
| S | Sulphur |
| SCSI | Soil Conservation Service of Iceland |
| SC | Soil Carbon |
| SD | Standard Deviation |
| SN | Soil Nitrogen |
| SOM | Soil Organic Matter |
| TBI | Tea-bag Index |
| $t\ ha^{-1}\ yr^{-1}$ | tonnes per hectare per year |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| USA | United States of America |
| USD or US$ | United States dollars |

# Acknowledgements

First and foremost, I would like to express my immense gratitude to my parents, Mr. B.M. Gupta and Mrs. Minakshi Gupta, who have always supported my education and without their encouragement, sacrifices, and financial support, I would not have even imagined to be able to live in Iceland and start my research journey.

I would like to express my deepest and heartfelt gratitude to my supervisors: Dr. Mariana L. Tamayo, Dr. Magnús H. Jóhannsson, and Dr. Utra Mankasingh. My few words cannot do justice to the amount of encouragement, invaluable guidance, unwavering support, endless patience, and insightful feedback I received from all three of them. They have been my guiding lanterns and have spent hours with me in the field and laboratory. I am grateful to them for sharing with me their vast scientific knowledge and expertise which has been instrumental in shaping the direction of this thesis. This thesis could not have been completed without them. I am also grateful to Dr. Magnús H. Jóhannsson for providing me with the Icelandic translation of the thesis abstract.

I am also indebted to my thesis examiner, Úlfur Óskarsson from the Icelandic Forest Service for his constructive criticism and valuable suggestions, which greatly enriched the quality of this work.

I am thankful to the Soil Conservation Service of Iceland and its staff for providing me with support required during the course of this thesis. I would like to thank Anne Bau for providing me with necessary laboratory space, and equipment for this thesis. I would like to thank Guðný Rut Guðnadóttir and Urður Einarsdóttir for their patience in teaching me how to collect vegetation survey data. I would also like to thank Bára Jónsdóttir and Hubertine Petra M Kamphuis for helping me during laboratory work at Hella. I am grateful to Therese Sundberg for providing me with delicious food and lunch conversations during my stay at Hella. My sincere appreciation extends to Jóna María Eiríksdóttir, Jón Jónsson, Pétur Gunnarsson, Margrét Óskarsdóttir, Ölvir Styrmisson, Þorsteinn Kristinsson, Magnús Þór Einarsson, Jakub Tomasz Sidor, Gústav Magnús Ásbjörnsson, Elín Fjóla Þórarinsdóttir, Elín Fríða Sigurðardóttir, Dagmar Björg Jóhannesdóttir and Hrefna Jensdóttir for making my stay at Hella comfortable. I am grateful to the Soil Conservation Service of Iceland, Keldnaholt for performing the C/N analysis for my soil samples and transporting my samples and laboratory stuff between Reykjavik and Hella.

I am indebted to Veðurstofa Íslands for providing me with weather data related to my thesis.

I would like to extend my appreciation to Julia Brenner for her invaluable guidance, willingness to share her knowledge, and for providing me the opportunity to participate in the bokashi treatment application at Geitansandur, Iceland in May 2022.

I am thankful to University of Iceland for offering the Master’s program in Environment and Natural Resources and for the outstanding efforts of the professors and faculty members at this institution. I would like to thank Bjargey Anna Guðbrandsdóttir for her guidance and continuous support. I am also grateful to Nína M. Saviolidis for her support and assistance.

I would like to extend my deepest gratitude to Prof. Brynhildur Davíðsdóttir, Prof. Þröstur Þorsteinsson, and Prof. Lára Jóhannsdóttir for their continuous encouragement, academic support, and appreciation during my master’s program. I would also like to thank my class fellows for the necessary peer support. I am indebted to Susanne Claudia Möckel and Egill Erlendsson for permitting me to use their laboratory located in University of Iceland - Askja. I am also indebted to Gylfi Snær Sigurðsson and Sigurbjörg Björnsdóttir of the Psychometric Center of the Health Science Institute, University of Iceland for providing me guidance in statistics related to my thesis.

I would then like to extend my gratitude to my bachelor’s supervisors from India, Dr. Akhilesh Arora and Dr. Manoj Soni, and my engineering mentors: Mr. Rajeev Nagpal, Ms. Sabiha Begum, Mr. Charanjit Singh Dhiman, and Mr. Kshitiz Sikka, all of whose mentorship has always been an inspiration to me and for their continuous motivation.

Lastly, I would like to acknowledge and thank my friends, family, and loved ones from Iceland, India, and Europe who provided me with encouraging words, boundless affection, and endless love: Keshav, Nidhi, Neha, my lovely nieces - Nayra & Samayra, my best friend - Vivek, Sabiha, Priya, Nagender, Nikita, Fanney, Darya, Diana, Deepali, Klara, Wies, Julita, Marina, and Hemali.

# 1 Chapter 1 - Literature Review

## 1.1 Introduction

Soil is a limited and a non-renewable resource, and healthy soils are a basic prerequisite for terrestrial life on Earth (European Commission et al., 2020). Soils meet various needs like food and energy, and ensure the provision of essential ecosystem services like biomass production, erosion control, freshwater availability, habitat (from microorganisms to mammals), and climate regulation to name a few (Pierzynski & Brajendra, 2017). Even though soils are fundamental to life on Earth, they are threatened by anthropogenic activities at an alarming rate and reaching critical limits which can have disastrous consequences for humanity (Pierzynski & Brajendra, 2017). The most severe threats to soil include soil erosion, change in soil organic carbon (SOC) and nutrient imbalance followed by “soil salinization and sodification, soil sealing and land take, loss of soil biodiversity, soil contamination, soil acidification, soil compaction and waterlogging” (Pierzynski & Brajendra, 2017). Climate change exacerbates these soil threats through increased temperatures and altered precipitation patterns, intensifying processes like erosion and degradation (IPCC, 2019). The resulting impact on soil structure and fertility poses significant challenges for sustainable land management and agriculture, further jeopardizing global food security (FAO, 2016). Integration of soil into policy formulation has been lacking in the majority of the world's regions due to various reasons such as lack of readily accessible evidence for policy action, challenges associated with privately owned natural resources, changes in soils over long-time scales, and delayed response to critical thresholds by communities and institutions (FAO & ITPS, 2015b). The global lack of legislations and policies for soil management and conservation is evident in the limited attention given to soil in international agreements (Montanarella, 2015a, 2015b; Ruppel, 2022). The intricate relationship between soil-based ecosystem services, soil functions, and soil threats is evident (Bünemann et al., 2018). For instance, soil erosion disrupts soil structure by accelerating the loss of topsoil, impairing water regulation processes, which subsequently reduces water availability for ecosystems (Brady & Weil, 2014). Similarly, loss of soil organic carbon affects soil fauna, subsequently disturbing nutrient cycling of carbon and nitrogen, and causing changes in soil’s capacity to sequester carbon and leading to unsustainable agroecosystems (Brussaard et al., 2007). The combination of soil threats, anthropogenic climate change and lack of legislation and policies for protecting soil as an essential resource, leads to further deterioration of soil functions and processes. This deterioration consequentially becomes another threat to soil-based ecosystem services creating a positive feedback loop.

## 1.2 Soil degradation and use of synthetic fertilizers

Humans are heavily dependent on soils and have been exploiting them for agricultural purposes for about 12000 years (National Geographic Society, 2023). The rapidly increasing human population, currently at eight billion (Wilmoth et al., 2023), requires a vast food supply, 95% of which comes from soil (Borrelli et al., 2020; FAO, n.d.). This has led to the excessive production and consumption of synthetic or chemical fertilizers to boost agricultural production. Since 1990, there has been approximately a 46% increase in global agricultural use of inorganic fertilizers (56% nitrogen, 24% phosphorus and 20% potassium) and in 2020, the total amounted to about 200 million tonnes (FAO, 2022c). The nitrogen-based synthetic fertilizers are manufactured by converting atmospheric nitrogen into ammonia using the methane-fed Haber Bosch process, which emits 1.5 to 1.6 tonnes of carbon dioxide ($CO_2$) equivalent for each tonne of produced ammonia ($NH_3$) and accounts for 1.2% of global anthropogenic $CO_2$ emissions (Smith et al., 2020). These nitrogen-based synthetic fertilizers added to managed soils then again contribute to greenhouse gas (GHGs) emissions in the form of nitrous oxide, $N_2O$ (FAO, 2022a, 2022b). After the addition of nitrogen based synthetic fertilizers, microbial processes (nitrification and denitrification) emit $N_2O$ directly, while leaching processes cause indirect emissions of $N_2O$. The direct $N_2O$ emissions associated with the increasing use of synthetic fertilizers have also been on the rise since 1990 (FAO, 2022a). These inorganic fertilizers, being highly soluble in water, are also transported from soils by run-off water to large water reservoirs causing eutrophication (Jwaideh et al., 2022).

Soil degradation is accelerated by extensive use of these inorganic or synthetic fertilizers in modern agricultural practice to increase crop yields in a short amount of time (Kopittke et al., 2019). Chemical fertilizers enhance crop productivity and soil fertility by altering physicochemical and biological properties of soil (Pahalvi et al., 2021; Ram et al., 2016). Their continuous use causes changes in soil organic matter (Hao et al., 2008; Li et al., 2017; Schjønning et al., 1994) which then couples with a decrease in quality of agricultural soil (Jadhao et al., 2019; Stehlíková et al., 2016). The extensive application of chemical fertilizers hardens the soil, reduces soil fertility (Castillo et al., 2022; Pilbeam et al., 2005), pollutes air, water, and soil (Ghaly & Ramakrishnan, 2015), and decreases important nutrients of soil and minerals (Chen et al., 2010), thereby resulting in environmental hazards (Rashmi et al., 2020; Savci, 2012a, 2012b). Their use alone is sufficient to weaken microbial activity in the cropping system (Hao et al., 2008; Jangid et al., 2011; Li et al., 2022). The continuous application of these chemical fertilizers can alter the pH of soil causing soil acidification (Chakraborty et al., 2011; Verde et al., 2010), stunting plant growth (Kleinschmidt & Gerdemann, 1972) and lead to the emission of greenhouse gases (Chataut et al., 2023; FAO, 2022b; Walling & Vaneeckhaute, 2020). All these factors can affect soil biodiversity by disrupting overall soil health (Pahalvi et al., 2021). The excessive use of chemical fertilizers may help achieve fast-paced crop production for economic yields in the short term. However, in the long run, chemical fertilizers degrade soils, devoid them of their organic sources and weaken their natural ability to perform functions and ecosystem-based services, consequently making them unproductive (Massah & Azadegan, 2016; Raghavendra et al., 2020). In some cases, the excessive use of synthetic fertilizers can even cause soil acidification (Qiao et al., 2018) and land deterioration (Chaudhuri et al., 2023). This can hinder long term food security at the global level, as well as global biogeochemical cycles that are responsible for maintaining global temperatures (Mirzabaev et al., 2019; Smith et al., 2019). To keep up with the increased demand for fertilizers, fertilizer production increases which further causes GHG emissions into the environment (FAO, 2022a; Ouikhalfan et al., 2022; Smith et al., 2020). The chemical fertilizers are also expensive for farmers, especially when they are imported and dependent on the international market and producers (Baffes & Koh, 2023; European Commission, n.d.-a; World Bank Group, 2023). Russia is a leading producer and exporter of potassium, nitrogen, and phosphorus fertilizers (FAO, 2022d; Gay et al., 2022; OECD/FAO, 2023) and the current situation of Russian aggression in Ukraine has highlighted how geopolitics can make the importation of fertilizers and other goods more difficult and expensive (United Nations, 2022). These costs not only include the buying prices, but also the future costs associated with food prices, slowly developing soil infertility, and machinery and practices required to heal the soil from the overuse of chemical fertilizers (European Commission et al., 2020; OECD/FAO, 2023).

Soil continues to degrade at steep rates due to anthropogenic impacts, with 33% of the Earth's soils already degraded and over 90% at a risk of degradation by 2050 (European Commission Joint Research Centre, n.d.; FAO, n.d.; FAO & ITPS, 2015c). Soil erosion, which is one of the major causes of soil degradation (FAO & ITPS, 2015c; Montanarella et al., 2016; Panagos et al., 2019), is ongoing at an average rate of 3.2 to 19.8 t $ha^{-1}$ $yr^{-1}$ for Europe alone and exceeds the rate of soil renewal (1.4 t $ha^{-1}$ $yr^{-1}$) through weathering and pedogenesis for 24% of the EU (Panagos et al., 2015; Verheijen et al., 2009). Given this, it is essential to understand soil degradation and implement effective actions towards soil conservation by treating soil as an ecosystem rather than a daily commodity. Soil is a non-renewable finite resource (FAO, 2015) and soil formation and restoration take much longer than its usage and degradation (Ferreira et al., 2022; Nearing et al., 2017; Panagos et al., 2019; Panagos et al., 2015). According to FAO (n.d.), it takes about 1000 years to produce just 2-3 cm of soil and this can vary with the type and state of soil (Brady & Weil, 2014). This highlights the importance of scientifically examining various factors that are involved in soil formation as well as restoration in order to deal with the problems facing this limited resource. This is especially necessary for relatively young soils, such as Icelandic Andosols and Vitrosols, which are prone to degradation due to a positive feedback loop caused by human activities, evolving soil composition, and extreme weather conditions (Arnalds, 2004, 2015; Crofts, 2011).

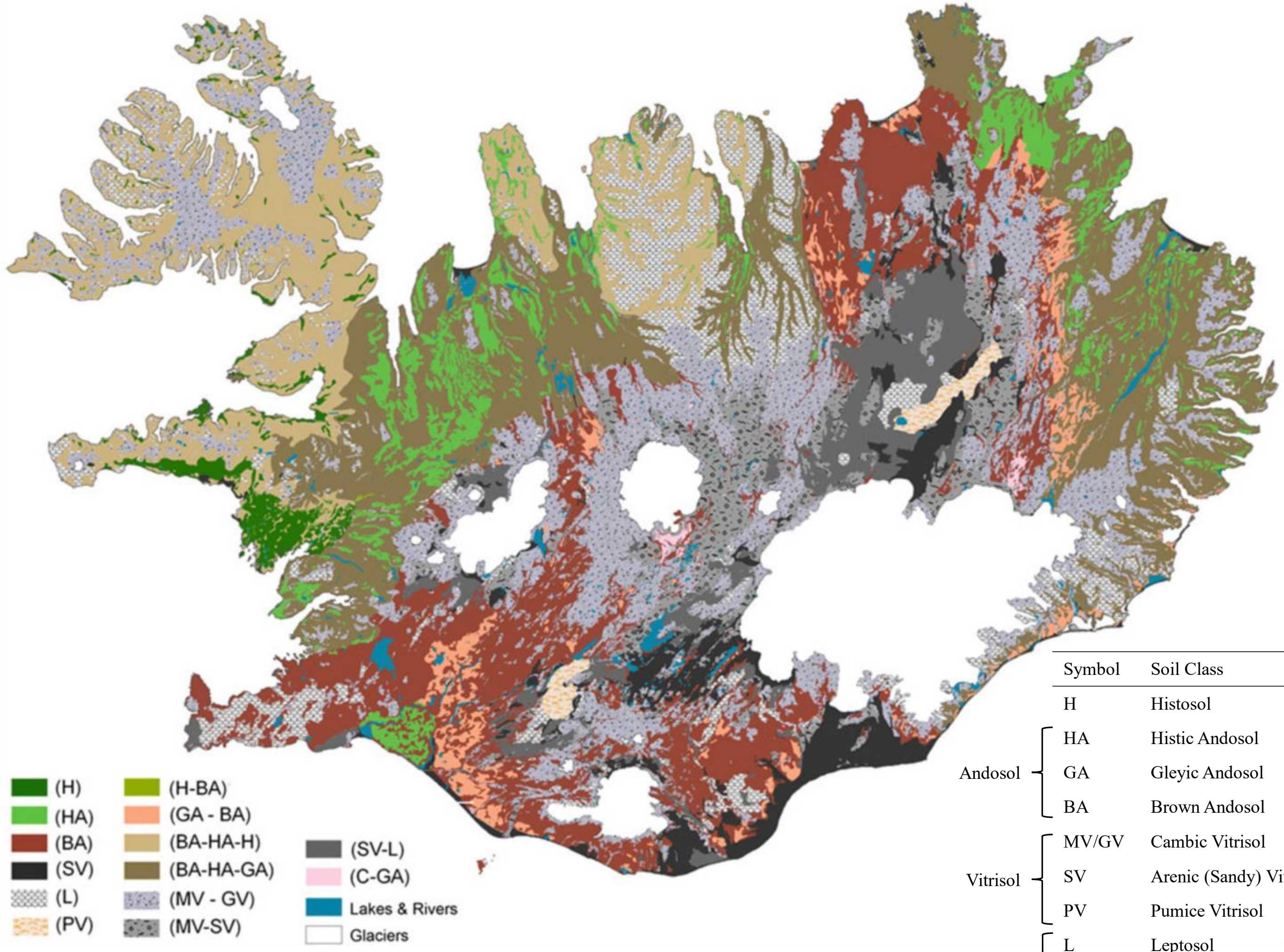
## 1.3 Soil restoration through organic soil amendments

The use of organic soil amendments as an alternative to chemical fertilizers has been gaining popularity, due to their potential capacity of assisting soil functions and processes alongside providing required nutrients for plant growth (Diacono & Montemurro, 2011; Guerrero et al., 2001; Hueso-González et al., 2018). The European Union Soil Strategy for 2030 also mentions the use of sustainable soil management practices to cut down fertilizer costs and environmental stresses caused by overuse of synthetic fertilizers (European Commission Directorate-General for Environment, 2021a, 2021b). Organic soil amendments assist the soil formation process and provide soil with long term restoration ability (Diacono & Montemurro, 2011). Other environmental benefits include improved soil quality, reduced GHG emissions and environmental pollution, enhanced nutrient cycling, increased carbon sequestration, and mitigation of climate change in the long-term (Aytenew & Bore, 2020; Diacono & Montemurro, 2011; Gravuer et al., 2019; Hueso-González et al., 2018; Scotti et al., 2013). The use of waste as a form of an organic soil amendment has the potential to reduce the problem of landfills and associated GHG emissions and promote circular economy (Arias et al., 2022; European Commission, n.d.-b). In addition, organic soil amendments can decrease the use of synthetic fertilizers, increase food quality (Hornick, 1992; Li et al., 2022), and promote waste reuse (Beesigamukama et al., 2023; Golueke & Diaz, 1996; Jones & Healey, 2010). In the long-term, they can also reduce the costs associated with imported fertilizers, waste management and soil restoration efforts by promoting the use of locally sourced soil amendments, both for agricultural production as well as soil restoration, such as compost made from municipal waste or household food waste, sewage sludge, poultry manure, bone meal and seaweed/kelp compost (Brady & Weil, 2014; Gómez-Sagasti et al., 2018; Mekuria et al., 2013). The European Commission’s first action plan to achieve circular economy also stresses the importance of using organic and waste-based fertilizers to facilitate circulation of recycled nutrients (European Commission, 2015). Organic soil amendments also have possible drawbacks and challenges such as bulkiness, low and irregular nutrient content, high C/N ratios (Möller & Schultheiß, 2015; NRCC, 1983; Quynh & Kazuto, 2018; Silva, 2018), high costs of transportation and application (Kuppusamy et al., 2016; Mekuria et al., 2013; Šarauskis et al., 2021; Wang et al., 2018), threats to human and animal health due to risk of pathogens (Azevedo & Stout, 1974; Crane et al., 1983; Goss et al., 2013) and harmful gas emissions like $H_2S$, $NH_3$, $CO_2$, and $CH_4$ (Goss et al., 2013; Kirkhorn & Garry, 2000; Zhang et al., 2010), lack of quality control causing eutrophication and ground water contamination (Azevedo & Stout, 1974; Goss et al., 2013; Janzen et al., 1974). Due to the aforementioned disadvantages, these soil amendments need to be scientifically tested to assess and optimise their use for agricultural and land restoration purposes.

## 1.4 Status of soils in Iceland

“The parent materials of all Icelandic soils are volcanic in origin” (Arnalds, 2004), with a mixture of tephra layers and aeolian sediments consisting mostly of volcanic glass (Arnalds, 2004). Icelandic soils are unique as they are relatively young, receive large amounts of aeolian inputs, are of basaltic origin, occur in low temperatures with a wide range of precipitation, and their surface has little vegetation cover, some with a desert like appearance (Arnalds, 2004, 2015). Icelandic soils are mainly categorised as Histosols, Andosols, Vitrisols, and other soils (e.g. Leptosols, Cryosols, and Calcisols) as shown in *Figure 1.1* (Arnalds, 2004, 2015). Andosols, covering over 50% of Icelandic soils, are further classified as Histic, Gleyic, and Brown Andosols based on the amount of steady aeolian input and drainage category (Arnalds, 2004, 2015). Vitrisols, constituting about 30% of Icelandic soils, are subdivided into four classes as Cambic, Gravelly, Arenic and Pumice Vitrisols (Arnalds, 2004, 2015). Histosols have the highest carbon content (>20%) and water holding capacity with acidic pH (4 to 5.5). Vitrisols have very low carbon content (<1.5%), low water holding capacity and alkaline pH (7-7.9), while Andosols lie between Histosols and Vitrisols in terms of carbon content, water holding capacity, and pH range (Arnalds, 2015).

Icelandic soils tend to retain high amounts of phosphorus (> 90% for Andosols and 25-80% for Vitrisols) reflecting the presence of allophane in these soils (Arnalds, 2004). Andosols also have a tendency to accumulate organic matter through formation of allophane-organic matter complexes and metal humus complexes and can even store more carbon reserves per unit area in comparison to other dryland soils (Arnalds, 2015). As the basaltic material weathers, it releases calcium and tends to react with atmospheric $CO_2$ to form bicarbonate and $CaCO_3$ which can precipitate both in the oceans and rocks (Arnalds, 2015). This highlights how land degradation, caused by overexploitation of these volcanic soils, leads to the reduction of carbon levels in Icelandic soils, and causes the release of $CO_2$ into the atmosphere (Arnalds, 2015). Therefore, rapid carbon sequestration can be achieved by restoring these degraded areas in volcanic regions (Arnalds, 2015). At a global scale, Andosols have double the rate of soil organic carbon sequestration compared to other soils, indicating the great potential of carbon sequestration in Iceland (Crofts, 2011).



| | Symbol | Soil Class | Identification | $pH(H_2O)$ |
|---|---|---|---|---|
| | H | Histosol | > 20% C | 4-5.5 |
| Andosol | HA | Histic Andosol | 12-20 % C | 4.5-5.5 |
| | GA | Gleyic Andosol | < 12% C ; gleiing/mottles | 4.5-7.2 |
| | BA | Brown Andosol | < 12 % C, dry ; >6 % allophane | 5.5-7.5 |
| Vitrisol | MV/GV | Cambic Vitrisol | < 1.5 % C ; <6 % allophane | |
| | SV | Arenic (Sandy) Vitrisol | Sand, <1.5 % C | 7-7.9 |
| | PV | Pumice Vitrisol | Pumice >2 mm | |
| Other soils | L | Leptosol | Rock/scree | n/a |
| | C | Cryosol | Permafrost | n/a |

*n/a: data not available*

*Figure 1.1 Icelandic soils and their types. Map taken from Arnalds (2015) and $pH(H_2O)$ data for soil classes taken from Arnalds (2004)*

## ***Soil degradation in Iceland***

Iceland is well-known today for its vast barren landscape, but the iconic scenery is a relatively recent development as it is believed to have been covered with lush vegetation and woodlands before the first Norse settlers arrived in the late ninth century (Jónsson, 2004). The country used to be vegetated at the time of settlement (~900 AD), with forest and shrublands covering up to 25% of Iceland (Arnalds, 2015; Crofts, 2011). Forest cover was reduced to <1% by 1950 and is now about 1.9%, increasing the cover of barren land (Crofts, 2011; Eysteinsson, 2017). This has been linked to intensive human utilization of the land following the settlement. The overexploitation of land caused by human activities such as deforestation and overgrazing, especially during colonisation of Iceland disrupted the pre-existing delicate balance between harsh growing conditions, sensitive vegetation, and slow soil formation (Crofts, 2011). These human activities provided ideal conditions for wind and soil erosion, leading to the desertification of Icelandic soils (Crofts, 2011). In general, this desertification occurred in six phases. Firstly, the extensive cover of birch, forbs, grasses, and willows was replaced by heathland. Then grazing and vegetation removal caused development of erosion spots and patches, followed by the appearance of erosion fronts and escarpments, and islands of original vegetation and soil as erosion escarpment (Icelandic term: rofabarð). The vegetation and soil then increasingly began to disappear. The end point was a true desert surface of bare glacial till or sand, with poor water retention capacity, low nutrient status, no organic matter, and no seed sources (Aradóttir, 2003; Arnalds et al., 2001; Crofts, 2011). About 1.6 billion tonnes of $CO_2$ have been lost owing to three million hectares of soil and vegetation loss (Crofts, 2011). Other than the 13th century, loss of vegetation and soil erosion were greatest in the 19th century (Crofts, 2011). Based on the recent findings of the GróLind project, there is severe erosion in 37% of Iceland and 29% of the country's grazing areas (Marteinsdóttir & Stefánsson, 2020).

## ***Soil restoration efforts in Iceland***

The history of reclamation activities in Iceland dates to the early 20th century. In 1907, the first legislation on land reclamation and soil conservation was introduced as "*a Bill on forestation, soil reclamation and defences against desertification*" (Crofts, 2011). To begin with, the focus was mainly on forestation based on the "*Act on Forestry and Mitigation of Soil Erosion of 1907*" (Runólfsson, 1987). Laws that were passed in 1914 (Act on Land Reclamation) and 1923 established the foundation of what later became the Soil Conservation Service (Runólfsson, 1987; Runólfsson & Arnalds, 2004).

Fertilizers were first used for increasing vegetation cover during the 1950s, with further testing and trials performed at Gunnarsholt (Crofts, 2011). The process of spreading fertilizer and seeds over challenging terrain for land reclamation was done for many years using aircrafts, and heavy equipment such as tractors on land (Arnalds et al., 1987; Crofts, 2011; Runólfsson, 1987). The effect of fertilization on vegetation cover varied based on the type of soils, but there was no general consensus on the level and mix of fertilizers (Crofts, 2011). The research took a wider approach in 1990s and had the goal to foster soil formation and vegetation succession and included activities such as investigating soil fauna, assessing carbon sequestration potential on land reclamation sites, mapping soil erosion in Iceland, establishing a geographical information system, and cooperative approaches like training programmes in restoration (Crofts, 2011). In recent years, one of the most ambitious soil reclamation projects in Iceland is the Mt. Hekla afforestation project, which began in 2007 (Aradóttir et al., 2013; Hekluskógar, 2015; Óskarsson et al., n.d.). The 900 square km area had historically been forested with birch and willow, but over time the soil succumbed to severe soil erosion and desertification due to a combination of volcanic activity and human induced disturbances. The goal of the project was to create a stable ecosystem that could withstand the inevitable volcanic eruptions from Mt. Hekla, using methods such as fertilisers and grasses to stabilise the volcanic surface layer of the soil. The project has been a success and large areas have now been transformed from desert landscapes to grassy fields and young birchwood forests (Óskarsson et al., n.d.). This supports the possibility that introducing nutrient rich soil amendments to the Icelandic Andosols may prove effective for restoration.

## 1.5 Current research on efficacy of organic soil amendments

This section synthesizes current literature and research related to the efficacy of organic soil amendments and their effects on soil properties, especially those of Andosols, and subarctic vegetation growth. This is helpful in finding trends and to identify gaps, challenges, and future research priorities for implementing soil restoration activities using organic soil amendments, highlighting current research involving degraded Andosols in subarctic regions. Various combinations of search strings such as organic soil amendments, soil properties, Andosols, subarctic vegetation, synthetic fertilizers, and types of organic soil amendments were used to find relevant literature since 1970. *Table **1.1*** shows the number of publications found via Google Scholar and Web of Science using different string combinations. Due to the high number of publications on Google Scholar, the Web of Science was used primarily to find relevant literature related to the effects of organic soil amendments on soil properties and vegetation growth for Andosols and subarctic vegetation. In addition, publications were also used from GróLind (n.d.), GRÓ LRT (n.d.), SCSI (n.d.-b) and Skemman (n.d.) for research focussed on Iceland.

*Table 1.1 Number of publications based on keyword searches via Web of Science and Google Scholar.*

| **Keywords used** | **Number of Publications** | |
|---|---|---|
| | Web of Science | Google Scholar |
| organic soil amendments + Andosols | 12 | 10700 |
| organic soil amendments + subarctic vegetation | 7 | 12600 |
| organic soil amendments + soil properties + Andosols | 5 | 9610 |
| organic soil amendments + vegetation + Andosols | 0 | 10400 |
| poultry waste + soil properties + Andosols | 1 | 1740 |
| synthetic fertilizers + soil properties + Andosols | 1 | 9520 |
| bokashi + soil properties + Andosols | 0 | 78 |
| bonemeal + soil properties + Andosols | 0 | 78 |
| chicken manure + soil properties + Andosols | 0 | 1920 |
| bokashi + vegetation + Andosols | 0 | 218 |
| bonemeal + vegetation + Andosols | 0 | 84 |
| chicken manure + vegetation + Andosols | 0 | 2070 |
| poultry waste + vegetation + Andosols | 0 | 1830 |

## ***Organic soil amendments, Andosols, and subarctic vegetation***

Overall, 14 publications that were relevant or partially relevant to the effects of organic amendments on Andosols were found on the Web of Science using the search strings ‘organic soil amendments’ and ‘Andosols’ OR ‘organic soil amendments’, ‘soil properties’ and ‘Andosols’ OR ‘soil amendments’, ‘soil properties’, and ‘Andosols’ OR ‘fertilizers’, ‘soil properties’, and ‘volcanic soil’ (*Table 1.2*). Organic amendments seem to show promising results related to changes in soil properties of Andosols, such as increasing soil pH due to liming and heat treatment (Verde et al., 2010). They can also decrease soil pH due to acidic nature of some amendments (Hirzel et al., 2018; Krause et al., 2016; Verde et al., 2010). For example, Krause et al. (2016) and Hirzel et al. (2018) found that addition of compost caused an increase in soil pH, while chemical fertilizer application was responsible for a steady decrease in soil pH. Verde et al. (2010) also observed a similar decrease in soil pH due to addition of chemical fertilizer, but an increase in soil pH due to liming and heat treatment. Furthermore, organic amendments can stabilise soil organic carbon (Reid & Naeth, 2005b) through microbial processing of substrates causing an increase in mineral-associated surfaces and microbial biomass (Wilhelm et al., 2022). They can increase carbon mineralization through liming and phosphate application (Matsuoka-Uno et al., 2022), and also increase soil carbon sequestration with biochar application (Koga et al., 2017). In contrast, Castillo et al. (2022) found a decrease in soil organic carbon and microbial biomass carbon by more than 50% over 20 years of peanut monoculture in comparison to one year cultivation, while Oshima et al. (2015) and Verde et al. (2010) saw a decrease in total carbon due to heating. Organic amendments can reduce metal contamination (Gorbacheva et al., 2009; Hagner et al., 2021; Verde et al., 2010), sequester chlordecone an organochlorine insecticide (Clostre et al., 2014), and increase disease suppression in subsoil (Oshima et al., 2015). They can increase levels of phosphorus and are effective in mitigating phosphorus deficiency (Hirzel et al., 2018; Krause et al., 2016; Takahashi, 2014; Wickramatilake et al., 2010). Moreover, organic amendments can increase pools of nitrogen and carbon (Liu et al., 2020; Matsuoka-Uno et al., 2022), and nutrient uptake (Krause et al., 2016; Reid & Naeth, 2005a, 2005b; Wickramatilake et al., 2010). For example, Wickramatilake et al. (2010) found that phosphorus uptake increased by the addition of compost, poultry manure and rock phosphate. Takahashi (2014) observed that organic phosphorus remained the same for soils with or without compost, while the inorganic phosphorus increased significantly after 22 years of compost application. Organic amendments such as biochar can also increase soil porosity (Koga et al., 2017). Treatments such as liming, phosphorus addition, horse manure, and sewage sludge can increase the soil’s cation exchange capacity (Anda & Dahlgren, 2020; Guadalix & Pardo, 1994; Reid & Naeth, 2005b). Several studies highlight how high temperature and chemical fertilization can decrease soil carbon, soil CEC, soil pH, and increase soil salinity (Hirzel et al., 2018; Oshima et al., 2015; Verde et al., 2010). Compost, as an organic amendment, showed potential for mitigating soil acidification and phosphorus deficiency (Krause et al., 2016) but it was also associated with higher methane emissions especially in paddy fields (Kajiura et al., 2018). Organic amendments, such as liming materials and biochar, offer great potential for soil carbon sequestration in Andosols and serve as a powerful strategy for mitigating global warming (Koga et al., 2017; Verde et al., 2010).

Seven publications on the effects of organic amendments on subarctic vegetation were found using the search strings ‘organic soil amendments’ and ‘subarctic vegetation’ (*Table 1.3*).

Organic amendments, such as compost, peat moss, and sewage sludge, seem to be promising towards increasing plant growth and crop yields (Hagner et al., 2021; Krause et al., 2016; Reid & Naeth, 2005b) while making the ecosystem resilient to changes with nutrient addition (Liu et al., 2020) in the long term. Organic amendments, like sewage sludge, peat moss, and papermill sludge, showed an increase in nutrient availability (Reid & Naeth, 2005b). Amendments that added direct phosphorus and nitrogen also seemed to increase carbon and nitrogen pools while enhancing plant growth in the long-term (Liu et al., 2020). Hagner et al. (2021) found that biochar application not only facilitates grass succession and higher plant biomass, but it also decreases the accumulation of metals in plant tissues. One study found that even though lake sediments show promising plant growth initially, this growth decreases after two seasons and is  negatively affected at higher application rates (Reid & Naeth, 2005a, 2005b). Giesler et al. (2012) stress that although the prominent view is that northern ecosystems are limited by nitrogen, another co-limiting nutrient in subarctic tundra is phosphorus. Moreover, Reid and Naeth (2005a) state the need to address both structural and nutrient limitation to favour plant growth. Organic amendments such as biochar, sewage sludge, and peat moss seem to be effective substitutions for chemical fertilizers to increase plant growth.

Additionally, 17 publications were found from GróLind (n.d.), GRÓ LRT (n.d.), SCSI (n.d.-b) and Skemman (n.d.), which focussed on changes in Andosols and subarctic vegetation in Iceland due to the application of organic amendments (*Table 1.4*). Overall, organic soil amendments had positive impacts on soil properties and vegetation growth. For example, Asare (2019) observed an increase in soil organic matter due to application of bonemeal. The total soil nitrogen increased by presence of tea-leaved willows (*Salix phylicifolia*) (Balikoowa, 2014) and purple beach pea (*Lathyrus japonicus*) (Battogtokh, 2018). Tjilumbu (2012) mentions the reclamation of eroded areas as a potential strategy to increase soil carbon, nitrogen, and plant biomass over decades and highlights the influence of vegetation in accumulation of aeolian material and soil development. Soumana (2013) emphasizes the increase in soil carbon and nitrogen when soil pH decreases with restoration age. Treatments such as bio-slurry (Berihu, 2021), composted municipal waste (Mdolo, 2016), and tea-leaved willows (Balikoowa, 2014) show increase in soil phosphorus. Nootka lupine (*Lupinus nootkatensis*) also mobilizes phosphorus in Icelandic Andosols increasing available phosphorus for plants and seems as a potential cost-effective method for phosphorus mobilization (Nakanyala, 2012), but care is needed as this plant is an invasive species in Iceland (Magnusson, 2010). Guðmundsson et al. (2014) observed that any fertilizer surplus phosphorus in soil increases only in top 5cm of soil even if the phosphorus application rate increases and most of it is inorganically bound. Poulsen (2011) investigated the negative effect of fluoride pollution in soil on its health and fertility and observed the toxicity of high fluoride concentration on soil microbial communities and phosphatase activity. Chemical fertilizer increased vegetation cover and vegetation height (Brenner, 2016), but they were also responsible for increased $CO_2$ efflux and had little effect on tree growth (Jónsson & Sigurðsson, 2010). Research on sunflower seed cake as an organic amendment showed potential for replacing inorganic fertilizers to increase maize production (Mbewe, 2015). However, some studies did not find any significant changes in soil properties and vegetation cover due to addition of organic amendments such as bonemeal, sewage sludge, and chicken manure (Asare, 2019; Brenner, 2016). Organic soil amendments such as bonemeal, sewage sludge, sunflower seed cakes, chicken manure, and tree thinning residues have future potential for increasing soil organic carbon stocks (Asare, 2019; Áskelsdóttir, 2012) and improving soil health by increasing nutrient input during the soil formation phase (Möckel, 2016; Tjilumbu, 2012). Land management practices including natural regeneration (Teferi, 2011), regenerative agriculture (Hill, 2023), and presence of plants like purple beach pea (Battogtokh, 2018) and tea-leaved willows (Balikoowa, 2014) also acted as a low-cost alternative to synthetic fertilizers for vegetation growth and soil health improvement, benefiting long term land restoration of severely degraded soils (Balikoowa, 2014; Teferi, 2011).

*Table 1.2 Summary of key findings of literature review on effects of soil amendments on Andosols. Search strings such as "organic soil amendments", "Andosols", "soil properties", "fertilizers", and/or "volcanic soil" were used on the Web of Science to find articles. Relevant articles mentioned the effects of soil amendments on Andosols, while partially relevant articles mentioned effects of amendments on any type of soil.*

| S. No. | Publication | Relevance | Result Summary |
|---|---|---|---|
| 1 | Krause et al. (2016) | Relevant | - CaSa compost (containing sanitized human excreta and biochar) most effective in mitigation of soil acidification and phosphorus deficiency<br>- Biogas slurry, standard compost, and CaSa compost enhanced crop productivity and viable substitutes of synthetic fertilizers |
| 2 | Clostre et al. (2014) | Partially relevant | - Compost provides a substitute method to phytoextraction or microbial degradation of chlordecone (organochlorine insecticide and popular soil pollutant)<br>- Compost lowered transfer of chlordecone in radish and cucumber at field scales |
| 3 | Kajiura et al. (2018) | Partially relevant | - Andosols had lowest $CH_4$ emissions among all soil types compared<br>- Manure, Compost, and straw incorporation increased $CH_4$ emissions in rice paddy fields<br>- No effect on N2O emission due to change in levels of Nitrogen fertilizer application |
| 4 | Verde et al. (2010) | Relevant | - Total N & total S decreased with an increase in temperature<br>- pH of leachates decreased for all treatments, with lowest being in control and only tilling treatment<br>- Higher release of Al and $Ca^{2+}$ in heated soils relative to unheated soils<br>- Heat had negative influence on $Ca^{2+}$ solubilization in limed soils<br>- Higher solubilization of $SO_4^{-2}$ and release of $NO_3^-$ in fertilized soils than non-fertilized soils |
| 5 | Wilhelm et al. (2022) | Partially relevant | - Soil organic carbon stabilised in soil with low rainfall |
| 6 | Oshima et al. (2015) | Partially relevant | - In soil heated at 400 ℃, cation exchange capacity decreases while soluble aluminium quantity increases compared to subsoil<br>- Addition of $Al(OH)_3$ and Al-humic acid increase disease suppression in subsoil |
| 7 | Anda and Dahlgren (2020) | Partially relevant | - Long-term land use changes caused reduction in allophane materials with an increase in associated Al-humus complexes in upper two horizons of tea plantation soils, and reduction in ferrihydrite in horticultural soils |

| | | | |
|---|---|---|---|
| | | | - Soil management practices effectively change surface charge characteristics |
| 8 | Takahashi (2014) | Partially relevant | - Inorganic phosphorus (P) increased significantly after 22 years of compost application<br>- Organic phosphorus was same for both composted and non-composted soils<br>- Inorganic phosphorus existed more in recalcitrant fractions for composted crop residue than animal manure compost |
| 9 | Matsuoka-Uno et al. (2022) | Partially relevant | For allophanic Andosols:<br>- Liming boosted mineralization of C and N irrespective of temperature which was enhanced by phosphate application<br>- Phosphate application may expedite mineralization of N at lower temperatures |
| 10 | Castillo et al. (2022) | Partially relevant | - 20 years of peanut monoculture decreased soil fertility |
| 11 | Guadalix and Pardo (1994) | Relevant | - P addition alone did not affect soil pH and exchangeable Al contents of soils<br>- Prior addition of $CaCO_3$ had little effect on P concentration in solution while $CaSiO_3$ increased solution P |
| 12 | Koga et al. (2017) | Relevant | - Biochar had impact only on yield and quality of harvest for soybean grain, but no impact for potatoes, winter wheat, sugar beet |
| 13 | Wickramatilake et al. (2010) | Relevant | - Highest P uptake by plants with poultry manure, proceeded by cattle manure, P-adjusted sawdust, and sewage sludge<br>- P uptake by plants was five times greater with compost addition than without<br>- Microbial biomass P was higher with rock phosphate supplementation added with poultry manure or cattle manure<br>- Plant uptake of P from rock phosphate is boosted by compost amendment, especially poultry or cattle manure |
| 14 | Hirzel et al. (2018) | Relevant | - Exchangeable K, Ca, and Mg were highest for compost and lowest for purely lysine treatment |

*Table 1.3 Key findings of literature review on the effects of soil amendments on subarctic vegetation. Search strings "organic soil amendments and "subarctic vegetation" were used on the Web of Science to find articles. Relevant articles mentioned the effects of soil amendments on subarctic vegetation, and partially relevant articles mentioned effects of amendments on any type of vegetation.*

| S. No. | Publication | Relevance | Result Summary |
|---|---|---|---|
| 1 | Reid and Naeth (2005a) | Relevant | - Papermill sludge and peat moss both increase water and nutrient holding capacity and overall structure of tailings<br>- Available calcium did not increase by calcium additions |
| 2 | Reid and Naeth (2005b) | Relevant | Under field study,<br>- Plant growth on kimberlite tailings improved over unamended tailing materials<br>- Peat moss increased water holding capacities<br>- Sewage sludge found effective in nutrient provision<br>- No increase in available calcium by calcium addition |
| 3 | Liu et al. (2020) | Relevant | - Addition of P alone increased pools of C and N in vascular cryptograms<br>- After 8-10 years of nutrient addition, subarctic tundra ecosystem achieved a steady state of resilience to further changes 6 years post-cessation of addition |
| 4 | Giesler et al. (2012) | Partially relevant | - Biotic control linked to cold climate probably more important for P availability by sorption |
| 5 | Hagner et al. (2021) | Relevant | - Composted sewage sludge (CSS) enhanced plant growth<br>- Addition of biochar to till soil-CSS mixture enabled grass succession and higher plant biomass<br>- Biochar application decreased accumulation of metals (such as Al, Cr, Fe) in plant tissues |
| 6 | Männistö et al. (2016) | Partially relevant | - Response of bacterial communities to increase in available N were similar in both N-poor and N-rich soils under heavy and light grazing<br>- N addition caused increase of abundance of *Actinobacteria* and decrease in respiration |
| 7 | Gorbacheva et al. (2009) | Partially relevant | - Metal distributions increased in humic acids fractions reducing mobile amounts of Ni and Cu |

*Table 1.4 Key findings of publications found on the portals of GróLind (n.d.), GRÓ LRT (n.d.), SCSI (n.d.-b) and Skemman (n.d.), focusing on changes in Andosols and subarctic vegetation in Iceland due to the application of organic soil amendments. Relevant articles mentioned the effects of organic soil amendments on Andosols and subarctic vegetation. Partially relevant articles discussed the effects of organic soil amendments or any other amendment strategy on soils and vegetation in Iceland.*

| **S. No.** | **Publication** | **Relevance** | **Result Summary** |
|---|---|---|---|
| 1 | Teferi (2011) | Partially relevant | - Natural regeneration is cost effective and efficient for restoration of land, but response might be delayed in severely degraded areas<br>- Using adaptive grasses and their fertilization for stabilizing moving sand and volcanic ash is crucial before restoring native vegetation |
| 2 | Soumana (2013) | Partially relevant | - Increase in soil nitrogen and carbon as soil pH decreased with restoration age |
| 3 | Asare (2019) | Relevant | - Bonemeal application caused an increase in SOM and soil’s water holding capacity as compared to no addition |
| 4 | Balikoowa (2014) | Partially relevant | ‘Tea-leaved’ willows<br>- Increase total C, N, P in soil<br>- Corrects soil pH to benefit plants that thrive in low pH<br>- Increases foliar cover and improves stability to erosion of soil due to wind and water<br>- Economical substitute for fertilizer application to restore land |
| 5 | Battogtokh (2018) | Partially relevant | - Purple beach pea increased total soil N and C in the top 5 cm layer of soil and also affected the growth rate of ryegrass<br>- Purple beach pea beneficial for revegetation of eroded areas in Iceland |
| 6 | Mdolo (2016) | Partially relevant | - Municipal waste generated in Iceland is enough to meet phosphorus requirement of restoration work<br>- Potential reduction in the cost associated with compost production, transportation, and application which are higher than that of inorganic fertilizer<br>- Need to understand interactions among waste, plant, metal, and soil along with mineralization of nutrients specific to Iceland |

| | | | |
|---|---|---|---|
| 7 | Nakanyala (2012) | Partially relevant | - Nootka lupine mobilizes phosphorus in Icelandic Andosols, thereby increasing plant-available P<br>- Mobilizing phosphorus can be potential cost-effective method |
| 8 | Berihu (2021) | Relevant | - Bulk density of soil decreased with increase in soil moisture after application of bio-slurry<br>- Available P increased due to treatments with high level of inorganic P and/or bio-slurry |
| 9 | Mbewe (2015) | Relevant | - Application of both sunflower seed cake and inorganic fertilizer increased biomass of plant, chlorophyll present in maize leaves, and height of plants<br>- Application of sunflower seed cake had positive influence on stem diameter<br>- Sunflower seed cake has potentially comparable maize production in comparison to inorganic fertilizer |
| 10 | Tjilumbu (2012) | Partially relevant | - Reclamation of eroded areas has potential to increase aboveground plant biomass, soil nitrogen, soil carbon, and vegetation density over decades, i.e., over longer time period<br>- Vegetation accumulates aeolian material and influences soil development |
| 11 | Poulsen (2011) | Partially relevant | - Phosphatase activity decreased at 1000ppm of fluoride concentration<br>- High fluoride concentration is toxic for soil microbial communities<br>- Acute fluoride pollutions (e.g., volcanic eruptions) might have negative effect on soil health and fertility |
| 12 | Guðmundsson et al. (2014) | Partially relevant | - All surplus applied phosphorus was in top 10cm with maximum increase in top 5cm of soil with most of surplus phosphorus being inorganically bound<br>- Available phosphorus increased only in top 5cm of soil with increase in phosphorus application rate |
| 13 | Jónsson and Sigurðsson (2010) | Partially relevant | In first treatment year:<br>- Fertilization increased soil $CO_2$ efflux, while thinning intensity decreased it<br>- Thinning did not change foliage nutrient content, while fertilization increased it |
| 14 | Möckel (2016) | Partially relevant | - Sites with lower soil C/N ratio enhance nutrient binding ability due to greater state of decomposition<br>- Histosols struggled to reverse anthropogenic vegetation destruction and enhanced erosion, while were resilient to degradation by climate factor only<br>- Need to critically interpret soil C/N ratios as a proxy for decomposition rates for soils with heterogenous history of vegetation |
| 15 | Brenner (2016) | Relevant | Post five years of application,<br>- Chemical fertilizer (with 150 kg/ha of N) increased vegetation cover (as moss cover) and vegetation height, and the treated plots exhibited greater amounts of ammonium |

| | | | |
|---|---|---|---|
| | | | - No effects on soil parameters or vegetation cover due to organic fertilizer treatments (bonemeal, sewage sludge, chicken manure) |
| 16 | Hill (2023) | Partially relevant | - Soil health improved or maintained 3 years after transition to regenerative agricultural practices<br>- Energy Return on Investment increased by 23 % due to decrease in energy input cost from synthetic fertilizers |
| 17 | Áskelsdóttir (2012) | Partially relevant | - SOC stock increased with increased N-input at hayfields established at eroded soils, by increasing plant production and soil organic matter |

## 1.6 Research gaps and challenges

The literature review on the efficacy of organic soil amendments in changing soil properties of Andosols and subarctic vegetation highlights the potential of organic amendments, such as sewage sludge, bone meal, poultry manure, compost from food waste, biochar, sunflower cake seeds, and many more as a replacement for chemical or synthetic fertilizers (Asare, 2019; Berihu, 2021; Brenner, 2016; Hagner et al., 2021; Mbewe, 2015). Synthetic fertilizers are not only costly to farmers due to high import prices and the ongoing Russian-Ukraine conflict (Broom, 2023; World Bank Group, 2023), but they also hamper the restoration of soil (Chaudhuri et al., 2023; Tripathi et al., 2020). For instance, Chaudhuri et al. (2023) found that one of the factors exacerbating state-wise land degradation and desertification hazards in India was increased and unregulated use of NPK-based fertilizers. Qiao et al. (2018) observed increase in acidification of soils with tea plantations due to N-fertilization, causing imbalance in soil nutrients and aggravating the level of aluminium toxicity which may threaten tea quality and production. As per Tripathi et al. (2020), continued addition of N-based synthetic fertilizers may cause reduction in the base cations (e.g. Ca and Mg) present in soil and often causing aluminium toxicity. Tripathi et al. (2020) also emphasizes that acidification of soil due to continuous N addition can affect the quality of soil organic matter by interfering with the process of SOM decomposition and SOM mineralization. This can be true for the relatively young and degraded soils of Iceland, especially those soils which have low amount of SOM (Arnalds, 2015). Organic soil amendments seem to be showing positive effects towards healing the soil for its long-term health (Hirzel et al., 2018; Koga et al., 2017; Krause et al., 2016; Liu et al., 2020) and making it easier to reuse the waste generated in the region as part of promoting circular economy. However, the limited research on this topic, especially in Iceland, makes it difficult for optimising the application amount of soil amendments that can heal the soil and help reduce human impacts on the environment. This creates an opportunity for new research projects, such as investigating the efficacy of locally available organic amendments (e.g., bonemeal, chicken manure, municipal waste compost, sewage sludge, biochar) on Icelandic Andosols and vegetation for varied time periods, as well as identifying organic amendments that can replace chemical fertilizers to reduce the high cost of imported fertilizers. These research projects can be beneficial to advise stakeholders and guide the policy around soil restoration through scientific knowledge.

# 2 Chapter 2 – Effects of soil amendments on Icelandic soil properties and vegetation growth

## 2.1 Introduction

Soil is essential for meeting various needs like food, energy, and ecosystem services such as erosion control, production of biomass, freshwater availability, habitat (for microorganisms to mammals), and climate regulation, among others (Pierzynski & Brajendra, 2017). Healthy soil constitutes the Earth's largest terrestrial reservoir of carbon, and roughly 95% of the world's food supply is cultivated in soil (FAO, 2017). However, humans have been over-exploiting this non-renewable resource. Although soil is degraded through natural events like volcanic eruptions, landslides and soil erosion, the damage done by humans is greater (Richardson et al., 2023; Stockholm Resilience Centre, 2023) and, in some cases, irreversible leading to desertification and stripping the soil of its ability to recover over time (Chaudhuri et al., 2023; Mirzabaev et al., 2019; Olsson et al., 2019). Soil continues to degrade at steep rates due to anthropogenic impacts, with 33% of the Earth's soils already degraded and over 90% at a risk of degradation by 2050 (European Commission Joint Research Centre, n.d.; FAO, n.d.; FAO & ITPS, 2015c). The major drivers to global soil degradation include deforestation, growing human population, pollution and waste disposal, rapid urban expansion, unsustainable practices for soil management, and climate change (FAO & ITPS, 2015c). These not only lead to overexploitation of global soil resources to manage the rising demand, but also cause uncertainty in future predictions of ecosystem services provided by them. In addition, climate change impacts soils with unpredictable water availability due to changes in temperature and precipitation patterns (Konapala et al., 2020; Padrón et al., 2020; Zhou et al., 2022). Decomposition of soil organic carbon may also increase with changes in soil moisture and temperature induced by warming, which can further intensify risks of erosion and desertification (Montanarella et al., 2016).

At present, the major global threats to soil are “soil erosion”, “loss of soil organic carbon”, and “nutrient imbalance” (Montanarella et al., 2016). Pierzynski and Brajendra (2017) emphasize that the erosion of agricultural land is a significant problem to global soil resources and the rates of soil erosion on arable or heavily grazed lands are about 100 to 1000 times greater than the natural background erosion rates. Furthermore, these erosion rates significantly exceed the established rates of soil formation (FAO & ITPS, 2015a). Soil erosion negatively affects global agriculture as well as leads to contamination of water bodies with nutrients and sediments, diminishing water quality (Pierzynski & Brajendra, 2017; Shah et al., 2022). The erosion-induced nutrient losses can be compensated with the use of synthetic fertilizers which are expensive, having an annual expenditure exceeding US$30 million (FAO & ITPS, 2015a; Mosheim, 2019). These fertilizers may compensate the nutrient loss of soil in the short-term, but do not solve this problem in the long run.

Instead, long-term excessive use of chemical fertilizers has been associated with the increased risk of soil acidification (Qiao et al., 2018) and land deterioration (Chaudhuri et al., 2023). About 716 billion tonnes of soil organic carbon is stored in the top 30 cm of soil and land use changes, such as conversion of forests into croplands and draining peatlands for agriculture and commercial forestry, mismanagement of agricultural land and global climate change are the primary drivers for the loss of soil organic carbon stock globally (Pierzynski & Brajendra, 2017). Climate change alters temperature and precipitation patterns, accelerating the decomposition of soil organic matter and emitting various greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$) (Field et al., 2007; Leirós et al., 1999; Plante & Conant, 2014).

The increasing demand for food due to a rapidly growing world-population has also led to extensive use of synthetic fertilizers in agriculture to boost production (Ritchie, 2017; Stewart et al., 2005). Synthetic fertilizer substantially enhances both plant growth and the uptake of nutrients, but over longer periods, they can cause imbalance in the soil functions and processes by leaving an increasing proportion of the added nutrients behind in the soil (Pahalvi et al., 2021). If these additional nutrients are not the limiting nutrients needed by the plants, they can decrease plant growth by exacerbating the existing imbalance in the system (Brady & Weil, 2014; Savci, 2012a, 2012b). The extensive use of synthetic fertilizers causes accelerated soil degradation at the cost of high crop yields in the short-term (Kopittke et al., 2019), hardens the soil, reduces soil fertility (Castillo et al., 2022; Pilbeam et al., 2005), pollutes air, water, and soil (Ghaly & Ramakrishnan, 2015), and reduces important nutrients of soil and minerals (Chen et al., 2010), thereby resulting in environmental hazards (Rashmi et al., 2020; Savci, 2012a, 2012b).

Soil formation takes more than 100 years (Hall et al., 1982; Hurni, 1983; Kölbl et al., 2014) while soil continues to degrade at steep rates due to anthropogenic impacts, with 33% of the Earth's soils already degraded and over 90% of the Earth’s soils being at a risk of degradation by 2050 (European Commission Joint Research Centre, n.d.; FAO, n.d.; FAO & ITPS, 2015c). To effectively address soil degradation, it is imperative to understand the threats, functions, ecosystem services and processes, and provide long term solutions to improve soil health and return its ability to regenerate (Joint Research Centre et al., 2009; Pereira & Martinez-Murillo, 2018). Other related concerns that need tackling include food waste, increasing number of landfills and their associated GHG emissions (Kaza et al., 2018; Nicholls et al., 2021; United Nations Environment Programme, 2021), costs of synthetic fertilizers (Alexander et al., 2023; Mosheim, 2019), soil associated imbalance in biogeochemical cycles (Berhe et al., 2018; Quinton et al., 2010), food insecurity (The World Bank, 2023), and finding substitute methods for soil restoration (Bradshaw, 1984; Chee et al., 2017; Farrell et al., 2020; Teng & Chen, 2019).

In Iceland, land reclamation and restoration activities conducted by SCSI often include reduced grazing, direct seeding, fertilization and/or seeding of areas after investigating status of soil health and vegetation in order to improve Icelandic soils and revegetate barren areas (Brenner, 2016; Crofts, 2011). Mt. Hekla afforestation project and Farmers grow the land (*Icelandic name: Bændur græða landið*) are two of the most ambitious reclamation projects in Iceland (S.Nickayin et al., 2022). On one hand, Mt. Hekla afforestation project focused on methods such as fertilizers and grasses to stabilise the volcanic surface layer of the soil and has transformed large areas of desert landscapes to grassy fields and young birchwood forest (Aradóttir et al., 2013; Hekluskógar, 2015; Óskarsson et al., n.d.), while on the other hand, Farmers grow the land project focuses on empowering and supporting landowners in cooperation with SCSI to reclaim their lands, and increase the vegetation cover and resistance to soil erosion (S.Nickayin et al., 2022; SCSI, n.d.-a).

In recent years, using soil organic amendments as a substitute for synthetic fertilizers is gaining popularity for soil restoration (Diacono & Montemurro, 2011; Guerrero et al., 2001; Hueso-González et al., 2018). They have a huge potential of replacing synthetic fertilizers by reducing long term production costs and treating soil as an ecosystem rather than a daily commodity. Organic amendments have the potential of reversing soil degradation by building up soil organic matter, sequestrating atmospheric carbon in soils and increasing the soil's resilience to climate change (Chari & Taylor, 2022; Chen et al., 2010; Chowdhury et al., 2021; Diacono & Montemurro, 2011). There have been several studies (Aparna et al., 2014; Brenner, 2016; Hueso-González et al., 2018; Zheng et al., 2023) on finding new alternatives to synthetic fertilizers that are also safe for the environment. However, the amount of research and development for organic soil amendments in subarctic Andosols is comparatively less and new. This makes it a great opportunity to study the potential of organic soil amendments as a replacement for synthetic fertilizers for restoring soils, especially in a country like Iceland.

In this study, the main goal was to determine how various types of organic soil amendments, sourced domestically, affected soil properties in Iceland, the vegetation growth, and litter decomposition. With this broader goal in mind, the following research questions were addressed:

1) What are the effects of various soil amendments on soil properties?
2) What are the effects of various soil amendments on vegetation growth? How do they vary between years?
3) How do different types of soil amendments affect litter decomposition and stabilisation?

The null hypotheses tested were:

1) There is no significant difference in soil properties based on type of soil amendments applied.
2) There is no significant difference in vegetation growth based on type of soil amendments used or between years.
3) There is no difference in litter decomposition and stabilisation based on types of soil amendments.

# 2.2 Methodology

## 2.2.1 Study site description

### 2.2.1.1 Study site

The study site was located in an eroded area at Geitasandur, Rangárþing ytra municipality, Iceland with GPS coordinates of 63° 49.903' N, 20° 10.952' W, ca. 70 m above sea level (Magnús H. Jóhannsson, personal communication, April 26, 2023). The chosen study site was flat and seemingly uniform with regards to vegetation as shown in *Figure* ***2.1***. The soils in the region are classified mainly as Andosols and Vitrisols (Arnalds, 2015). Data gathered from the weather station in Hella, located near to Geitasandur, showed that the average annual temperature for both 2021 and 2022 was 4.7℃, and the average summer temperature was 11℃ for 2021 and 10.6℃ for 2022 (Icelandic Meteorological Office, personal communication, June 07, 2023). Since the precipitation is not recorded at Hella weather station, the precipitation data from the weather station in Sámsstaðir was used. Based on these data, the average annual rainfall was 80 mm for 2021 and 99 mm for 2022, and the average summer (June, July, August) rainfall was recorded as 68 mm for 2021 and 102 mm for 2022 (Icelandic Meteorological Office, personal communication, June 07, 2023).

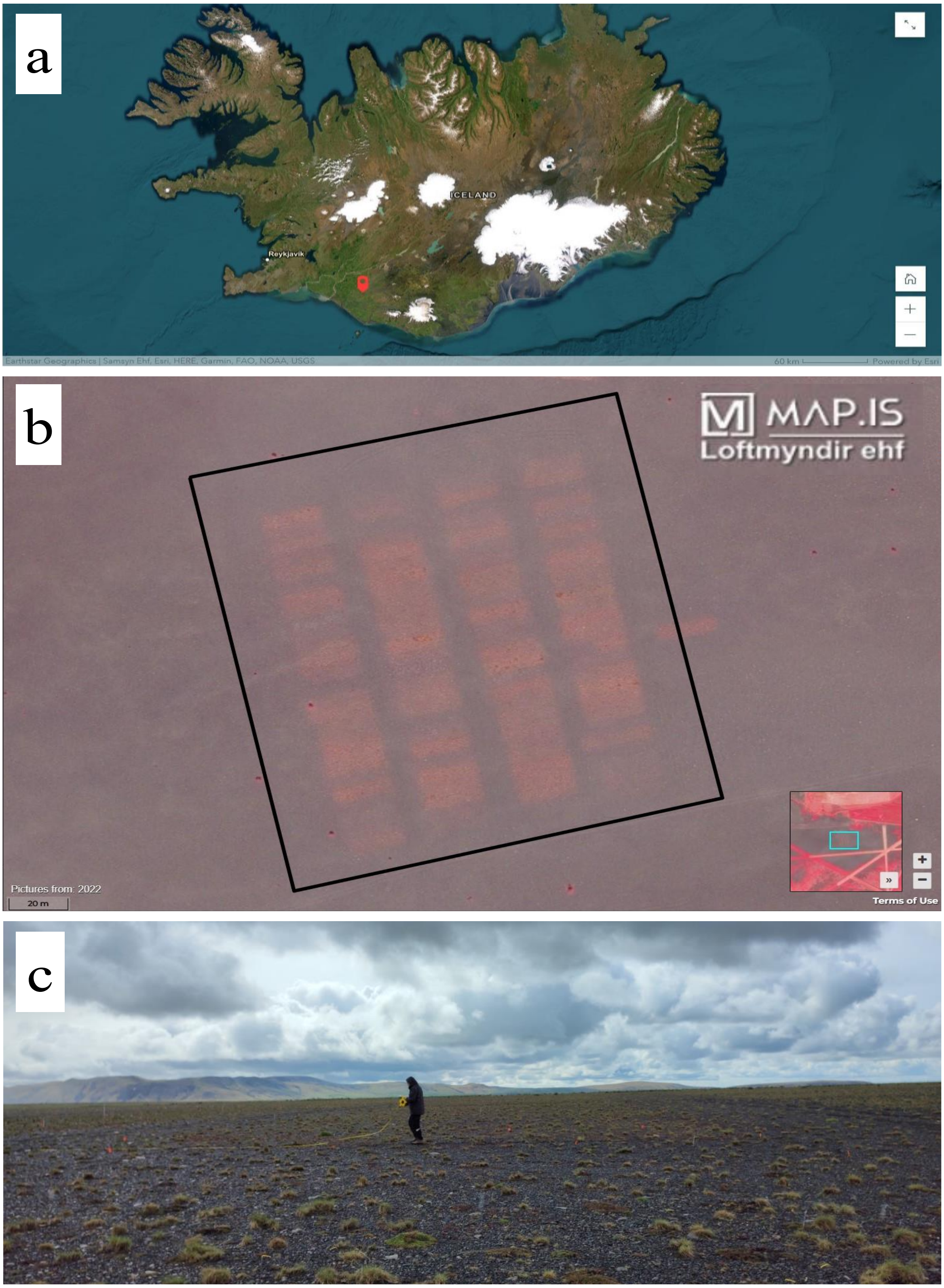


*Figure 2.1 Study site in Geitasandur, Iceland. (a) Location of study site (63° 49.903' N, 20° 10.952' W, ca. 70m above sea level) at Geitasandur, Rangárþing ytra municipality shown in red on the map of Iceland (ArcGIS StoryMaps, 2023), (b) Zoomed-in aerial image of study site (Loftmyndir ehf., 2022) and (c) On the ground photograph of the study site taken in May 2022 (Photo by Parnika Gupta, 2022).*

### 2.2.1.2 Experimental Design

The experimental study site at Geitasandur, Iceland has a total area of 130 m x 130 m which is sub-divided into four blocks, each 20 m x 5 m and spaced at an equal distance of 10 m (*Figure 2.2*). This experimental study site is part of an ongoing land reclamation project conducted by Soil Conservation Service of Iceland. For the scope of this thesis, each soil amendment treatment was replicated four times while the control was replicated eight times, equating to a total of 36 sampled plots (*Figure* **2.2**). The organic soil amendments used for this study were selected to have similar nitrogen content as that of the chemical fertilizer treatment (50 kg N/ha) which is the preferred amount when using the latter in reclamation projects (Magnús H. Jóhannsson, personal communication, May 25, 2022 and December 07, 2023). However, practically, at least three times more N would be applied in the form of organic amendments due to the slow release of nutrients from them compared to chemical fertilizer (Magnús H. Jóhannsson, personal communication, December 07, 2023).

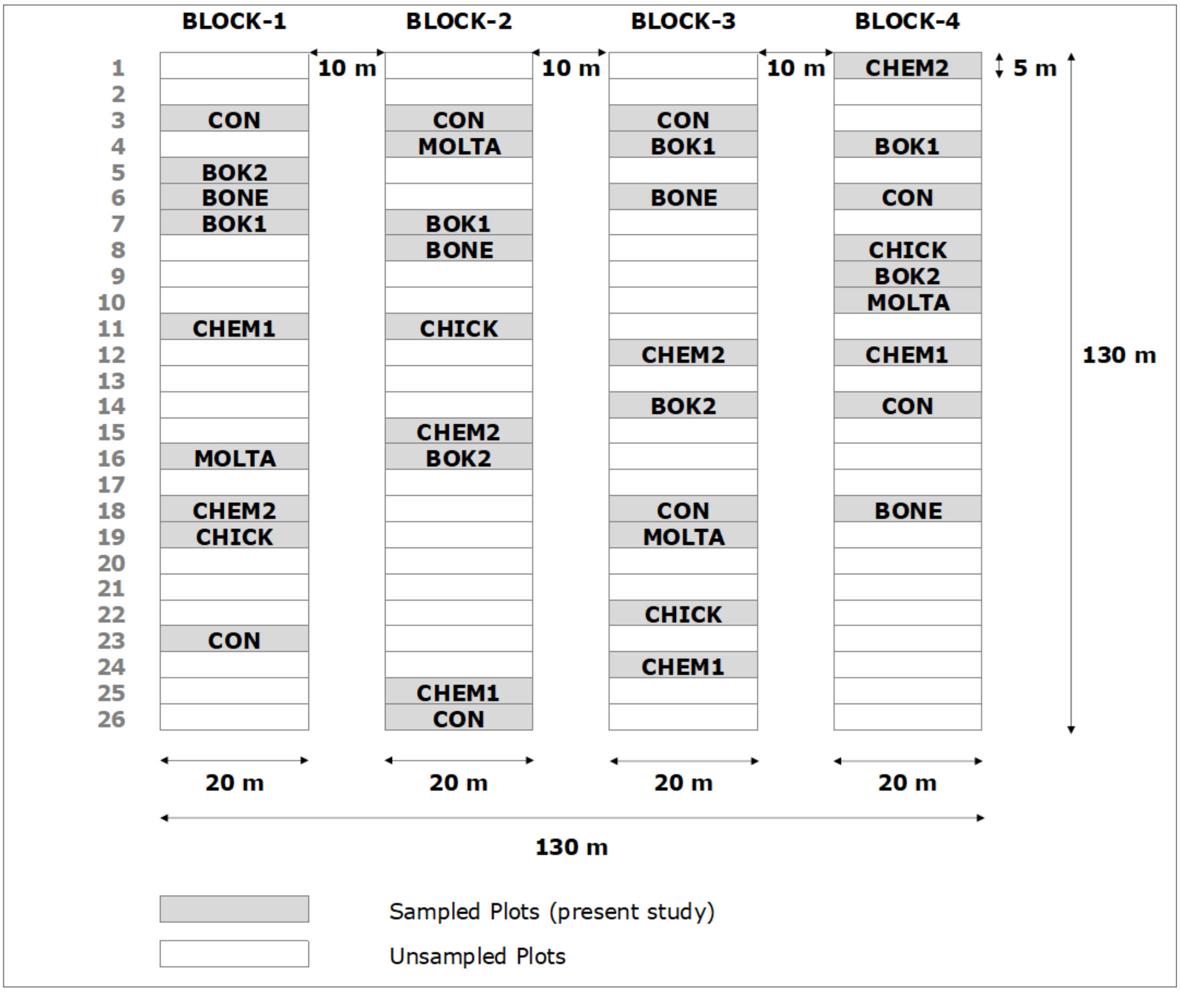


*Figure 2.2 Experimental design of the study site. The site was 130 m x 130 m and 36 plots out of 104 were sampled (shown in grey) for the study. The following types of soil amendments were used: CON = Control (no amendment used), BOK1 = Bokashi compost 1, BOK2 = Bokashi compost 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, MOLTA = Molta compost. All the plots (both sampled and unsampled) are part of an ongoing land reclamation project conducted by Soil Conservation Service of Iceland.*

All treatments were applied during the period of 25-27 May 2021, except the bokashi treatments which were not ready in May 2021. The bokashi treatments were applied instead in September 2021 and May 2022 (*Figure* ***2.3***). To ensure uniform distribution of the soil amendments, the amendments were weighed prior to application, and then evenly applied by hand across the surface of each treatment plot. No raking or tilling was performed to incorporate them into the soil. A description of the soil amendments chosen for this study is in *Table* ***2.1***.

*Figure 2.3 Bokashi treatment application in May 2022 (Photo by Julia Brenner, 2022).*

*Table 2.1 Description of applied soil amendments based on data received from Magnús H. Jóhannsson (personal communication, September 20, 2023) and Julia Brenner (personal communication, September 26, 2023). All treatments (bonemeal, chemical fertilizer 1, chemical fertilizer 2, chicken manure, and Molta compost) were applied in May 2021 with the exception of bokashi compost 1 and bokashi compost 2 which were applied in September 2021 and May 2022 respectively. Note: na - data not available.*

| | | | **Total nutrients applied through amendments** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Type of Soil Amendments** | **Description** | **Total amendment applied (kg/ha)** | C (kg/ha) | N (kg/ha) | C/N ratio | P (kg/ha) | K (kg/ha) | S (kg/ha) | **Source of amendments** | **Type of waste used** |
| CON | Control (untreated) | - | - | - | - | - | - | - | - | - |
| BOK1 | Bokashi compost 1 | 2000 | 199 | 15.5 | 15.0 | na | na | na | Melta ehf. | Organic household waste |
| BOK2 | Bokashi compost 2 | 2000 | 199 | 15.5 | 15.0 | na | na | na | Melta ehf. | Organic household waste |
| BONE | Bone meal | 535 | 369 | 50 | 8.6 | 12.2 | 3.4 | 2.9 | Orkugerðin ehf. | Animal slaughterhouse bone waste |
| CHEM1 | Chemical fertilizer 1 | 200 | 0 | 50 | 0 | 4.4 | 0 | 5.0 | Skeljungur ehf. | - |
| CHEM2 | Chemical fertilizer 2 | 400 | 0 | 100 | 0 | 8.8 | 0 | 10.0 | Skeljungur ehf. | - |
| CHICK | Chicken manure | 2793 | 1424 | 100 | 16.6 | 15.4 | 55.0 | 11.7 | Sláturfélag Suðurlands svf. | Excretory waste from chicken |
| MOLTA | Molta compost | 7143 | 2838 | 100 | 33.1 | 40.7 | 17.9 | 10.7 | Molta ehf. | Waste from meat & fish processors, slaughterhouses; Organic household waste, wood shavings, and paper |

## 2.2.2 Measurements

### 2.2.2.1 Tea-Bag Index Study (TBI)

The tea-bag index experiment was performed as per the method and calculations described in Keuskamp et al. (2013). Each treatment plot used three pairs of teabags (each pair consisting of one Lipton green tea and one Lipton rooibos tea). The location of each pair inside the treatment plots was chosen randomly. In total, 108 pairs of teabags were used. The teabags were buried at the study site on 25 May 2022 and then were recovered on 29 August 2022 (*Figure **2.4***). The relative mass loss of green tea was used as the basis for calculation of decomposable fraction of green tea ($a_g$) and the litter stabilisation factor, S was calculated using equation:

$$S = 1 - \frac{a_g}{H_g} \qquad [1]$$

where $a_g$ is decomposable fraction of green tea, and $H_g$ is Hydrolysable fraction of green tea (Keuskamp et al., 2013). Litter decomposition rate (k) was calculated using the equation:

$$k = \frac{\log_e\left(\frac{a_r}{W_r - (1 - a_r)}\right)}{t} \qquad [2]$$

where $W_r$ is the relative remaining mass of rooibos tea (g $g^{-1}$), t is incubation period (96 days in this study), and $a_r$ is the decomposable fraction of rooibos tea (Keuskamp et al., 2013). The value of $a_r$ is calculated using stabilisation factor, S as estimated in equation [1] and hydrolysable fraction of rooibos tea, $H_r$ (Keuskamp et al., 2013). The value of $H_g$ and $H_r$ used are 0.842 g $g^{-1}$ and 0.552 g $g^{-1}$ respectively as given in Keuskamp et al. (2013).

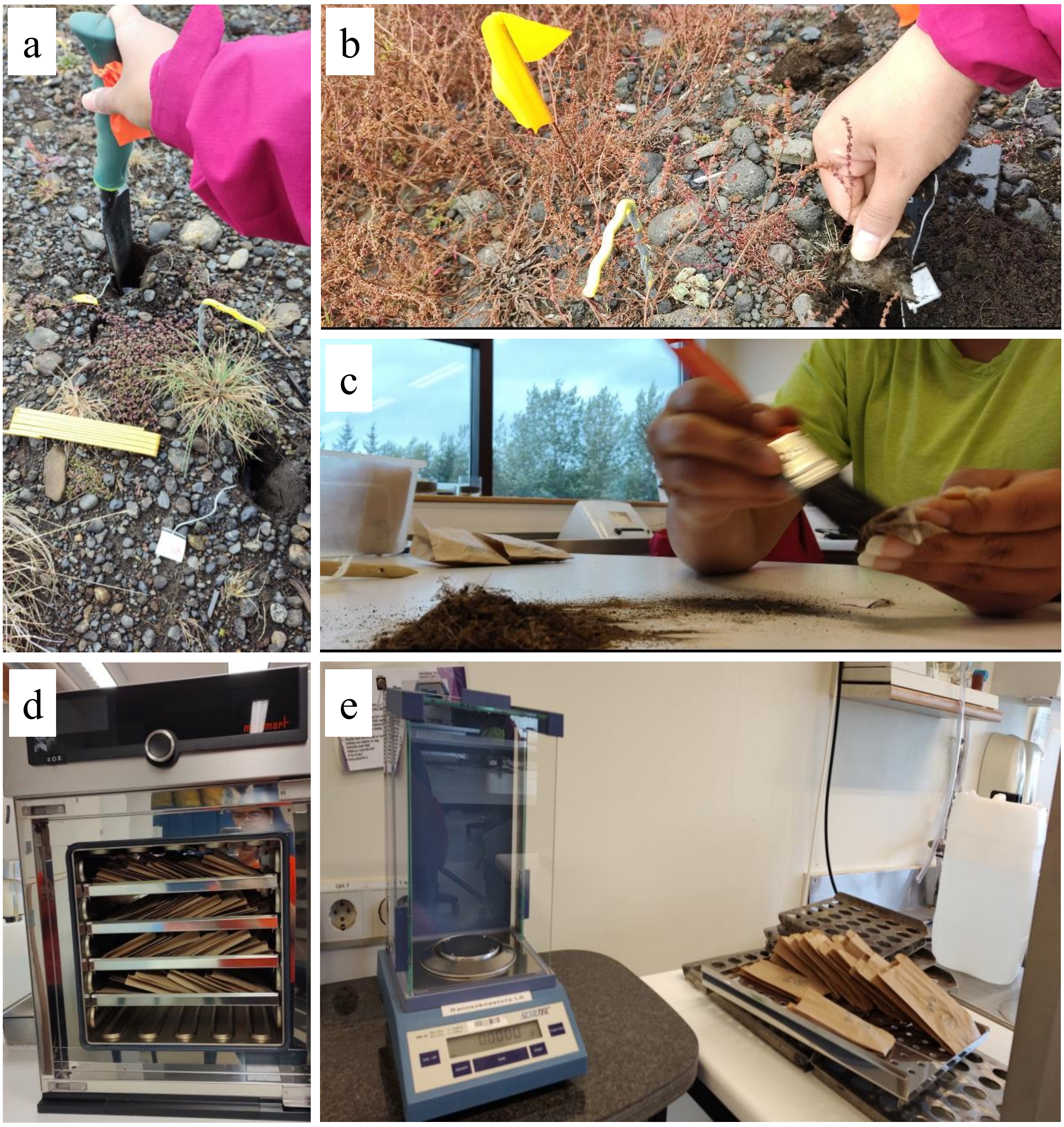


*Figure 2.4 Teabag study. (a) Burying teabags, (b) Recovering teabags after 96 days, (c) Removing adhered soil particles from teabags, (d) Oven drying teabags at 70℃ for at least 48 hours, and (e) Recording oven-dried mass of teabags (Photos by Parnika Gupta, 2022).*

#### 2.2.2.2 Soil sampling and analysis

**Soil sample collection & preparation**

Soil samples were collected on 24 May 2022 from the study site (*Figure **2.1***). A total of 36 soil samples were collected as shown in *Figure **2.5*** and stored at 4°C. Soil samples were collected using a cylindrical soil probe. Each soil sample consisted of ten soil cores collected at the depth of 10 cm from randomly chosen locations inside each treatment plot and was then stored in a separate and pre-labelled plastic bag. Each soil sample weighed 1 kg approximately.

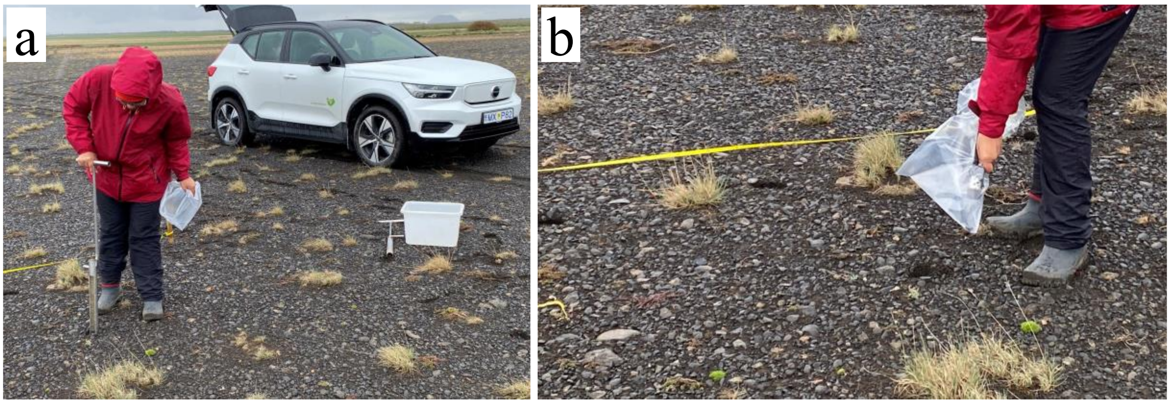


*Figure 2.5 (a)-(b) Soil sample collection from the study site at Geitasandur. (Photos by Magnús H. Jóhannsson, 2022).*

All the soil samples were air dried at room temperature and were passed through a 2 mm sieve to separate any fine roots or gravel (>2mm). The sieved samples (<2mm) were then divided quantitatively into four parts using a riffle sample splitter. Each part was approximately one-fourth of the original sieved soil sample. Out of these four, one part was stored as uncrushed subsample, and another was stored after crushing using a soil grinder (Cross Beater Mill SK 300, Retsch GmbH, Germany, mesh size 1mm), and the remaining two parts were stored as reserves. Both uncrushed (<2mm) and crushed (<1mm) subsamples were stored in a 50ml polypropylene tube and an air-tight zip-lock bags and labelled (*Figure **2.6***). Each apparatus used was cleaned between each soil sample to avoid contamination. The crushed subsample (size <1mm) was used for measuring soil organic matter, soil carbon, and soil nitrogen, while the uncrushed subsample (size <2mm) was used for measuring soil pH(water) and soil available carbon.

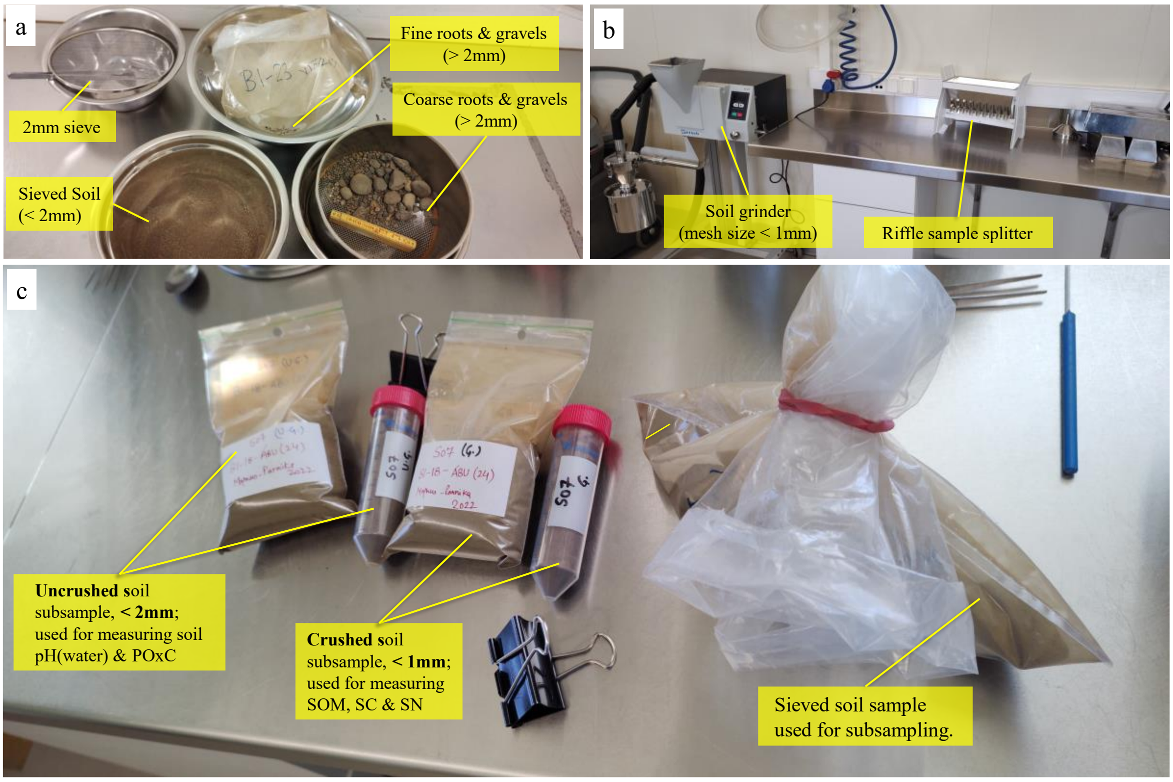


*Figure 2.6 Soil sample preparation. (a) Soil sieving, (b) Soil subsampling setup, and (c) Soil subsamples: crushed (<1mm), & uncrushed (<2mm) (Photos by Parnika Gupta, 2022).*

## Soil organic matter content

Soil organic matter was measured using the loss on ignition method (Allen et al., 1986) involving dry combustion of soil at 550°C as shown in *Figure* **2.7**. An aliquot (4-7g) was taken from each soil subsample (air dried and crushed, <1mm soil) and weighed into crucibles. These crucibles were weighed at room temperature, oven dried at 105°C for at least 24 hours and re-weighed at 105°C. Then, they were placed in a muffle furnace (Thermo Fisher Scientific ™ Thermolyne™ Benchtop Muffle Furnace, USA, Model no. F48020-33-80) for dry combustion by ignition at 550°C for 5 hours. After cooling and oven-drying at 105°C, weights of these crucibles were recorded. Each soil sample was analysed in triplicate.

Soil organic matter percentage (SOM%) was calculated from loss on ignition (LOI%) equation:

$$\mathrm{SOM}\ \% = \mathrm{LOI}\ \% = \frac{\mathrm{W}_{\mathrm{soil\ (pre-ignition)}} - \mathrm{W}_{\mathrm{soil\ (post-ignition)}}}{\mathrm{W}_{\mathrm{soil\ (pre-ignition)}}} \times 100 \qquad [3]$$

where $\mathrm{W}_{\mathrm{soil\ (pre\text{-}ignition)}}$ is the weight of soil before ignition, $\mathrm{W}_{\mathrm{soil\ (post\text{-}ignition)}}$ is the weight of soil after ignition.

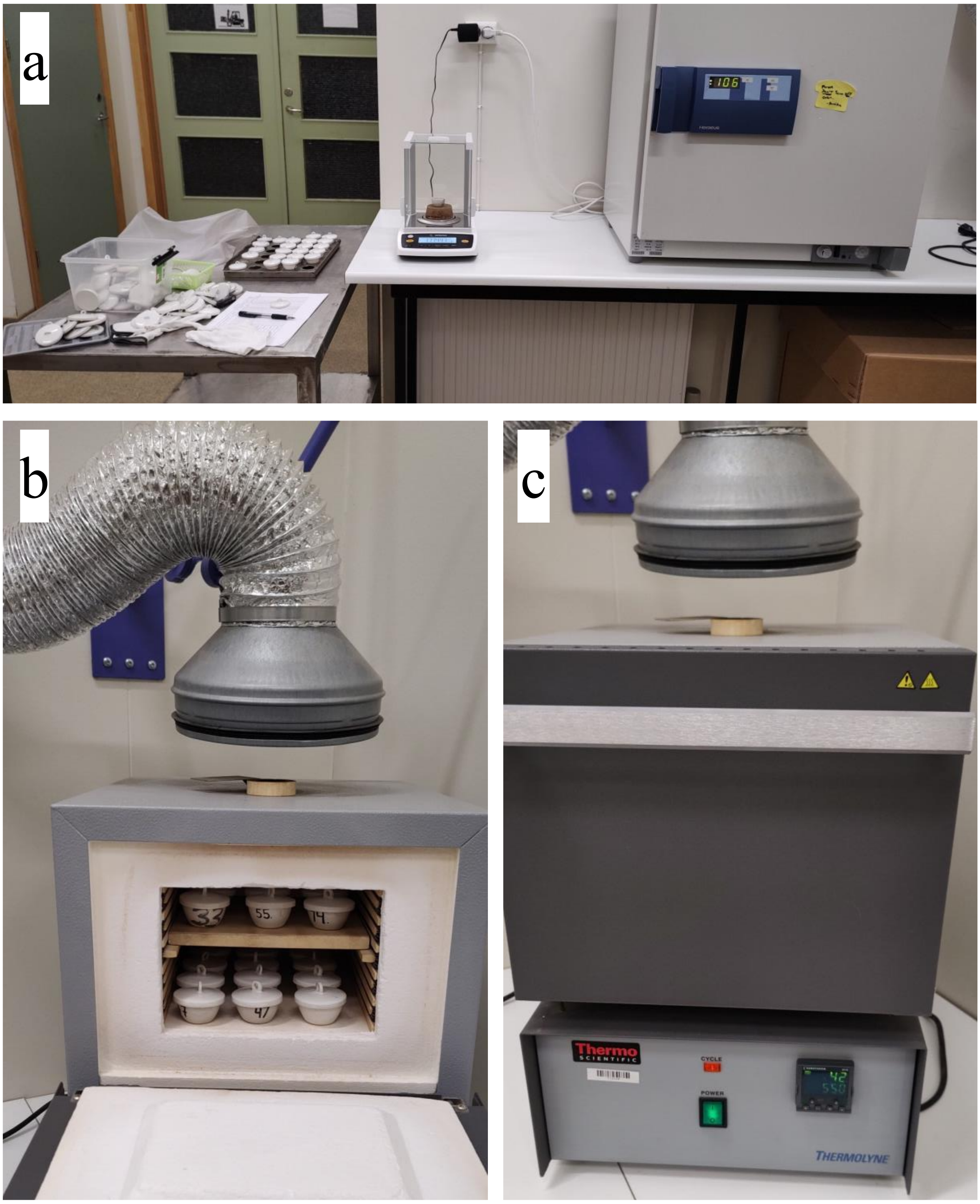


*Figure 2.7 Soil organic matter measurement setup. (a) Recording oven-dried weights of pre-ignition and post-ignition soil aliquots, and (b)-(c) Muffle furnace used for ignition at 550°C. (Photos by Parnika Gupta, 2022)*

### Soil pH

Soil pH was measured as described in Blakemore et al. (1987) and the setup is shown in *Figure **2.8***. The soil to water ratio (mass by volume) used was 1:2.5. Each soil sample was analysed in duplicate. An aliquot (10g ± 0.05) was taken from each soil sample (air dried and < 2mm soil) and mixed with 25ml of de-ionized water. This mixture was then stirred vigorously for 15 minutes using a vibrational shaker and left to stand overnight. The soil pH(water) was measured using pH meter (OAKTON® pH/CON 510 benchtop meter, USA). The re-calibration of pH meter was performed between every 12 replicates.

*Figure 2.8 Soil pH(water) measurement setup (Photo by Parnika Gupta, 2022).*

### Soil carbon, nitrogen, and carbon to nitrogen ratio

Soil carbon and nitrogen percentages were measured using element analysis according to the Dumas combustion method (VarioMAX C/N instrument, Elementar Analysensysteme GmbH, Germany). Chemical analysis was performed by the Soil Conservation Service of Iceland on an aliquot (3.5g ± 0.3) taken from each soil sample (air dried, crushed, < 2mm). The soil carbon and soil nitrogen were corrected for dry matter fraction. Soil carbon to nitrogen ratio (Soil C/N ratio) was calculated using equation:

$$\text{Soil C/N ratio} = \frac{SC\ \%}{SN\ \%} \times \frac{14.0067\ \text{g/mole}}{12.011\ \text{g/mole}} \qquad [4]$$

where SC % is soil carbon percentage, SN % is soil nitrogen percentage, 14.0067 g $\text{mole}^{-1}$ is the molecular mass of nitrogen, and 12.011 g $\text{mole}^{-1}$ is the molecular mass of carbon.

## Soil available carbon

Soil available carbon was measured by analysing permanganate-oxidizable carbon (POXC) using method described in Culman (2017), Hurisso et al. (2016), and Weil et al. (2003) on selected samples. Block-3 samples (*Figure 2.2*) were analysed. Each soil sample was analysed in duplicate.

An aliquot (2.5g ± 0.05) taken from a soil subsample (air dried, uncrushed, <2mm) was mixed with 2ml of 0.2M $KMnO_4$ and 18ml of deionized water in a 50ml polypropylene centrifuge tube. The tube was immediately shaken for exactly two minutes at 200 rpm using a shaker (New Brunswick Innova® 2000 Platform Shaker, USA), and allowed to stand in a rack for 10 minutes for the soil to settle. Icelandic soils have very fine particles which may not settle upon centrifugation. Therefore, two drops of Superfloc® was added to each tube, then the tubes were placed into a centrifuge at 4000 rpm for nine minutes (Thermo Scientific™ Sorvall™ ST 16R Centrifuge, Germany). Then, 0.5 ml of the supernatant was placed in a 50 ml volumetric flask and made up to volume by adding with 49.5 ml of deionized water. A quartz cuvette (path length,10mm) was filled with ca. 3ml of this diluted solution and placed in the spectrophotometer (Thermo Scientific™ GENESYS™ 10S UV-Visible Spectrophotometer, Germany) to record absorbance at 550 nm. The soil available carbon (POXC, mg $kg^{-1}$ soil) was calculated using equation:

$$\begin{aligned}\mathrm{POXC} = {} & [0.02\, mol\, L^{-1} - (a + b \times Abs)] \times (9000\, mg\, C\, mol^{-1}) \\ & \times \left(\frac{0.02\, L}{W} \times 1000\right)\end{aligned} \quad [5]$$

where *0.02 mol* $L^{-1}$ is the initial concentration of the $KMnO_4$ solution, *a* is the intercept of the standard calibration curve, *b* is the slope of the standard calibration curve, *Abs* is the recorded absorbance value, *9000 mg C* $mol^{-1}$ is the amount of carbon oxidised by 1 mole of $MnO_4^-$ during reduction of $Mn^{7+}$ to $Mn^{4+}$, 0.02 L is the volume of $KMnO_4$ solution, and *W* is the weight (g) of soil used. The equation of the standard calibration curve obtained was y = 0.0436x - 0.0001. All negative concentrations for POXC were rounded to zero.

### 2.2.2.3 Vegetation measurements

Vegetation data was collected by the Soil Conservation Service of Iceland from August to mid-October both in 2021 and 2022. Five 50cm x 50cm quadrats were placed randomly in each treatment plot (*Figure 2.9*) to determine total vegetation cover and vegetation height of tallest plant species. Specific plant taxa cover were recorded using a modified Braun-Blanquet scale (Braun-Blanquet et al., 1932) as shown in *Table 2.2*.

*Table 2.2 Modified Braun-Blanquet cover scale based on (Braun-Blanquet et al., 1932) and recorded vegetation parameters.*

| Braun-Blanquet cover scale (modified) | Vegetation parameters |
|---|---|
| 0 : Absent | Total vegetation cover |
| + : << 1% | Total unvegetated cover |
| 1 : < 1% | Mosses cover |
| 2 : 1-5% | Lichens cover |
| 3 : 6-10% | Grasses cover |
| 4 : 11-15% | Flowering dicots cover |
| 5 : 16-25% | |
| 6 : 26-50% | |
| 7 : 51-75% | |
| 8 : 76-100% | |

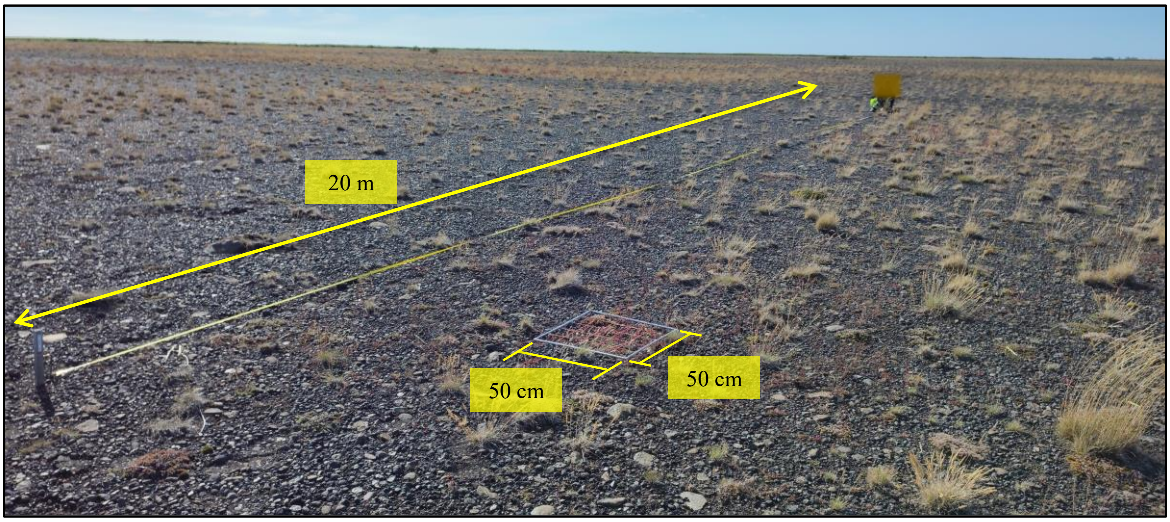


*Figure 2.9 Vegetation data sampling from the study site at Geitasandur. A 20m long sampling plot with a 50 cm x 50 cm quadrat placed inside it are shown to indicate difference in dimensions. (Photo by Parnika Gupta, 2022)*

### 2.2.3 Statistical Analysis

The data were analysed using IBM® SPSS® Statistics Version 27, USA. For 2021, vegetation survey data related to five types of soil amendments were collected after one growing season and classified into five categories: CON (Control, n = 8), BONE (Bonemeal, n = 4), CHEM1 (Chemical fertilizer 1, n = 4), CHEM2 (Chemical fertilizer 2, n = 4), and CHICK (Chicken manure, n = 4). For year 2022, soil properties, vegetation parameters and teabag index data related to eight types of soil amendments were collected after two growing seasons (except for BOK1 and BOK2 where the vegetation growth parameters in 2022 were measured after one growing season due to their late application) and classified into eight categories: CON (Control, n = 8), BONE (Bonemeal, n = 4), CHEM1 (Chemical fertilizer 1, n = 4), CHEM2 (Chemical fertilizer 2, n = 4), BOK1 (Bokashi 1, n = 4), BOK2 (Bokashi 2, n = 4), CHICK (Chicken manure, n = 4), and MOLTA (Molta compost, n = 4). Growing season here refers to months of June, July, August (i.e., after application of soil amendments in May 2021 for BONE, CHEM1, CHEM2, CHICK, MOLTA) due to the recorded precipitation and temperatures in Iceland during these months.

*Litter decomposition and stabilisation*

A one-way ANOVA, followed by a post-hoc Tukey's test (Tukey's HSD $\alpha = 0.05$) along with Bonferroni correction were conducted to determine if any of the eight soil amendments (CON, BOK1, BOK2, BONE, CHEM1, CHEM2, CHICK, MOLTA) had any significant effect on litter decomposition rate. To determine if there was any significant difference between litter stabilisation factor based on type of soil amendments, a Kruskal-Wallis H test was performed, followed by a post-hoc test (medians/distribution) for pairwise comparisons using Dunn's procedure with Bonferroni adjustment.

*Soil properties*

Variables such as soil organic matter and soil carbon-to-nitrogen ratio, were transformed using square-root and reciprocal transformations respectively to improve normality. To determine which soil amendments had significant effects on soil properties for 2022, one-way ANOVAs, followed by a post-hoc Tukey's test (Tukey's HSD $\alpha = 0.05$) along with Bonferroni correction were conducted. A Welch-ANOVA, followed by Games-Howell post hoc test, was used for variables that had a heterogeneity of variance, such as soil organic matter and soil carbon. When the variables were not normally distributed or had outliers, such as soil pH(water), a Kruskal-Wallis H test was performed, followed by a post-hoc test (medians/distribution) for pairwise comparisons using Dunn's procedure with Bonferroni adjustment. The soil available carbon (POXC) was not statistically analysed as it was only calculated using one block as an estimation.

*Vegetation growth parameters for 2021*

Variables, such as flowering dicots cover and vegetation height, were transformed using square-root and log10 transformations respectively to improve normality. To determine if the five soil amendments (CON, BONE, CHEM1, CHEM2, CHICK) had any significant effect on vegetation growth parameters for 2021, one-way ANOVAs, followed by a post-hoc Tukey's test (Tukey's HSD $\alpha = 0.05$) along with Bonferroni correction were conducted. A Welch-ANOVA, followed by Games-Howell post hoc test, was used for variables that had a heterogeneity of variance, such as vegetation height. When the variables were not normally distributed or had outliers, such as vegetation cover, moss cover, lichen cover, and grass cover, a Kruskal-Wallis H test was performed, followed by a post-hoc test (medians/distribution) for pairwise comparisons using Dunn's procedure with Bonferroni adjustment.

*Vegetation growth parameters for 2022*

Variables such as vegetation cover and flowering dicots cover were transformed using square-root transformations to improve normality. To determine if eight soil amendments (CON, BOK1, BOK2, BONE, CHEM1, CHEM2, CHICK, MOLTA) had any significant effect on vegetation growth parameters for 2022, one-way ANOVAs, followed by a post-hoc Tukey's test (Tukey's HSD $\alpha = 0.05$) along with Bonferroni correction were conducted. When the variables were not normally distributed or had outliers, such as moss cover, lichen cover, grass cover, and vegetation height, a Kruskal-Wallis H test was performed, followed by a post-hoc test (medians/distribution) for pairwise comparisons using Dunn's procedure with Bonferroni adjustment.

*Vegetation growth parameters for 2021 vs 2022*

The vegetation survey data did not follow the assumptions of parametric data analysis. Hence, related-samples Wilcoxon signed rank test was used to determine if a vegetation growth parameter varied significantly between 2021 and 2022. Furthermore, to determine if there were any significant differences between the vegetation growth parameters, the years (2021, 2022), and five soil amendments (CON, BONE, CHEM1, CHEM2, CHICK), a related-samples Friedman's two-way ANOVA by ranks, followed by a post-hoc test of pairwise comparisons with Bonferroni adjustment was conducted.

*Correlations between parameters*

To test for significant relationships between soil and vegetation parameters for 2022, a Spearman rank test was performed, using a p-value $<0.01$ to determine significant correlations.

# 2.3 Results

## 2.3.1 Litter decomposition and stabilisation

The litter decomposition rate was highest for soils treated with CHICK and lowest for those with CHEM2 (*Table 2.3*). The observed litter decomposition pattern was as followed: CHICK > BOK1 > CHEM1 > BONE > MOLTA > CON > BOK2 > CHEM2 (*Figure 2.10*). However, the differences between these soil amendment groups were not statistically significant (F(7, 28) = 1.212, p = 0.329).

The litter stabilisation factor was highest for soils treated with CHICK and lowest for those with BOK2 (*Table 2.3*). The observed litter stabilisation sequence was the following: CHICK > BONE > CHEM2 > MOLTA > CHEM1 > BOK1 > CON > BOK2 (*Figure 2.10*). These differences between the soil amendment groups were statistically significant ($\chi^2(7) = 19.841$, p = 0.006). The litter stabilisation factor of soils treated with CHICK was significantly higher than those in the CON (p = 0.033) and BOK2 (p = 0.020).

*Table 2.3 Litter decomposition and stabilisation. Both litter decomposition rate and stabilisation factor were measured using a tea-bag index study performed in 2022. Teabags were buried at the depth of 8 cm and incubated for 96 days. Data are presented as means (standard deviation) for eight types of soil amendments: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bone meal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, and MOLTA = Molta compost. Note that the litter stabilisation factor of soils treated with CHICK was significantly higher than those in the CON (p = 0.033) and BOK2 (p = 0.020).*

| **Amendments** | **Litter Decomposition Rate (k) (g g-1 per day)** | **Litter Stabilisation Factor (S) (unitless)** |
|---|---|---|
| CON (n=8) | 0.0078 (0.0018) | 0.40 (0.02) |
| BOK1 (n=4) | 0.0094 (0.0021) | 0.40 (0.03) |
| BOK2 (n=4) | 0.0075 (0.0005) | 0.39 (0.02) |
| BONE (n=4) | 0.0083 (0.0007) | 0.44 (0.01) |
| CHEM1 (n=4) | 0.0087 (0.0018) | 0.41 (0.02) |
| CHEM2 (n=4) | 0.0072 (0.0016) | 0.42 (0.01) |
| CHICK (n=4) | 0.0097 (0.0007) | 0.45 (0.01) |
| MOLTA (n=4) | 0.0079 (0.0023) | 0.41 (0.01) |
| Total (n=36) | 0.0082 (0.0017) | 0.41 (0.03) |

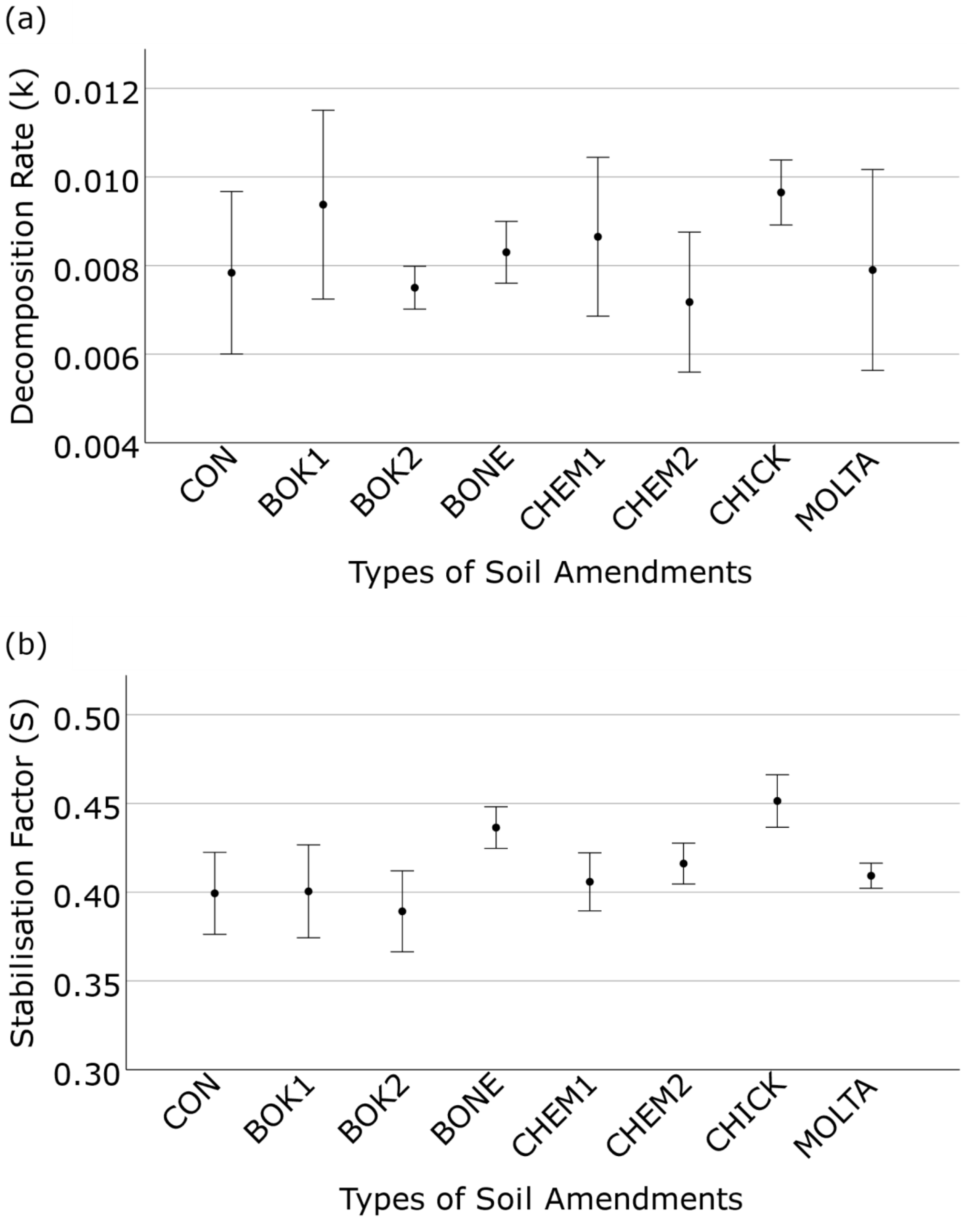


*Figure 2.10 (a) Litter decomposition rate (k) and (b) Stabilization factor (S) from tea-bag study experiment expressed as mean ± standard deviation for eight soil amendments: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bone meal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, and MOLTA = Molta compost. Note that the litter stabilisation factor of soils treated with CHICK was significantly higher than those in the CON (p = 0.033) and BOK2 (p = 0.020).*

### 2.3.2 Soil properties

Soil organic matter for all soil samples was 1.97 ± 0.29 % (Mean ± Standard deviation). The SOM was highest in soils treated with CHICK and BOK1, and lowest in the CON (*Table 2.4*). The observed SOM sequence exhibited the following pattern: BOK1, CHICK > BONE, CHEM1 > MOLTA > CHEM2 > BOK2 > CON (*Appendix A*, *Figure A.1a*). However, these differences among the soil amendment groups were not statistically significant (Welch's F(7, 10.875) = 0.805, p = 0.601).

Soil carbon for all soil samples was 0.251 ± 0.023 %, being highest in soils treated with CHEM2 and lowest in the CON (*Table 2.4*). The observed soil carbon pattern was as follows: CHEM2 > CHICK > CHEM1 > MOLTA > BOK1 > BOK2 > BONE > CON (*Appendix A, Figure A.1c*). Soil carbon did not vary significantly between the soil amendment groups (Welch's F (7, 10.514) = 1.733, p = 0.203).

Soil nitrogen for all soil samples was 0.028 ± 0.002 %. The highest soil nitrogen was in soils treated with CHEM1 and lowest in those with BONE (*Table 2.4*). Soil nitrogen showed the following pattern: CHEM > CHEM2 > BOK2 > CHICK, BOK1 > MOLTA > CON > BONE (*Appendix A, Figure A.1d*). Soil nitrogen, however, was not significantly different between the soil amendment groups (F(7, 28) = 1.250, p = 0.310).

Soil carbon to nitrogen ratio for all soil samples was 10.59 ± 0.58. It was highest for soil treated with CHEM2 and lowest for those with BOK2 (*Table 2.4*), showing the following pattern: CHEM2 > CHICK > MOLTA > CON > BONE > CHEM1 > BOK1 > BOK2 (*Appendix A, Figure A.1b*). The differences between these soil amendment groups were not statistically significant (F(7, 28) = 0.881, p = 0.534).

Soil pH(water) for all soil samples was near neutral pH at 6.82 ± 0.06. The highest soil pH was for soils treated with BONE and lowest for those with CHEM2 (*Table 2.4*), following this pattern: BONE > CON > BOK2, BOK1 > MOLTA > CHEM1 > CHICK > CHEM2 (*Figure 2.11*). The differences in soil pH between these soil amendment groups were statistically significant ($\chi^2(7) = 16.420$, p = 0.022). Soil pH(water) for soils treated with BONE was significantly higher than those treated with CHEM2 (p = 0.027).

Overall soil available carbon for soil samples from block-3 was 63.49 mg of POXC per kg of soil, with the highest values in soils treated with BOK1 and lowest in those from the CON. The following pattern was seen regarding overall soil available carbon and the amendments: BOK1 > BONE > BOK2 > CHEM1 > CHICK > CHEM2 > MOLTA > CON (*Table 2.5*).

*Table 2.4 Soil properties of soil samples collected from Geitasandur in May 2022. Samples were collected for eight types of soil amendments (CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, MOLTA = Molta compost). The data are presented as means (standard deviations). Note that Soil pH(water) for BONE plots was significantly higher than those treated with CHEM2 (p = 0.027).*

| **Amendments** | **SOM %** | **Soil C %** | **Soil N %** | **Soil C/N ratio** | **Soil pH(water)** |
|---|---|---|---|---|---|
| CON<br>(n=8) | 1.83 (0.24) | 0.241 (0.012) | 0.026 (0.001) | 10.61 (0.59) | 6.85 (0.05) |
| BOK1<br>(n=4) | 2.09 (0.45) | 0.253 (0.013) | 0.028 (0.002) | 10.48 (0.47) | 6.84 (0.02) |
| BOK2<br>(n=4) | 1.88 (0.40) | 0.245 (0.019) | 0.028 (0.002) | 10.06 (0.59) | 6.84 (0.04) |
| BONE<br>(n=4) | 2.04 (0.31) | 0.236 (0.016) | 0.026 (0.001) | 10.54 (0.37) | 6.88 (0.04) |
| CHEM1<br>(n=4) | 2.04 (0.49) | 0.263 (0.042) | 0.029 (0.003) | 10.52 (0.54) | 6.81 (0.12) |
| CHEM2<br>(n=4) | 1.94 (0.10) | 0.268 (0.016) | 0.029 (0.001) | 10.93 (0.76) | 6.76 (0.04) |
| CHICK<br>(n=4) | 2.09 (0.13) | 0.263 (0.016) | 0.028 (0.002) | 10.89 (0.38) | 6.77 (0.05) |
| MOLTA<br>(n=4) | 1.99 (0.14) | 0.254 (0.034) | 0.028 (0.003) | 10.69 (0.81) | 6.82 (0.01) |
| Total<br>(n=36) | 1.97 (0.29) | 0.251 (0.023) | 0.028 (0.002) | 10.59 (0.58) | 6.82 (0.06) |

*Table 2.5 Soil available carbon (POXC). Nine soil samples from the study site's block-3 were collected in May 2022 for eight types of soil amendments (CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, MOLTA = Molta compost). Data shown are only estimates, and no statistical analyses were performed due to small sample sizes.*

| **Amendments** | **POXC (mg/kg of soil)** |
|---|---|
| CON<br>(n=2) | 14.27 |
| BOK1<br>(n=1) | 123.58 |
| BOK2<br>(n=1) | 80.78 |
| BONE<br>(n=1) | 102.46 |
| CHEM1<br>(n=1) | 71.75 |
| CHEM2<br>(n=1) | 44.59 |
| CHICK<br>(n=1) | 51.89 |
| MOLTA<br>(n=1) | 18.57 |
| Total<br>(n=9) | 63.49 |

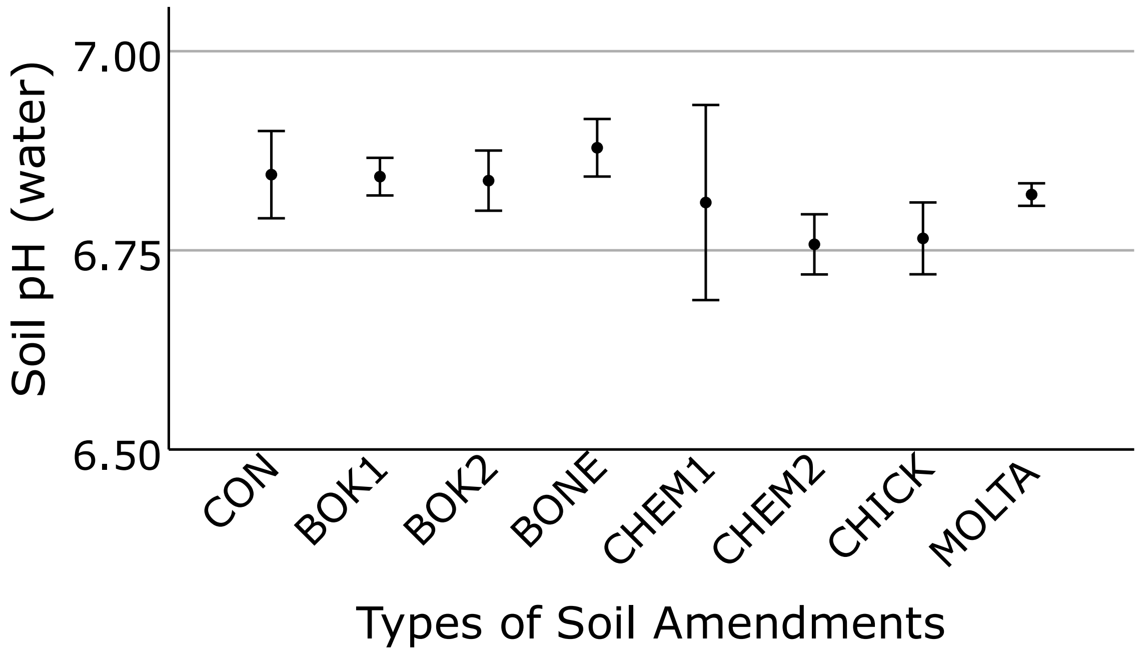


*Figure 2.11 Soil pH(water) presented as means ± standard deviations for the following soil amendments: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, and MOLTA = Molta compost. Note that Soil pH(water) for soils treated with BONE was significantly higher than those treated with CHEM2 (p = 0.027).*

## 2.3.3 Vegetation Growth Parameters

### 2.3.3.1 Vegetation survey data from 2021

Vegetation cover for all sampled plots in 2021 was 13.1 ± 7.1% (Mean ± Standard deviation), with the highest cover observed in plots treated with CHEM2 and the lowest in the CON (*Table 2.6*). The observed sequence was: CHEM2 > CHEM1 > CHICK > BONE > CON (*Appendix B, Figure B.1a*). Although a significant difference was found in the vegetation cover among the soil amendments ($\chi^2(4) = 10.628$, $p = 0.031$), comparisons between individual amendments were not significant ($p > 0.05$).

Vegetation height was 3.43 ± 1.45 cm for all sampled plots in 2021. It was highest in plots treated with CHEM2 and lowest in the CON (*Table 2.6*), showing this pattern: CHEM2 > CHEM1 > CHICK > BONE > CON (*Figure 2.12a*). The vegetation height was significantly different among the soil amendments (Welch's $F(4, 8.369) = 9.388$, $p = 0.004$), where CON plots had significantly shorter vegetation than those with CHEM1 ($p = 0.041$), CHEM2 ($p = 0.001$), and CHICK ($p = 0.024$).

*Vegetation taxa: Mosses, lichens, grasses, and flowering dicots.*

Moss cover for all sampled plots was 0.3 ± 0.2%, but it was not significantly different between any of the soil amendments ($\chi^2(4) = 0.698$, $p = 0.952$). Likewise, lichen cover was 0.4 ± 0.3% and there was no significant difference among the soil amendments ($\chi^2(4) = 1.532$, $p = 0.821$) (*Table 2.6* and *Appendix B, Figure B.1c & Figure B.1d*).

Grass cover was 4.9 ± 3.3%, being highest in plots with CHEM2 and lowest in the CON (*Table 2.6*), showing this ordered sequence: CHEM2 > CHICK > CHEM1 > BONE > CON (*Figure 2.12b*). Grass cover was significantly different between the soil amendments ($\chi^2(4) = 17.720$, $p = 0.001$), with CON plots having significantly less grass cover than those with CHEM2 ($p = 0.001$).

Lastly, flowering dicots cover in 2021 for all sampled plots was 8.6 ± 5.4% , with the highest cover in plots treated with CHEM1 and lowest for the CON (*Table 2.6*), showing the ordered sequence as: CHEM1 > CHICK > CHEM2 > BONE > CON (*Appendix B, Figure B.1b*). The differences in the flowering dicots cover among the soil amendments were not statistically significant ($F(4,19) = 1.839$, $p = 0.163$).

*Table 2.6 Vegetation parameters for soil amendments in 2021. Five types of soil amendments were used (CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure). Both means and standard deviations (shown in parentheses) are included. Note that vegetation height (cm) in CON plots was significantly lower than those with CHEM1 (p = 0.041), CHEM2 (p = 0.001), and CHICK (p = 0.024). Also, CON plots had significantly less grass cover than CHEM2 plots (p = 0.001).*

| **Amendments** | **Vegetation Cover (%)** | **Vegetation Height (cm)** | **Moss Cover (%)** | **Lichen Cover (%)** | **Grass Cover (%)** | **Flowering Dicots Cover (%)** |
|---|---|---|---|---|---|---|
| CON (n=8) | 6.9 (4.8) | 2.19 (0.83) | 0.3 (0.3) | 0.3 (0.2) | 1.9 (1.1) | 5.0 (2.7) |
| BONE (n=4) | 13.8 (4.4) | 2.84 (1.54) | 0.3 (0.2) | 0.6 (0.5) | 4.0 (1.9) | 9.5 (5.1) |
| CHEM1 (n=4) | 16.8 (5.7) | 3.99 (0.89) | 0.3 (0.2) | 0.3 (0.3) | 5.5 (1.9) | 11.7 (6.7) |
| CHEM2 (n=4) | 18.3 (7.2) | 5.42 (0.61) | 0.4 (0.3) | 0.4 (0.3) | 10.3 (1.9) | 10.3 (6.4) |
| CHICK (n=4) | 16.3 (7.8) | 3.95 (0.67) | 0.3 (0.2) | 0.4 (0.5) | 5.7 (2.0) | 10.5 (6.3) |
| Total (n=24) | 13.1 (7.1) | 3.43 (1.45) | 0.3 (0.2) | 0.4 (0.3) | 4.9 (3.3) | 8.6 (5.4) |

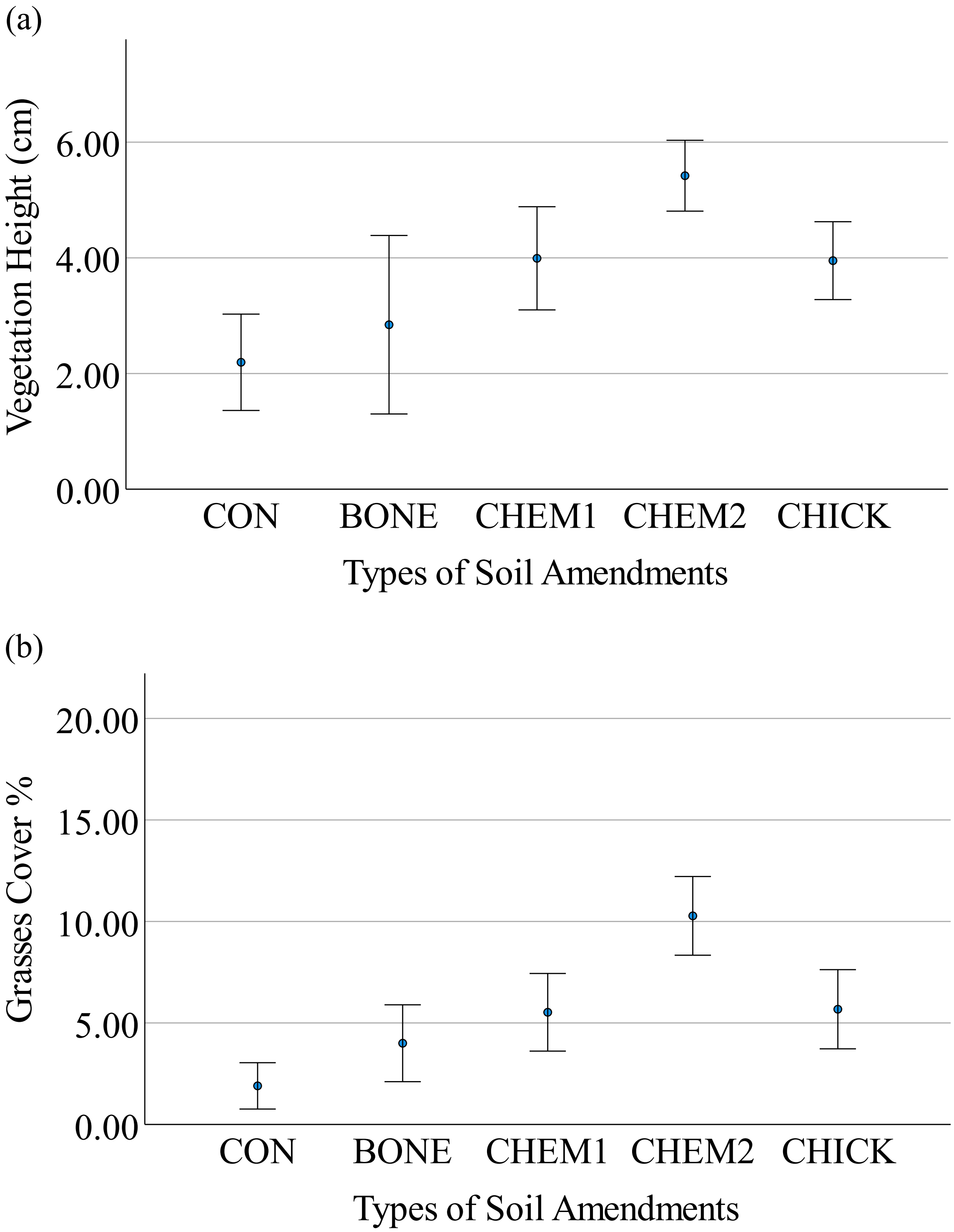


*Figure 2.12 Vegetation survey data (mean ± standard deviation) for soil amendments in 2021. Five types of soil amendments were used: CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure. (a) Vegetation height (cm), where CON plots had significantly shorter vegetation than those with CHEM1 ($p = 0.041$), CHEM2($p = 0.001$), and CHICK ($p = 0.024$). (b) Grass cover %, where CON plots had significantly less grass cover than CHEM2 plots ($p = 0.001$).*

### 2.3.3.2 Vegetation survey data from 2022

Vegetation cover for all sampled plots in 2022 was 12.6 ± 7.1% (Mean ± Standard deviation) as shown in *Table 2.7*. The vegetation cover was highest in soils treated with CHEM2 and lowest in the CON. The observed vegetation cover sequence was as follows: CHEM2 > CHICK > BONE > CHEM1 > MOLTA > BOK1 > BOK2 > CON (*Figure 2.13a*), and there were significant differences in vegetation cover among the soil amendments ($F(7,28) = 9.185$, $p < 0.001$, $\omega^2 = 0.608$). Specifically, the vegetation cover for CON was significantly lower from that of BONE ($p = 0.003$) and CHICK ($p < 0.001$), while the vegetation cover for plots treated with CHEM2 was significantly higher from those in the CON ($p < 0.001$), BOK1 ($p = 0.01$), BOK2 ($p = 0.002$), and MOLTA ($p = 0.02$).

Vegetation height for all sampled plots was 6.82 ± 6.39 cm (*Table 2.7*), with the tallest vegetation in plots treated with CHEM2 and shortest vegetation in those treated with BOK2. The following height pattern was observed: CHEM2 > CHICK > CHEM1 > BONE > MOLTA > BOK1 > CON > BOK2 (*Figure 2.13b*). Significant differences in vegetation heights were found among the soil amendment groups ($\chi^2(7) = 24.670$, $p < 0.001$). Vegetation height for CON plots was significantly lower than those with CHEM2 ($p = 0.02$) and CHICK ($p = 0.015$).

*Vegetation taxa: Mosses, lichens, grasses, and flowering dicots.*

Moss cover for all sampled plots in 2022 was 0.2 ± 0.2% (*Table 2.7*), and no significant differences were found among the soil amendments ($\chi^2(7) = 4.225$, $p = 0.754$) (*Appendix C, Figure C.1a*). Similarly, lichen cover for all sampled plots was 0.2 ± 0.2% (*Table 2.7*), with no significant differences detected among soil amendments ($\chi^2(7) = 1.226$, $p = 0.990$) (*Appendix C, Figure C.1b*).

Grass cover for all sampled plots was 4.5 ± 2.9% (*Table 2.7*), with the highest cover in plots treated with CHEM2 and lowest in the CON. The observed pattern for grass cover was: CHEM2 > CHICK > CHEM1 > MOLTA > BONE > BOK1 > BOK2 > CON (*Figure 2.13c*). Grass cover varied significantly among the soil amendments ($\chi^2(7) = 24.137$, $p = 0.001$). CON plots had significantly lower grass cover than plots treated with CHEM2 ($p < 0.001$) and CHICK ($p = 0.033$).

Flowering dicots cover for all sampled plots was 8.4 ± 5.7%, with highest cover in plots treated with CHEM2 and lowest in those with BOK1 (*Table 2.7*). The pattern observed was: CHEM2 > CHICK > BONE > CHEM1 > MOLTA > CON > BOK2 > BOK1 (*Appendix C, Figure C.1c*). Although a significant difference was found in the flowering dicot cover among the soil amendments ($F(7,28) = 3.208$, $p = 0.013$, $\omega^2 = 0.300$), comparisons between individual amendments were not significant ($p > 0.05$).

.

*Table 2.7 Vegetation parameters for soil amendments in 2022. The amendments were CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, and MOLTA = Molta compost. Means and Standard deviations (shown in parentheses) are presented. Note: CON plots had significantly less vegetation cover than BONE (p = 0.003) and CHICK (p < 0.001); and CHEM2 had significantly more vegetation cover than CON (p < 0.001), BOK1 (p = 0.01), BOK2 (p = 0.002), and MOLTA (p = 0.02). CON plots had significantly shorter vegetation than those with CHEM2 (p = 0.02) and CHICK (p = 0.015). Also, CON plots had significantly less grass cover than those with CHEM2 (p < 0.001) and CHICK plots (p = 0.033).*

| **Amendments** | **Vegetation Cover (%)** | **Vegetation Height (cm)** | **Moss Cover (%)** | **Lichen Cover (%)** | **Grass Cover (%)** | **Flowering Dicots Cover (%)** |
|---|---|---|---|---|---|---|
| CON (n=8) | 5.9 (3.6) | 2.42 (2.31) | 0.2 (0.2) | 0.2 (0.1) | 1.9 (1.1) | 5.3 (4. 8) |
| BOK1 (n=4) | 9.8 (2.8) | 3.06 (1.20) | 0.2 (0.1) | 0.2 (0.2) | 3.9 (2.0) | 5.0 (1.7) |
| BOK2 (n=4) | 8.4 (3.7) | 1.79 (0.51) | 0.2 (0.2) | 0.2 (0.1) | 3.1 (1.0) | 5.1 (2.8) |
| BONE (n=4) | 16.5 (2.6) | 6.11 (1.95) | 0.2 (0.2) | 0.3 (0.3) | 4.1 (2.1) | 11.3 (3.2) |
| CHEM1 (n=4) | 13.5 (5.1) | 8.94 (5.73) | 0.1 (0.1) | 0.2 (0.2) | 4.5 (1.5) | 8.7 (4.9) |
| CHEM2 (n=4) | 24.3 (8.6) | 16.19 (7.57) | 0.2 (0.2) | 0.3 (0.4) | 10.8 (2.6) | 15.2 (9.4) |
| CHICK (n=4) | 18.8 (4.7) | 15.41 (5.26) | 0.1 (0.1) | 0.2 (0.2) | 6.0 (1.4) | 13.0 (5.2) |
| MOLTA (n=4) | 10.3 (1.2) | 5.06 (3.30) | 0.3 (0.2) | 0.2 (0.1) | 4.4 (0.9) | 7.0 (1.1) |
| Total (n=36) | 12.6 (7.1) | 6.82 (6.39) | 0.2 (0.2) | 0.2 (0.2) | 4.5 (2.9) | 8.4 (5.7) |

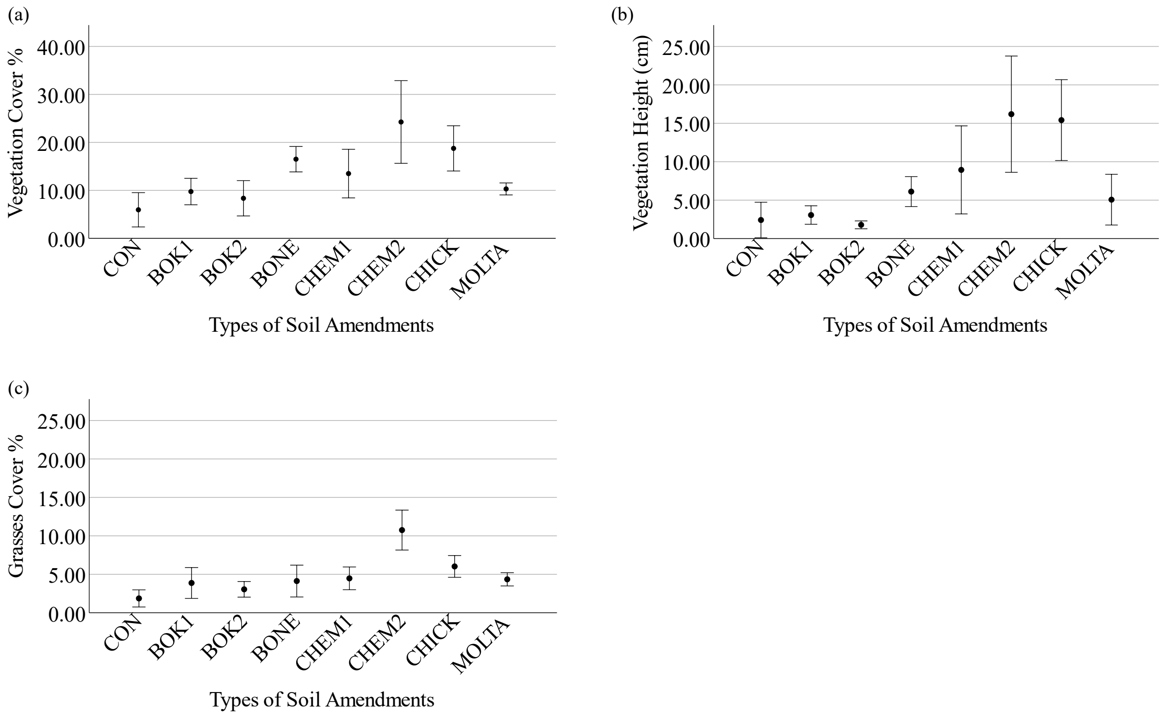


*Figure 2.13 Vegetation survey data (means ± standard deviations) for soil amendments in 2022. The eight types of soil amendments were: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, MOLTA = Molta compost. (a) Vegetation cover %, where CON plots had significantly less vegetation cover than those with BONE ($p = 0.003$) and CHICK ($p < 0.001$); and CHEM2 had significantly higher vegetation cover than CON ($p < 0.001$), BOK1 ($p = 0.01$), BOK2 ($p = 0.002$), and MOLTA ($p = 0.02$). (b) Vegetation height (cm), where CON plots had significantly shorter vegetation than those with CHEM2 ($p = 0.02$) and CHICK ($p = 0.015$). (c) Grass cover %, where CON plots had significantly less grass cover than those with CHEM2 ($p < 0.001$) and CHICK plots ($p = 0.033$).*

### 2.3.3.3 Vegetation survey data 2021 vs 2022

*Vegetation cover and vegetation height*

Overall vegetation cover for all sampled plots, irrespective of treatments, increased from 13.1 ± 7.1% (Mean ± Standard deviation) in 2021 to 14.2 ± 8.2% in 2022 (*Appendix D, Table D.1*), but this was not significantly different between the years ($z = 1.115$, $p = 0.265$). Vegetation cover was highest in plots with CHEM2-2022 and lowest in those in the CON-2022. The observed vegetation cover sequence was: CHEM2-2022 > CHICK-2022 > CHEM2-2021 > CHEM1-2021 > BONE-2022 > CHICK-2021 > BONE-2021 > CHEM1-2022 > CON-2021 > CON-2022 (*Figure 2.14a*). The difference in vegetation cover was statistically significant when compared between individual soil amendments within years, $\chi^2(9) = 21.092$, $p = 0.012$. Specifically, the vegetation cover for plots with CHEM2-2022 was significantly higher than those in the CON-2021 ($p = 0.032$) and CON-2022 ($p = 0.039$).

Similarly, overall vegetation height for all sampled plots, irrespective of treatments, increased from 3.43 ± 1.45 cm in 2021 to 8.58 ± 7.07 cm in 2022 (*Appendix D, Table D.1*), and these interannual differences were significant ($z = 3.314$, $p = 0.001$). Vegetation was tallest in plots with CHEM2-2022 and shortest in those with CON-2021. The observed sequence was: CHEM2-2022 > CHICK-2022 > CHEM1-2022 > BONE-2022 > CHEM2-2021 > CHEM1-2021 > CHICK-2021 > BONE-2021 > CON-2022 > CON-2021 (*Figure 2.14b*). The difference in vegetation height was statistically significant when compared between individual soil amendments within years, $\chi^2(9) = 30.873$, $p < 0.001$. Specifically, the vegetation height for plots with CHICK-2022 was significantly higher than those in the CON-2021 ($p = 0.048$) and CON-2022 ($p = 0.032$).

*Vegetation taxa: Mosses, lichens, grasses, and flowering dicots.*

Moss cover for all sampled plots, irrespective of treatments, was 0.3 ± 0.2% in 2021 and 0.2 ± 0.2% in 2022 (*Appendix D, Table D.2*) and this interannual difference was statistically significant between years ($z = -3.084$, $p = 0.001$), but comparisons between individual soil amendment treatments within years, were not significant, $\chi^2(9) = 12.990$, $p = 0.163$ (*Appendix D, Figure D.1a*). Similarly, lichen cover for all sampled plots, irrespective of treatments, was 0.4 ± 0.3% in 2021 and 0.2 ± 0.2% in 2022 (*Appendix D, Table D.2*), and this interannual difference was statistically significant between years ($z = -2.140$, $p = 0.032$), but comparisons between individual soil amendment treatments within years, were not significant, $\chi^2(9) = 5.026$, $p = 0.832$ (*Appendix D, Figure D.1b*).

Grass cover showed no significant difference between years, regardless of the treatments ($z = 0.190$, $p = 0.850$) and was 4.9 ± 3.3% in 2021 and 4.9 ± 3.4% in 2022 (*Appendix D, Table D.2*). Grass cover was highest in plots treated with CHEM2-2022 and lowest in those in the CON2021 and CON-2022, showing this pattern: CHEM2-2022 > CHEM2-2021 > CHICK-2022 > CHICK-2021 > CHEM1-2021 > CHEM1-2022 > BONE-2022 > BONE-2021 > CON-2022 = CON-2021 (*Figure 2.14c*). The difference in grass cover was statistically significant when compared between individual soil amendments within years, $\chi^2(9) = 29.752$, $p < 0.001$. Grass cover for CON-2021 plots was significantly lower than plots with CHEM2-2021 ($p = 0.008$) and CHEM2-2022 ($p = 0.005$). Similarly, grass cover for CON-2022 plots was significantly lower than plots with CHEM2-2021 ($p = 0.013$) and CHEM2-2022 ($p = 0.008$).

Lastly, flowering dicots cover also showed no significant difference between years (z = 1.234, p = 0.217) and was 8.6 ± 5.4% in 2021 and 9.8 ± 6.4% in 2022 (*Appendix D, Table D.2*). Flowering dicots cover was highest in plots with CHEM2-2022 and lowest in those in the CON-2021, and the observed pattern was: CHEM2-2022 > CHICK-2022 > CHEM1-2021 > BONE-2022 > CHICK-2021 > CHEM2-2021 > BONE-2021 > CHEM1-2022 > CON-2022 > CON-2021 (*Appendix D, Figure D.1c*). There was no significant difference in flowering dicots cover when compared between individual soil amendments within years ($\chi^2(9) = 15.513$, p = 0.078).

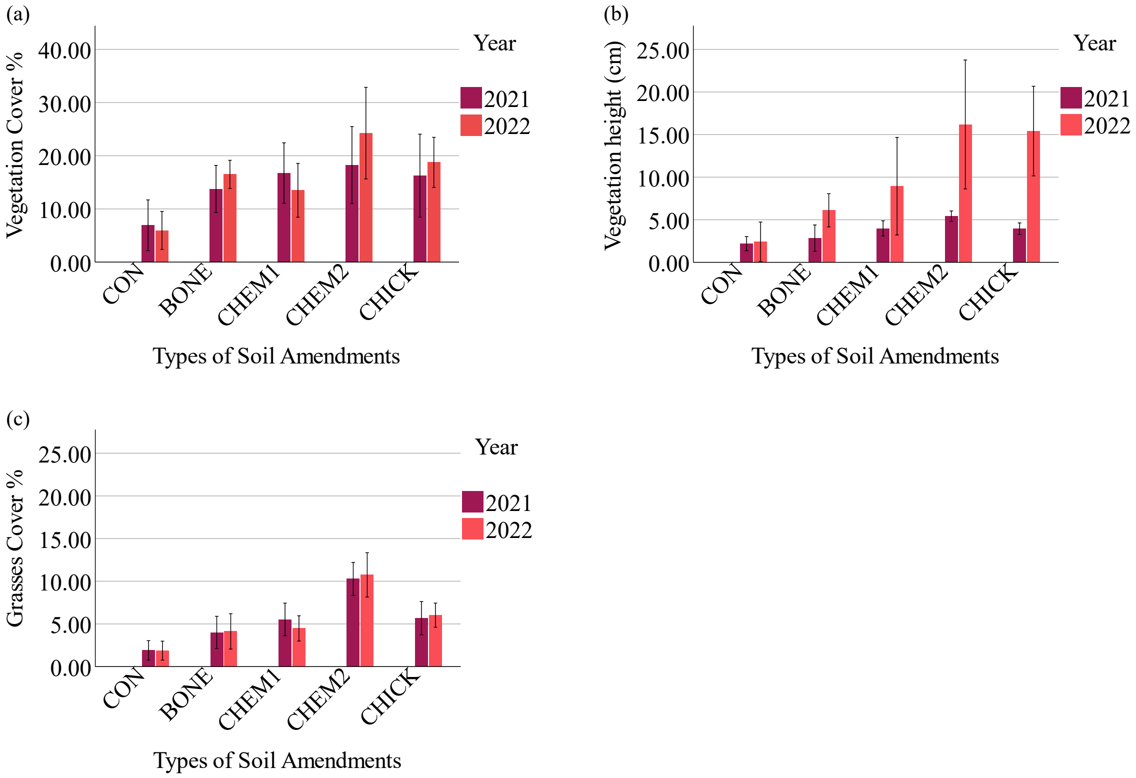


*Figure 2.14 Vegetation survey data (mean ± standard deviation) for soil amendments in 2021 and 2022. Five types of soil amendments were used: CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure. (a) Vegetation cover %, where CHEM2-2022 had significantly more vegetation cover than CON-2021 (p = 0.032) and CON-2022 (p = 0.039). (b) Vegetation height (cm), where CHICK-2022 plots had taller vegetation than CON-2021 (p = 0.048) and CON-2022 (p = 0.032). (c) Grass cover %, where CON-2021 plots had significantly less grass cover than CHEM2-2021 (p = 0.008) and CHEM2-2022 (p = 0.005); and CON-2022 plots had significantly less grass cover than CHEM2-2021 (p = 0.013) and CHEM2-2022 (p = 0.008).*

### 2.3.4 Correlations between parameters for 2022

Litter stabilisation factor was positively correlated with vegetation cover, vegetation height, grass cover and flowering dicots cover, but not with any other parameters of soil or vegetation (*Table 2.8*). Soil organic matter was also positively correlated with litter decomposition rate, soil nitrogen and moss cover. Soil carbon showed a strong positive correlation with soil nitrogen and soil carbon-to-nitrogen ratio.

Similarly, the vegetation cover showed a strong positive correlation with vegetation height, grass cover, and flowering dicots cover. Vegetation height was positively correlated with grass cover and flowering dicots cover (*Table 2.8*).

_Table 2.8 Spearman correlation coefficients between soil properties and vegetation parameters for the year 2022 (n = 36). Soil properties include litter decomposition rate (k, g g-1 per day), litter stabilisation factor (S, unitless), soil organic matter (SOM %), soil carbon (SC %), soil nitrogen (SN %), soil carbon to nitrogen ratio (Soil C/N ratio), & soil pH(water), and vegetation parameter include vegetation cover (Veg. %), vegetation height (Veg. Height, cm), moss cover (Moss %), lichen cover (Lichen %), grass cover (Grass %), and flowering dicots cover (Flowering Dicots %). Note: ** = $p < 0.01$_

| **Year 2022** | **k** | **S** | **SOM %** | **SC %** | **SN %** | **Soil C/N Ratio** | **Soil pH(water)** | **Veg%** | **Veg. Height (cm)** |
|---|---|---|---|---|---|---|---|---|---|
| **k** | | | | | | | | | |
| **S** | 0.120 | | | | | | | | |
| **SOM %** | 0.708** | 0.102 | | | | | | | |
| **SC %** | 0.126 | 0.061 | 0.333 | | | | | | |
| **SN %** | 0.315 | -0.001 | 0.424** | 0.792** | | | | | |
| **Soil C/N Ratio** | -0.143 | 0.113 | 0.105 | 0.479** | -0.076 | | | | |
| **Soil pH(water)** | 0.158 | -0.224 | 0.055 | -0.207 | 0.077 | -0.320 | | | |
| **Veg%** | -0.019 | 0.461** | 0.068 | 0.328 | 0.128 | 0.303 | -0.260 | | |
| **Veg. Height (cm)** | 0.248 | 0.492** | 0.217 | 0.232 | 0.164 | 0.169 | -0.269 | 0.735** | |
| **Moss %** | 0.322 | 0.142 | 0.475** | -0.138 | -0.022 | -0.113 | 0.091 | -0.065 | 0.149 |
| **Lichen %** | -0.063 | 0.158 | -0.002 | -0.015 | -0.058 | 0.039 | -0.079 | 0.002 | 0.030 |
| **Grass %** | 0.028 | 0.460** | 0.054 | 0.348 | 0.298 | 0.029 | -0.425 | 0.714** | 0.743** |
| **Flowering Dicots %** | -0.102 | 0.488** | 0.041 | 0.265 | 0.080 | 0.335 | -0.218 | 0.879** | 0.589** |

# 2.4 Discussion and recommendations

## 2.4.1 Soil properties

This research shows the sensitivity of soil pH to the addition of new materials in the soil, especially chemical fertilizer 2 (CHEM2) and bone meal (BONE). Soil pH(water) increased with the addition of bonemeal (BONE) in comparison to that of chemical fertilizer 2 (CHEM2). The increasing pH of soil may be explained by the presence of calcium and phosphorus in the bonemeal (BONE) amendment which acts as a liming agent and causes the increase in OH- ions in soil solution (Matsuoka-Uno et al., 2022; Verde et al., 2010). The decrease in soil pH due to chemical fertilizer 2 (CHEM2) could be due to the nitrification of any excess or unused readily available nitrogen that was added through the application of chemical fertilizer 2 (CHEM2). This process of nitrification is associated with microbial activity and produces nitric acid, thus increasing the acidity of soil and lowering the soil pH (Li et al., 2023). Another factor influencing this decrease of soil pH can be the increase in vegetation cover observed in the plots treated with chemical fertilizer 2 (CHEM2). Many studies have found that soil pH tends to decrease with increase in vegetation cover and soil organic carbon, even with a narrow range of soil pH (Arnalds, 2015; Arnalds et al., 2013; Fujii et al., 2012; Mankasingh & Gísladóttir, 2019; Vilmundardóttir et al., 2014). For instance, Mankasingh and Gísladóttir (2019) observed lower soil pH(KCl) in vegetated soils than that of sparsely vegetated soils irrespective of soil profile depth. Arnalds et al. (2013) also observed significant decreases in pH for sandy gravel soils in south of Iceland after five and seven years post revegetation and fertilization in comparison to control plots that were untreated and had sparse vegetation. These observed changes in the soil pH may also indicate that the buffering capacity of soils may be insufficient to provide resistance to pH changes due to addition of soil amendments (Lumbanraja & Evangelou, 1991; Magdoff & Bartlett, 1985). Mankasingh and Gísladóttir (2019) also observed a strong correlation of cation exchange capacity to soil pH for sites with sparse vegetation. However, the buffering capacity and CEC of the soil were not measured in this study, but it would be helpful to measure them in the future to assess their relationship with soil pH under different types of organic soil amendments. The increase in soil pH aligns with the findings of Verde et al. (2010), where the liming and heating of soils also increased soil pH. Moreover, Zheng et al. (2023) found an increase in soil pH due to the addition of variable amounts of bone meal. However, the increase in soil pH in this study is not in agreement with the results of Nogalska et al. (2017), where the increased doses of meat and bone meal (80 - 200 kg N/ha) supplemented with mineral potassium applied over three years resulted in decreased soil pH. Long term research is needed to further assess the differences in soil pH between chemical fertilizer 2 (CHEM2) and bonemeal (BONE). This may be helpful to identify whether locally sourced bonemeal can be an alternative to imported chemical fertilizers for increasing soil pH, especially for those soils which have been facing acidification due to continuous application of chemical fertilizers (Massah & Azadegan, 2016; Montanarella et al., 2016; Savci, 2012a).

The type of soil amendment used had no significant effect on soil organic matter, soil carbon, soil nitrogen, and soil carbon to nitrogen ratio. These results align with the slow process of soil development (Möckel, 2016; Vilmundardóttir et al., 2014) through addition of soil amendments (Liu et al., 2020; Takahashi, 2014). Changes in soil properties due to soil amendments of any kind are slow and long-term, ranging from a few years to several decades (Ballantine & Schneider, 2009; Hill, 2023; Paustian et al., 1992) and hence, the time period of this study (2 years) may be too short to detect any significant changes in soil properties. This highlights the need for long-term monitoring of soil properties and development given different soil amendments. Diligent monitoring of the long-term effects of these amendments on soil health can help optimize resource use, reduce waste, reduce landfills, and enhance the sustainability of agricultural and restoration practices, aligning with the principles of the circular economy, which emphasizes the efficient use of resources and minimizing environmental impact (European Commission Directorate-General for Environment, 2021a, 2021b).

The soil available carbon, measured on a single block within the study area, is only an estimate and do not show a complete picture due to the small sample size used. Despite this, soil amendments such as bokashi compost (BOK1, BOK2) and bonemeal (BONE) had the highest soil available carbon, whereas Molta compost (MOLTA) was very similar to the control (CON) plots. Soil available carbon represents the readily available carbon that can be used directly by soil biota (Brussaard, 2012; Brussaard et al., 2007; Lladó et al., 2017). The addition of amendments with high amounts of readily available carbon may help restore soil biodiversity (Li et al., 2022; Pushkareva et al., 2021) and resilience to climate change (Cheng et al., 2023; Liu et al., 2020). The large variation in  soil available carbon values highlights the need to study the amount of labile carbon at various time intervals post amendment application. This will help identify locally available organic alternatives to chemical fertilizers.

### 2.4.2 Vegetation growth parameters

In just one growing season (2021), chemical fertilizer plots (CHEM1, CHEM2) and plots with chicken manure ((CHICK) had significantly taller vegetation (1.8-2.5x) than the control plots. In addition, chemical fertilizer 2 (CHEM2) plots had significantly more grass cover (5.4x), than the controls. This trend continued in the plots treated with chemical fertilizer 2 after two growing seasons post application. Furthermore, plots with chemical fertilizer 2 (CHEM2) had significantly more vegetation cover after two growing seasons than the controls (CON) and the organic amendment plots with bokashi compost (BOK1, BOK2), and Molta compost (MOLTA). Nonetheless, plots treated with chicken manure (CHICK) showed significantly higher vegetation cover (~3x) relative to the controls after two growing seasons. The changes in vegetation parameters seen in this study indicate that addition of chemical fertilizers result in measurable changes in the vegetation growth parameters (e.g., vegetation cover, grass cover, vegetation height) which are noticeable in the short-term (one growing season). Whereas the use of organic amendments such as bonemeal and chicken manure take longer (at least two growing seasons) to yield noticeable changes in vegetation. This can be explained as the addition of chemical fertilizers provides readily available nutrients to the soil, making it easier for plants to take them up, than the complex forms of nutrients found in the other organic soil amendments (Anda & Dahlgren, 2020; Lopes et al., 2021; Shaji et al., 2021; Verde et al., 2010; Wilhelm et al., 2022). Over time, the vegetation starts to increase, and vegetation growth parameters become measurable for plots treated with organic soil amendments mainly due to the increase in plant available nutrients after their decomposition progresses. The chemical fertilizer 1 (CHEM1) plots only had significantly taller vegetation than the controls (CON) in the first growing season. This may be explained by complete nutrient uptake by plants in the first growing season leaving limited nutrients for plants to use the following growing season. Alternatively, the added nutrients may have leached away so that none were left in the soil to be used the next year.

Since leached or plant available nutrients were not measured in this study, an important research priority is to measure nutrient availability for plants and amount of leached nutrients after the addition of soil amendments. This can be done by sampling soil at various depths and then comparing the availability of nutrients among various soil layers and corelating vegetation growth post amendment application (Brenner, 2016; Major et al., 2012; Möckel, 2016; Zaman et al., 2002).

Mosses, lichens, and flowering dicots cover did not change significantly between 2021 and 2022. This suggests that these vegetation taxa did not outcompete the growth of grasses within the two growing seasons and may likely need more time to show significant and measurable changes in growth based on the type of soil amendments. They may also require varied amounts of these soil amendments. Given this, measuring changes in slow growing vegetation taxa such as mosses and lichens, would benefit from longer term studies (>five years). Moreover, the vegetation parameters for plots treated with bokashi compost were very similar to the control plots. The late application of bokashi compost (BOK1 and BOK2) may have contributed to the lack of significant changes in vegetation. The bokashi treatments need to be evaluated further for their efficacy with respect to vegetation growth. A few studies conducted in Mexico and USA have found that bokashi compost can have positive effects on plant growth (Abo-Sido, 2018; Abo-Sido et al., 2021; Solís et al., 2016). Further research is required to assess if bokashi compost made from locally sourced organic waste can be an alternative to imported chemical fertilizers.

There seems to be a positive relationship between the amount of nitrogen applied through the soil amendments, time passed post application, and vegetation growth. The amount of applied nitrogen was directly proportional to the increase in vegetation cover for bonemeal (BONE, 50 kg N/ha), chicken manure (CHICK, 100 kg N/ha), and chemical fertilizers (CHEM1, 50 kg N/ha; CHEM2, 100 kg N/ha) in comparison to controls. This observation is in agreement with expected findings and with other studies, showing that an increase in applied nitrogen results in greater vegetation growth (Balikoowa, 2014; Hauck, 1981; Ingestad, 1977; Liu et al., 2020; Matsuoka-Uno et al., 2022; Tjilumbu, 2012). One of the major reasons for using synthetic nitrogen fertilizers is to increase crop yields. This highlights organic soil amendments such as bonemeal and chicken manure as potential alternatives that have similar amount of applied nitrogen and can replace chemical fertilizers without compromising vegetation growth. However, Molta compost (MOLTA) has the highest soil C/N ratio (33.1) among all soil amendments in this study but there was no significant change in vegetation cover for the plots treated with Molta compost (MOLTA, 100 kg N/ha) in comparison to control (CON) plots. This further indicates that amount of nitrogen applied may not be the sole factor responsible for the observed changes in vegetation growth over time. Instead, this may also depend on the soil C/N ratio, amount of soil nitrogen readily available post amendments along with the texture and type of soil amendments (Pascault et al., 2013). This is supported by the findings of Qian and Schoenau (2002) where in short-term, availability of nitrogen decreased when C/N ratio of organic amendment was over 15 indicating C/N ratio of manure had a significantly negative corelation with N mineralization for manure-amended soils. Qian and Schoenau (2002) also emphasizes that factors such as manure processing and forms can also be responsible for changes in available nitrogen in addition to C/N ratio of organic soil amendments. Since this study observed the response of vegetation growth parameters within two years post soil amendment application, further research is required to evaluate long-term changes. For instance, it would be useful to do a study measuring readily available nutrients (e.g., carbon, nitrogen, phosphorus) and changes in vegetation growth after each growing season post application for five and ten years and assess relationships between vegetation growth, amount of applied nitrogen, and readily available nutrients. This would help to identify and further explore the dynamics of nitrogen supplementation based on studies setup for time periods longer than two years.

### 2.4.3 Litter decomposition and stabilisation

In the tea-bag study, decomposition rate is indicative of short-term dynamics of new input into the soil, i.e., decomposition of labile fraction or labile compounds by microorganisms and mesofauna present in soil (Fujii et al., 2017; Keuskamp et al., 2013). Since the teabag study uses standardised material in the form of green and rooibos tea, decomposition rates are only indicative of microbial activity and do not provide information on actual decomposition of the added soil amendments (Duddigan et al., 2022). Decomposition rates did not vary significantly among the soil amendments, suggesting that the soils treated with various amendments had similarity in labile fractions or similar amounts of labile compounds present. These results contrasted with other studies where decomposition rates were significantly different due to amendment application (Duddigan et al., 2020; Duddigan et al., 2022). Microbial activities are sensitive to changes in temperature and moisture causing varied decomposition rates (Murphy et al., 1998; Withington & Sanford, 2007). This study did not consider soil moisture, but it is a research priority to assess the impacts of amendment application on decomposition rate and microbial activities in relation to changes in soil moisture and local temperature to find suitable locally sourced, sustainable alternatives to chemical fertilizers.

The stabilisation factor is indicative of long-term carbon storage (Elumeeva et al., 2018; Fujii et al., 2017; Keuskamp et al., 2013) and a significantly higher stabilisation factor was observed for soils treated with chicken manure (CHICK) than those in the control (CON) and bokashi 2 (BOK2) plots. This suggests that the recalcitrant carbon compounds or fractions present in plots treated with chicken manure may increase soil carbon stability, by taking longer to decompose than the control and bokashi treated soils. Recalcitrant carbon compounds tend to be responsible for the long-term accumulation of carbon making it possible to lower carbon emissions and increase carbon sequestration in soils (Ball et al., 2022; Daebeler et al., 2022; Lecerf et al., 2021; Liu et al., 2022; Martínez-García et al., 2021). This makes chicken manure a very promising soil amendment for long-term carbon sequestration in soils. A few studies conducted in China and USA have found that soil amendments such as chicken manure and biochar produced from chicken manure can have positive effects on carbon sequestration in soils (Huang et al., 2019; Xiao et al., 2018). However, this study in Geitasandur was relatively short term (2 years) to find conclusive evidence for soil carbon sequestration using chicken manure, further warranting the need for long term research. Cayci et al. (2017) observed some positive effects of chicken manure on soils such increased soil aggregation properties, soil organic carbon, and electrical conductivity, while Kacprzak et al. (2023) highlights harmful impacts of poultry manure, such as unbalanced C/N ratio and contamination due to pathogens. Further research is needed to study the carbon sequestration dynamics of these organic and chemical amendments. This could be done by conducting a teabag study on the same plots every year to see the effect of time on stabilisation factor among soil amendments. In addition, weekly measurements can be made to detect changes in decomposition and stabilisation of the litter. Such information would be helpful in identifying changes in litter over time and evaluating carbon sequestration potential of organic amendments.

### 2.4.4 Relation between soil properties and vegetation

The litter stabilisation measured in the teabag study is reflective of the k-strategist soil organisms and explains the strong positive correlation of stabilisation factor with the cover of vegetation, grasses, and flowering dicots, as well as vegetation height, because plants use nitrogen associated compounds to fasten their growth. The strong positive correlations of SOM with litter decomposition rate, soil nitrogen and mosses cover are related to the addition of soil amendments. Soil biota decomposes the added residue and breaks them down into smaller matter contributing directly to the soil organic matter (Brussaard et al., 2007). Changes in the soil organic matter is then directly related to soil properties such as soil aggregate size, and soil humic and non humic substances, which subsequently result in changes in nutrient cycling, and interactions between plant growth and soil nutrient cycling (Chari & Taylor, 2022; de Graaff et al., 2006; Hoffland et al., 2020). Soil organic matter is often lost from the soil in the form of carbon dioxide produced by the decomposition of soil microorganisms (Carney et al., 2007). The slow k-strategist soil organisms are responsible for the decomposition of recalcitrant compounds present in soil or added amendments (Meyer, 1994), while the rapid r-strategist soil organisms are responsible for decomposition of labile compounds (Kielak et al., 2009; Pan et al., 2022). The r-strategist organisms soon die from starvation after exhausting easily decomposed compounds, and continuously add to the soil organic matter (Brady & Weil, 2014; Pascault et al., 2013). The k-strategists organisms continue to degrade cellulose and lignin, and further the decomposition of dead microbial cells causing mineralisation and release of inorganic compounds such as nitrates and sulphates (Fontaine et al., 2003; Meyer, 1994; Pan et al., 2022). The remaining carbon in the soil is then converted into soil humus which is highly resistant and counts toward soil carbon storage by slightly increasing the stable pool of soil organic matter (Cotrufo et al., 2019; de Graaff et al., 2006; European Commission, 2019). Global rise in atmospheric $CO_2$ levels may have negative impacts on soil microbial communities (Sun et al., 2021). Further research is needed to investigate the effect of the global $CO_2$ levels on the corelation between litter stabilisation factor, vegetation growth and soil amendments.

Soil carbon showed a strong positive correlation with soil nitrogen and soil carbon-to-nitrogen ratio. This can be explained by close link between soil nitrogen and soil carbon. Nitrogen, when returned to soil, exists in equilibrium with a larger and much stable humus associated pool, and this equilibrium shifts towards immobilization and mineralization based on higher and lower input of carbon respectively with respect to added nitrogen input (Schlesinger, 2009; Singh, 2011). Lastly, the strong positive correlations of vegetation cover with vegetation height, grass cover and flowering dicots cover can be explained by the positive response of vegetation to increased nutrient availability (in ’t Zandt et al., 2019; Klanderud, 2008; Liu et al., 2020). Further research is required to monitor the response of vegetation in different amendment plots to see how the plant communities vary over time and to investigate if there is any competition within vegetation taxa due to nutrient addition through organic soil amendments.

## 2.5 Conclusion

This study was able to measure some changes in Icelandic soil properties and vegetation growth due to addition of various organic and chemical soil amendments. None of the soil amendments caused any significant changes to soil properties (SOM, SC, SN, soil C/N ratio), except soil pH which was sensitive to changes and significantly higher in bonemeal plots, than in plots where higher dose of chemical fertilizer (chemical fertilizer 2) was applied. This highlights the need for long-term monitoring of soil properties, development, and health given different soil amendments. Vegetation growth parameters such as grass cover and vegetation height were significantly higher in just one growing season due to addition of chemical fertilizer 2 in comparison to the controls. After two growing seasons post amendment application, vegetation cover also started to show measurable and significant changes with the use of chemical fertilizer 2, chicken manure, and bonemeal relative to the control plots. Long-term research on the changes in vegetation growth and succession post amendment application (e.g., 5 to 10 years post amendment) is a priority. This will help identify and further explore the dynamics of nitrogen supplementation over time. Furthermore, it will help evaluate other locally sourced organic amendments, such as bokashi compost and Molta compost. Although decomposition rate did not vary significantly among soil amendments, stabilisation factor was significantly higher for chicken manure than in the control and bokashi plots, indicating the long-term potential of carbon sequestration in soils treated with chicken manure. Based on this study, chicken manure and bonemeal are promising replacements for chemical fertilizers as they cause changes in soil acidity and vegetation that are measurable and significant within a short time period (2 years post application). Moreover, the cost associated with imported chemical fertilizers, especially for Iceland, may be reduced by using locally sourced organic amendments. With the help of a web calculator developed by SCSI and EFLA (n.d.), it is possible to calculate the cost of using various organic soil amendments for reclamation in comparison to using chemical fertilizer. Results from it show that depending on the type of organic amendment and transport distances, the organic materials sometimes cost less than using chemical fertilizer (e.g. chicken manure). Thus, in some cases, costs for reclamation can be reduced by using locally sourced materials. Although this study was only two-year long, the results suggest that chicken manure may potentially be useful for carbon sequestration and bonemeal can be used to increase soil alkalinity in regions where soils are facing threat of acidification, but long-term research is warranted. Additional research on locally sourced organic amendments and their long-term effects on soil, vegetation, and the environment, would be helpful to identify more options that can be a part of the sustainable agricultural practices in Iceland. Using these organic amendments for soil restoration activities promotes circular economy by reducing and reusing waste, which usually ends up in landfills and causes harmful emissions, and is an important step towards achieving carbon neutrality, guiding policies on soil restoration, and waste management in Iceland and around the world.

# References

Abo-Sido, N. (2018). *Analysis of the nutrient composition, efficacy, and sustainability of bokashi fertilizers* [Honors thesis, The Wellesley College]. https://repository.wellesley.edu/object/ir787

Abo-Sido, N., Goss, J. W., Griffith, A. B., & Klepac-Ceraj, V. (2021). *Microbial transformation of traditional fermented fertilizer bokashi alters chemical composition and improves plant growth* [preprint]. https://doi.org/10.1101/2021.08.01.454634 ; https://www.biorxiv.org/content/biorxiv/early/2021/08/02/2021.08.01.454634.full.pdf

Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S., & Rounsevell, M. D. A. (2023). High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. *Nature Food*, *4*(1), 84-95. https://doi.org/10.1038/s43016-022-00659-9

Allen, S. E., Grimshaw, H. M., & Rowland, A. P. (1986). Chemical Analysis. In P. D. Moore & S. B. Chapman (Eds.), *Methods of Plant Ecology* (Second ed., pp. 285-344). Blackwell Scientific Publications.

Anda, M., & Dahlgren, R. A. (2020). Mineralogical and surface charge characteristics of Andosols experiencing long-term, land-use change in West Java, Indonesia. *Soil Science and Plant Nutrition*, *66*(5), 702-713. https://doi.org/10.1080/00380768.2020.1820758

Aparna, K., Pasha, M. A., Rao, D. L. N., & Krishnaraj, P. U. (2014). Organic amendments as ecosystem engineers: Microbial, biochemical and genomic evidence of soil health improvement in a tropical arid zone field site. *Ecological Engineering*, *71*, 268-277. https://doi.org/https://doi.org/10.1016/j.ecoleng.2014.07.016

Aradóttir, Á. L. (2003). Restoration challenges and strategies in Iceland. *Briefing papers of the first SCAPE workshop, Alicante, Spain*, 61-65. Retrieved July 30, 2023, from https://www.researchgate.net/publication/238733982_Restoration_challenges_and_strategies_in_Iceland

Aradóttir, Á. L., Petursdottir, T., Halldorsson, G., Svavarsdottir, K., & Arnalds, O. (2013). Drivers of Ecological Restoration: Lessons from a Century of Restoration in Iceland. *Ecology and Society*, *18*(4). https://doi.org/10.5751/ES-05946-180433

ArcGIS StoryMaps. (2023). https://storymaps.arcgis.com/

Arias, O., Pulgar, J. A., & Soto, M. (2022). Application of organic wastes to soils and legislative intricacies in a circular economy context. *Clean Technologies and Environmental Policy*, *24*(6), 1871-1888. https://doi.org/10.1007/s10098-022-02293-2

Arnalds, O. (2004). Volcanic soils of Iceland. *CATENA*, *56*(1), 3-20. https://doi.org/10.1016/j.catena.2003.10.002

Arnalds, O. (2015). *The Soils of Iceland* (1st ed.). Springer. https://doi.org/10.1007/978-94-017-9621-7

Arnalds, O., Aradóttir, A. L., & Thorsteinsson, I. (1987). The Nature and Restoration of Denuded Areas in Iceland. *Arctic and Alpine Research*, *19*(4), 518-525. https://doi.org/10.2307/1551419

Arnalds, O., Orradottir, B., & Aradottir, A. L. (2013). Carbon accumulation in Icelandic desert Andosols during early stages of restoration. *Geoderma*, *193-194*, 172-179. https://doi.org/10.1016/j.geoderma.2012.10.018

Arnalds, O., Thorarinsdottir, E. F., Metusalemsson, S., Jonsson, A., Gretarsson, E., & Arnason, A. (2001). *SOIL EROSION IN ICELAND*. The Soil Conservation Service and the Agricultural Research Institute. https://www.researchgate.net/publication/285702002_Soil_Erosion_in_Iceland

Asare, W. (2019). *Effects of bone meal on physiochemical soil properties of a fertilized reclamation site in Iceland.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/effects-of-bone-meal-on-physiochemical-soil-properties-of-a-fertilized-reclamation-site-in-iceland

Áskelsdóttir, S. (2012). *Changes in soil organic carbon in four long-term hayfield fertilisation experiments in Iceland: Monitoring and modelling* [Master's Thesis, Agricultural University of Iceland]. Reykjavík,. http://hdl.handle.net/1946/13249

Aytenew, M., & Bore, G. (2020). Effects of Organic Amendments on Soil Fertility and Environmental Quality: A Review. *Journal of Plant Sciences*, *8*(5), 112-119. https://doi.org/10.11648/j.jps.20200805.12

Azevedo, J., & Stout, P. R. (1974). *Farm animal manures; an overview of their role in the agricultural environment* [Manual 44]. California Agricultural Experiment Station Extension Service, Division of Agricultural Sciences, Berkeley, University of California. Retrieved on December 09, 2023 from https://archive.org/details/farmanimalmanure44azev/mode/2up

Baffes, J., & Koh, W. C. (2023). *Fertilizer prices ease but affordability and availability issues linger*. World Bank. Retrieved August 29, 2023 from https://blogs.worldbank.org/opendata/fertilizer-prices-ease-affordability-and-availability-issues-linger

Balikoowa, K. (2014). *Effect of salix phylicifolia patched on microsite availability on degraded sites in Iceland.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/effect-of-salix-phylicifolia-patched-on-microsite-availability-on-degraded-sites-in-iceland

Ball, B. A., Haberkorn, M., & Ortiz, E. (2022). Mesofauna community influences litter chemical trajectories during early-stage litter decay. *Pedobiologia*, *95*, Article 150844. https://doi.org/10.1016/j.pedobi.2022.150844

Ballantine, K., & Schneider, R. (2009). Fifty-five years of soil development in restored freshwater depressional wetlands. *Ecological Applications*, *19*(6), 1467-1480. https://doi.org/https://doi.org/10.1890/07-0588.1

Battogtokh, B. (2018). *The effect of Lathyrus japonicus on soil fertility in Iceland.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/the-effect-of-lathyrus-japonicus-on-soil-fertility-in-iceland

Beesigamukama, D., Tanga, C. M., Sevgan, S., Ekesi, S., & Kelemu, S. (2023). Waste to value: Global perspective on the impact of entomocomposting on environmental health, greenhouse gas mitigation and soil bioremediation. *Science of The Total Environment*, *902*, 166067. https://doi.org/10.1016/j.scitotenv.2023.166067

Berhe, A. A., Barnes, R. T., Six, J., & Marín-Spiotta, E. (2018). Role of Soil Erosion in Biogeochemical Cycling of Essential Elements: Carbon, Nitrogen, and Phosphorus.

*Annual Review of Earth and Planetary Sciences*, *46*(1), 521-548. https://doi.org/10.1146/annurev-earth-082517-010018

Berihu, T. (2021). *The effects of applying a combination of bio-slurry and inorganic fertilizers on teff yield and soil properties in the highlands of northern Ethiopia.* GRÓ Land Restoration Training Programme [Final project]. https://www.grocentre.is/lrt/moya/gro/index/publication/the-effects-of-applying-a-combination-of-bio-slurry-and-inorganic-fertilizers-on-teff-yield-and-soil-properties-in-the-highlands-of-northern-ethiopia

Blakemore, L. C., Searle, P. L., & Daly, B. K. (1987). *Methods for Chemical Analysis of Soils*. NZ Soil Bureau Scientific Report 80. Department of Scientific and Industrial Research.

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*, *117*(36), 21994-22001. https://doi.org/doi:10.1073/pnas.2001403117

Bradshaw, A. D. (1984). Technology Lecture. Land restoration: now and in the future. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, *223*(1230), 1-23. https://doi.org/10.1098/rspb.1984.0079

Brady, N. C., & Weil, R. R. (2014). *Elements of the Nature and Properties of Soils* (3rd ed.). Pearson Education Limited.

Braun-Blanquet, J., Fuller, G. D., & Conrad, H. S. (1932). *Plant Sociology; the study of plant communities* (First ed.). McGraw-Hill.

Brenner, J. M. (2016). *Restoring Eroded Lands in Southern Iceland: Efficacy of Domestic, Organic Fertilizers in Sandy Gravel Soils* [Master's thesis, University of Iceland]. Reykjavik. http://hdl.handle.net/1946/26200

Broom, D. (2023). *This is how war in Europe is disrupting fertilizer supplies and threatening global food security*. World Economic Forum. Retrieved August 29, 2023 from https://www.weforum.org/agenda/2023/03/ukraine-fertilizer-food-security/

Brussaard, L. (2012). Chapter 1.3 Ecosystem Services Provided by the Soil Biota. In Diana H. Wall et. al. (Ed.), *Soil Ecology and Ecosystem Services* (1st ed., pp. 45-58). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199575923.003.0005

Brussaard, L., Pulleman, M. M., Ouédraogo, É., Mando, A., & Six, J. (2007). Soil fauna and soil function in the fabric of the food web. *Pedobiologia, 50*(6), 447-462. https://doi.org/10.1016/j.pedobi.2006.10.007

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030

Carney, K. M., Hungate, B. A., Drake, B. G., & Megonigal, J. P. (2007). Altered soil microbial community at elevated $CO_2$ leads to loss of soil carbon. *Proceedings of the National Academy of Sciences*, *104*(12), 4990-4995. https://doi.org/10.1073/pnas.0610045104

Castillo, X., Materna, J., Jannoura, R., & Joergensen, R. G. (2022). Peanut monoculture-induced decline in fertility of Andosols in Nicaragua. *Journal of Plant Nutrition and Soil Science*, *185*(5), 677-684. https://doi.org/10.1002/jpln.202200112

Cayci, G., Temiz, C., & Sözudogru Ok, S. (2017). The Effects of Fresh and Composted Chicken Manures on Some Soil Characteristics. *Communications in Soil Science and Plant Analysis*, *48*(13), 1528-1538. https://doi.org/10.1080/00103624.2017.1373794

Chakraborty, A., Chakrabarti, K., Chakraborty, A., & Ghosh, S. (2011). Effect of long-term fertilizers and manure application on microbial biomass and microbial activity of a tropical agricultural soil. *Biology and Fertility of Soils*, *47*(2), 227-233. https://doi.org/10.1007/s00374-010-0509-1

Chari, N. R., & Taylor, B. N. (2022). Soil organic matter formation and loss are mediated by root exudates in a temperate forest. *Nature Geoscience*, *15*(12), 1011-1016. https://doi.org/10.1038/s41561-022-01079-x

Chataut, G., Bhatta, B., Joshi, D., Subedi, K., & Kafle, K. (2023). Greenhouse gases emission from agricultural soil: A review. *Journal of Agriculture and Food Research*, *11*, 100533. https://doi.org/10.1016/j.jafr.2023.100533

Chaudhuri, S., Roy, M., McDonald, L. M., & Emendack, Y. (2023). Land Degradation-Desertification in Relation to Farming Practices in India: An Overview of Current Practices and Agro-Policy Perspectives. *Sustainability*, *15*(8), 6383. https://www.mdpi.com/2071-1050/15/8/6383

Chee, S. Y., Othman, A. G., Sim, Y. K., Mat Adam, A. N., & Firth, L. B. (2017). Land reclamation and artificial islands: Walking the tightrope between development and conservation. *Global Ecology and Conservation*, *12*, 80-95. https://doi.org/10.1016/j.gecco.2017.08.005

Chen, Y., Zhang, X., He, H., Xie, H., Yan, Y., Zhu, P., Ren, J., & Wang, L. (2010). Carbon and nitrogen pools in different aggregates of a Chinese Mollisol as influenced by long-term fertilization. *Journal of Soils and Sediments*, *10*(6), 1018-1026. https://doi.org/10.1007/s11368-009-0123-8

Cheng, A., Gajic, G., & Doni, F. (2023). Editorial: Soil biota and climate smart crops. *Front Plant Sci*, *14*, 1250831. https://doi.org/10.3389/fpls.2023.1250831

Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J. R., Kirkham, M. B., Hossain, M. Z., & Kim, G.-H. (2021). Chapter Two - Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 166, pp. 131-196). Academic Press. https://doi.org/10.1016/bs.agron.2020.10.001

Clostre, F., Woignier, T., Rangon, L., Fernandes, P., Soler, A., & Lesueur-Jannoyer, M. (2014). Field validation of chlordecone soil sequestration by organic matter addition. *Journal of Soils and Sediments*, *14*(1), 23-33. https://doi.org/10.1007/s11368-013-0790-3

Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience*, *12*(12), 989-994. https://doi.org/10.1038/s41561-019-0484-6

Crane, S. R., Moore, J. A., Grismer, M. E., & Miner, J. R. (1983). Bacterial Pollution from Agricultural Sources: A Review. *Transactions of the ASAE*, *26*(3), 858-0866. Retrieved December 09, 2023, from https://doi.org/10.13031/2013.34036 ; https://www.researchgate.net/publication/239441888_Bacterial_Pollution_From_Agricultural_Sources_A_Review

Crofts, R. (2011). *Healing the land : the story of land reclamation and soil conservation in Iceland*. Soil Conservation Service of Iceland. https://library.unccd.int/Details/fullCatalogue/133 ; http://www.rogercrofts.net/art_ice.html

Culman, S. (2017). *Protocol - Procedure for the Determination of Permanganate Oxidizable Carbon*. Kellogg Biological Station-Long Term Ecological Research Protocols, Hickory Corners, MI. Retrieved 20 June 2023 from https://lter.kbs.msu.edu/protocols/133

Daebeler, A., Petrová, E., Kinz, E., Grausenburger, S., Berthold, H., Sandén, T., Angel, R., & the high-school students of biology project groups I-III from 2018–2019. (2022). Pairing litter decomposition with microbial community structures using the Tea Bag Index (TBI). *SOIL*, *8*(1), 163-176. https://doi.org/10.5194/soil-8-163-2022

de Graaff, M.-A., Van GROENIGEN, K.-J., SIX, J., HUNGATE, B., & Van KESSEL, C. (2006). Interactions between plant growth and soil nutrient cycling under elevated CO2: a meta-analysis. *Global change biology*, *12*(11), 2077-2091. https://doi.org/10.1111/j.1365-2486.2006.01240.x

Diacono, M., & Montemurro, F. (2011). Long-Term Effects of Organic Amendments on Soil Fertility. In E. Lichtfouse, M. Hamelin, M. Navarrete, & P. Debaeke (Eds.), *Sustainable Agriculture Volume 2* (pp. 761-786). Springer Netherlands. https://doi.org/10.1007/978-94-007-0394-0_34

Duddigan, S., Alexander, P. D., Shaw, L. J., Sandén, T., & Collins, C. D. (2020). The Tea Bag Index—UK: Using Citizen/Community Science to Investigate Organic Matter Decomposition Rates in Domestic Gardens. *Sustainability*, *12*(17), 6895. https://www.mdpi.com/2071-1050/12/17/6895

Duddigan, S., Shaw, L. J., Alexander, P. D., & Collins, C. D. (2022). Effects of application of horticultural soil amendments on decomposition, quantity, stabilisation and quality of soil carbon. *Sci Rep*, *12*(1), 17631. https://doi.org/10.1038/s41598-022-22451-2

Elumeeva, T. G., Onipchenko, V. G., Akhmetzhanova, A. A., Makarov, M. I., & Keuskamp, J. A. (2018). Stabilization versus decomposition in alpine ecosystems of the Northwestern Caucasus: The results of a tea bag burial experiment. *Journal of Mountain Science*, *15*(8), 1633-1641. https://doi.org/10.1007/s11629-018-4960-z

European Commission. (2015). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS | Closing the loop - An EU action plan for the Circular Economy*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

European Commission. (2019). How soil organic matter composition affects carbon sequestration. *EU Science Hub*. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/how-soil-organic-matter-composition-affects-carbon-sequestration-2019-11-27_en

European Commission. (n.d.-a). *Ensuring availability and affordability of fertilisers*. Directorate-General for Agriculture and Rural Development. Retrieved July 04, 2023 from https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en#fertiliser-production

European Commission. (n.d.-b). *First circular economy action plan*. Retrieved August 20, 2023 from https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en

European Commission, Directorate-General for Research and Innovation, Directorate-General for Agriculture and Rural Development, Veerman, C., Correia, T. P., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., Emmett, B., Frison, E. A., Grand, A., Filchew, L. H., Kriaučiūnienė, Z., Pogrzeba, M., Soussana, J.-F., Olmo, C. V.,

& Wittkowski, R. (2020). *Caring for soil is caring for life – Ensure 75% of soils are healthy by 2030 for food, people, nature and climate – Report of the Mission board for Soil health and food* Publications Office of the European Union. https://data.europa.eu/doi/10.2777/821504

European Commission Directorate-General for Environment. (2021a). *EU Soil Strategy for 2030. Reaping the benefits of healthy soils for people, food, nature and climate. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. Brussels Retrieved from https://environment.ec.europa.eu/publications/eu-soil-strategy-2030_en

European Commission Directorate-General for Environment. (2021b). *Staff Working Document accompanying the 'EU Soil Strategy for 2030. Reaping the benefits of healthy soils for people, food, nature and climate. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS'*. Retrieved from https://environment.ec.europa.eu/publications/eu-soil-strategy-2030_en

European Commission Joint Research Centre. (n.d.). *European Soil Data Centre : EU Soil Observatory dashboard sources on Soil degradation, indicator, reference, and threshold used*. Retrieved July 16, 2023 from https://esdac.jrc.ec.europa.eu/euso/euso-dashboard-sources

Eysteinsson, T. (2017). Forestry in a Treeless Land. *Skógræktin (Icelandic Forest Service)*. https://www.skogur.is/static/files/2017/Forestry_in_treeless_land_BKL_210x260mm.pdf

FAO. (2015). *Soil is a non-renewable resource* [Fact sheets]. 2015 International Year of Soils, Rome, Italy. https://www.fao.org/soils-2015/resources/fact-sheets/en/

FAO. (2016). *Climate change and food security: risks and responses*. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/427091/

FAO. (2017). Voluntary Guidelines for Sustainable Soil Management. https://www.fao.org/publications/card/en/c/5544358d-f11f-4e9f-90ef-a37c3bf52db7

FAO. (2022a). Emissions from Synthetic fertilizers. In: FAO. Rome.

FAO. (2022b). *Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000-2020*. FAOSTAT Analytical Brief Series No. 50. Rome. https://www.fao.org/3/cc2672en/cc2672en.pdf

FAO. (2022c). *Inorganic fertilizers 1990–2020*. FAOSTAT Analytical Brief, no. 47. Rome. https://doi.org/10.4060/cc0947en

FAO. (2022d). *World Food and Agriculture – Statistical Yearbook 2022*. https://doi.org/10.4060/cc2211en

FAO. (n.d.). *Key messages - Global Symposium on Soil Erosion*. Retrieved September 03, 2023 from https://www.fao.org/about/meetings/soil-erosion-symposium/key-messages/en/

FAO, & ITPS. (2015a). Chapter 6 : Global soil status, processes and trends. In *Status of the World's Soil Resources (SWSR) – Main Report*. (pp. 100-167). https://www.fao.org/publications/card/es/c/f76e62e9-9ca1-4e99-9085-75ac4a81b107/

FAO, & ITPS. (2015b). Chapter 8 : Governance and policy responses to soil change. In *Status of the World's Soil Resources (SWSR) – Main Report*. (pp. 223-241).

https://www.fao.org/publications/card/es/c/f76e62e9-9ca1-4e99-9085-75ac4a81b107/

FAO, & ITPS. (2015c). *Status of the World's Soil Resources (SWSR) – Main Report*. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. https://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/

Farrell, H. L., Léger, A., Breed, M. F., & Gornish, E. S. (2020). Restoration, soil organisms, and soil processes: emerging approaches. *Restoration Ecology*, *28*, S307-S310.

Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of The Total Environment*, *805*, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Field, C. B., Lobell, D. B., Peters, H. A., & Chiariello, N. R. (2007). Feedbacks of Terrestrial Ecosystems to Climate Change. *Annual Review of Environment and Resources*, *32*(1), 1-29. https://doi.org/10.1146/annurev.energy.32.053006.141119

Fontaine, S., Mariotti, A., & Abbadie, L. (2003). The priming effect of organic matter: a question of microbial competition? *Soil Biology and Biochemistry*, *35*(6), 837-843. https://doi.org/10.1016/S0038-0717(03)00123-8

Fujii, K., Funakawa, S., & Kosaki, T. (2012). Soil Acidification: Natural Processes and Human Impact. *Pedologist*, *55*(3), 415-425. https://doi.org/10.18920/pedologist.55.3_415

Fujii, S., Mori, A. S., Koide, D., Makoto, K., Matsuoka, S., Osono, T., & Isbell, F. (2017). Disentangling relationships between plant diversity and decomposition processes under forest restoration. *Journal of Applied Ecology*, *54*(1), 80-90. https://doi.org/10.1111/1365-2664.12733

Gay, H., Frezal, C., & Adenäuer, M. (2022). *The impacts and policy implications of Russia's aggression against Ukraine on agricultural markets*. Organisation for Economic Co-operation and Development (OECD). Retrieved September 09, 2023 from https://www.oecd.org/ukraine-hub/policy-responses/the-impacts-and-policy-implications-of-russia-s-aggression-against-ukraine-on-agricultural-markets-0030a4cd/

Ghaly, A., & Ramakrishnan, V. (2015). Nitrogen sources and cycling in the ecosystem and its role in air, water and soil pollution: A critical review. *Journal of Pollution Effects & Control*, *3*(2), 1-26.

Giesler, R., Esberg, C., Lagerström, A., & Graae, B. J. (2012). Phosphorus availability and microbial respiration across different tundra vegetation types. *Biogeochemistry*, *108*(1), 429-445. https://doi.org/10.1007/s10533-011-9609-8

Golueke, C., & Diaz, L. (1996). Historical review of composting and its role in municipal waste management. In *The science of composting* (pp. 3-14). Springer.

Gómez-Sagasti, M. T., Hernández, A., Artetxe, U., Garbisu, C., & Becerril, J. M. (2018). How Valuable Are Organic Amendments as Tools for the Phytomanagement of Degraded Soils? The Knowns, Known Unknowns, and Unknowns [Original Research]. *Frontiers in Sustainable Food Systems*, *2*. https://doi.org/10.3389/fsufs.2018.00068

Gorbacheva, T. T., Kikuchi, R., & Gorbachev, P. A. (2009). Evaluation of extractable elements in artificial substratum made from sewage sludge: Approach to remediation of degraded land in the Arctic. *Land Degradation & Development*, *20*(2), 119-128. https://doi.org/https://doi.org/10.1002/ldr.878

Goss, M. J., Tubeileh, A., & Goorahoo, D. (2013). Chapter Five - A Review of the Use of Organic Amendments and the Risk to Human Health. . *Advances in Agronomy, 120*, 275–379. https://doi.org/10.1016/B978-0-12-407686-0.00005-1

Gravuer, K., Gennet, S., & Throop, H. L. (2019). Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. *Global change biology*, *25*(3), 1152–1170. https://doi.org/10.1111/gcb.14535

GRÓ LRT. (n.d.). *Land Restoration Training Programme under the auspices of UNESCO*. Retrieved August 07, 2023 from https://www.grocentre.is/lrt

GróLind. (n.d.). *The first long-term national vegetation and soil monitoring programme in Iceland based on an agreement between the Icelandic National Associations of Sheep Farmers, the Farmers Association of Iceland, Ministry of Industries and Innovation, and the Soil Conservation Service of Iceland.* Retrieved August 07, 2023 from https://grolind.is/

Guadalix, M. E., & Pardo, M. T. (1994). Effects of liming on soil properties and P solubility in some Spanish Andosols. *Geoderma*, *63*(1), 53-61. https://doi.org/10.1016/0016-7061(94)90109-0

Guðmundsson, T., Guðmundsson, S. T., & Þorvaldsson, G. (2014). Soil phosphorus fractionation in Icelandic long-term grassland field experiments. *Icelandic Agricultural Sciences*, *27*, 81-94. http://hdl.handle.net/1946/19877 ; https://ias.is/icelandic-agricultural-sciences-27-2014/

Guerrero, C., Gomez, I., Moral, R., Mataix-Solera, J., Mataix-Beneyto, J., & Hernandez, T. (2001). Reclamation of a burned forest soil with municipal waste compost: macronutrient dynamic and improved vegetation cover recovery [Article]. *Bioresource Technology*, *76*(3), 221-227. https://doi.org/10.1016/s0960-8524(00)00125-5

Hagner, M., Uusitalo, M., Ruhanen, H., Heiskanen, J., Peltola, R., Tiilikkala, K., Hyvönen, J., Sarala, P., & Mäkitalo, K. (2021). Amending mine tailing cover with compost and biochar: effects on vegetation establishment and metal bioaccumulation in the Finnish subarctic. *Environmental Science and Pollution Research, 28*(42), 59881-59898. https://doi.org/10.1007/s11356-021-14865-8

Hall, G. F., Daniels, R. B., & Foss, J. E. (1982). Rate of Soil Formation and Renewal in the USA. In *Determinants of Soil Loss Tolerance* (pp. 23-39). https://doi.org/10.2134/asaspecpub45.c3

Hao, X. H., Liu, S. L., Wu, J. S., Hu, R. G., Tong, C. L., & Su, Y. Y. (2008). Effect of long-term application of inorganic fertilizer and organic amendments on soil organic matter and microbial biomass in three subtropical paddy soils. *Nutrient Cycling in Agroecosystems*, *81*(1), 17-24. https://doi.org/10.1007/s10705-007-9145-z

Hauck, R. D. (1981). NITROGEN FERTILIZER EFFECTS ON NITROGEN CYCLE PROCESSES. *Ecological Bulletins*(33), 551-562. http://www.jstor.org/stable/45128688

Hekluskógar. (2015). *A introduction film on the Heklaforest project from 2006, by Profilm and Kristinn Þorsteinsson.* [Video]. YouTube. https://www.youtube.com/watch?v=5DFSN6lC8yw&ab_channel=Heklus

Hill, P. J. (2023). *Analysis of Regenerative Agriculture Practices on Soil and Energy. A case study and baseline analysis of soil health and Energy Return on Investment (EROI)* [MS dissertation, University of Iceland]. http://hdl.handle.net/1946/44534

Hirzel, J., Donnay, D., Fernández, C., Meier, S., Lagos, O., Mejias-Barrera, P., & Rodríguez, F. (2018). EVOLUTION OF NUTRIENTS AND SOIL CHEMICAL

PROPERTIES OF SEVEN ORGANIC FERTILIZERS IN TWO CONTRASTING SOILS UNDER CONTROLLED CONDITIONS. *Chilean journal of agricultural & animal sciences*, *34*, 77-88. http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0719-38902018000200077&nrm=iso

Hoffland, E., Kuyper, T. W., Comans, R. N. J., & Creamer, R. E. (2020). Eco-functionality of organic matter in soils. *Plant and Soil*, *455*(1), 1-22. https://doi.org/10.1007/s11104-020-04651-9

Hornick, S. B. (1992). Factors affecting the nutritional quality of crops. *American Journal of Alternative Agriculture*, *7*(1-2), 63-68. https://doi.org/10.1017/S0889189300004471

Huang, X., Jia, Z., Guo, J., Li, T., Sun, D., Meng, H., Yu, G., He, X., Ran, W., Zhang, S., Hong, J., & Shen, Q. (2019). Ten-year long-term organic fertilization enhances carbon sequestration and calcium-mediated stabilization of aggregate-associated organic carbon in a reclaimed Cambisol. *Geoderma*, *355*, 113880. https://doi.org/10.1016/j.geoderma.2019.113880

Hueso-González, P., Muñoz-Rojas, M., & Martínez-Murillo, J. F. (2018). The role of organic amendments in drylands restoration. *Current Opinion in Environmental Science & Health*, *5*, 1-6. https://doi.org/10.1016/j.coesh.2017.12.002

Hurisso, T. T., Culman, S. W., Horwath, W. R., Wade, J., Cass, D., Beniston, J. W., Bowles, T. M., Grandy, A. S., Franzluebbers, A. J., Schipanski, M. E., Lucas, S. T., & Ugarte, C. M. (2016). Comparison of Permanganate-Oxidizable Carbon and Mineralizable Carbon for Assessment of Organic Matter Stabilization and Mineralization. *Soil Science Society of America Journal*, *80*(5), 1352-1364. https://doi.org/10.2136/sssaj2016.04.0106

Hurni, H. (1983). Soil Erosion and Soil Formation in Agricultural Ecosystems: Ethiopia and Northern Thailand. *Mountain Research and Development*, *3*(2), 131-142. https://doi.org/10.2307/3672994

in 't Zandt, D., van den Brink, A., de Kroon, H., & Visser, E. J. W. (2019). Plant-soil feedback is shut down when nutrients come to town. *Plant and Soil*, *439*(1), 541-551. https://doi.org/10.1007/s11104-019-04050-9

Ingestad, T. (1977). Nitrogen and Plant Growth; Maximum Efficiency of Nitrogen Fertilizers. *Ambio*, *6*(2/3), 146-151. http://www.jstor.org/stable/4312265

IPCC. (2019). *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (P. R. Shukla, J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley, Eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157988

Jadhao, S., Mali, D., Kharche, V., Singh, M., Bhoyar, S., Kadu, P., Wanjari, R., & Sonune, B. (2019). Impact of continuous manuring and fertilization on changes in soil quality under sorghum-wheat sequence on a Vertisols. *Journal of the Indian society of soil science*, *67*(1), 55-64.

Jangid, K., Williams, M. A., Franzluebbers, A. J., Schmidt, T. M., Coleman, D. C., & Whitman, W. B. (2011). Land-use history has a stronger impact on soil microbial community composition than aboveground vegetation and soil properties. *Soil*

*Biology and Biochemistry*, *43*(10), 2184-2193. https://doi.org/10.1016/j.soilbio.2011.06.022

Janzen, J. J., Bodine, A. B., & Luszcz, L. J. (1974). A Survey of Effects of Animal Wastes on Stream Pollution from Selected Dairy Farms1. *Journal of Dairy Science*, *57*(2), 260-263. https://doi.org/10.3168/jds.S0022-0302(74)84869-1

Joint Research Centre, Institute for Environment Sustainability, Bigas, H., Gudbrandsson, G. I., Montanarella, L., & Arnalds, A. (2009). *Soil, society and global change : proceedings of the International Forum celebrating the centenary of conservation and restoration of soil vegetation in Iceland, 31 August - 4 September 2007, Selfoss, Iceland*. EU Publications Office. https://doi.org/10.2788/84964

Jones, D., & Healey, J. (2010). Organic Amendments for Remediation: Putting Waste to Good Use. *Elements*, *6*, 369-374. https://doi.org/10.2113/gselements.6.6.369

Jónsson, J. Á., & Sigurðsson, B. D. (2010). Effects of early thinning and fertilization on soil temperature and soil respiration in a poplar plantation. *Icelandic Agricultural Sciences*, *23*, 97-109. http://hdl.handle.net/1946/19929 ; https://ias.is/icelandic-agricultural-sciences-23-2010/

Jónsson, T. H. (2004). Stature of Sub-arctic Birch in Relation to Growth Rate, Lifespan and Tree Form. *Annals of Botany*, *94*(5), 753-762. https://doi.org/10.1093/aob/mch200

Jwaideh, M. A. A., Sutanudjaja, E. H., & Dalin, C. (2022). Global impacts of nitrogen and phosphorus fertiliser use for major crops on aquatic biodiversity. *The International Journal of Life Cycle Assessment*, *27*(8), 1058-1080. https://doi.org/10.1007/s11367-022-02078-1

Kacprzak, M., Malińska, K., Grosser, A., Sobik-Szołtysek, J., Wystalska, K., Dróżdż, D., Jasińska, A., & Meers, E. (2023). Cycles of carbon, nitrogen and phosphorus in poultry manure management technologies – environmental aspects. *Critical Reviews in Environmental Science and Technology*, *53*(8), 914-938. https://doi.org/10.1080/10643389.2022.2096983

Kajiura, M., Minamikawa, K., Tokida, T., Shirato, Y., & Wagai, R. (2018). Methane and nitrous oxide emissions from paddy fields in Japan: An assessment of controlling factor using an intensive regional data set. *Agriculture, Ecosystems & Environment*, *252*, 51-60. https://doi.org/10.1016/j.agee.2017.09.035

Kaza, S., Yao, L., Bhada-Tata, P., & Woerden, F. V. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications. https://openknowledge.worldbank.org/handle/10986/30317

Keuskamp, J. A., Dingemans, B. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution*, *4*(11), 1070-1075.

Kielak, A., Pijl, A. S., van Veen, J. A., & Kowalchuk, G. A. (2009). Phylogenetic diversity of Acidobacteria in a former agricultural soil. *The ISME Journal*, *3*(3), 378-382. https://doi.org/10.1038/ismej.2008.113

Kirkhorn, S. R., & Garry, V. F. (2000). Agricultural Lung Diseases. *Environmental health perspectives*, *108* (Suppl 4), 705-712. https://doi.org/10.1289/ehp.00108s4705

Klanderud, K. (2008). Species-Specific Responses of an Alpine Plant Community under Simulated Environmental Change. *Journal of Vegetation Science*, *19*(3), 363-372. https://doi.org/10.3170/2008-8-18376

Kleinschmidt, G., & Gerdemann, J. (1972). Stunting of citrus seedlings in fumigated nursery soils related to the absence of endomycorrhizae. *Phytopathology*, *62*(12), 1447-1453.

Koga, N., Shimoda, S., & Iwata, Y. (2017). Biochar Impacts on Crop Productivity and Greenhouse Gas Emissions from an Andosol. *Journal of Environmental Quality, 46*(1), 27-35. https://doi.org/10.2134/jeq2016.04.0156

Kölbl, A., Schad, P., Jahn, R., Amelung, W., Bannert, A., Cao, Z. H., Fiedler, S., Kalbitz, K., Lehndorff, E., Müller-Niggemann, C., Schloter, M., Schwark, L., Vogelsang, V., Wissing, L., & Kögel-Knabner, I. (2014). Accelerated soil formation due to paddy management on marshlands (Zhejiang Province, China). *Geoderma*, *228-229*, 67-89. https://doi.org/10.1016/j.geoderma.2013.09.005

Konapala, G., Mishra, A. K., Wada, Y., & Mann, M. E. (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications*, *11*(1), 3044. https://doi.org/10.1038/s41467-020-16757-w

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, *132*, 105078. https://doi.org/10.1016/j.envint.2019.105078

Krause, A., Nehls, T., George, E., & Kaupenjohann, M. (2016). Organic wastes from bioenergy and ecological sanitation as a soil fertility improver: a field experiment in a tropical Andosol. *SOIL*, *2*(2), 147-162. https://doi.org/10.5194/soil-2-147-2016

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., & Naidu, R. (2016). Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. *Environment International*, *87*, 1-12. https://doi.org/10.1016/j.envint.2015.10.018

Lecerf, A., Cébron, A., Gilbert, F., Danger, M., Roussel, H., & Maunoury-Danger, F. (2021). Using plant litter decomposition as an indicator of ecosystem response to soil contamination. *Ecological Indicators*, *125*, 107554. https://doi.org/10.1016/j.ecolind.2021.107554

Leirós, M. C., Trasar-Cepeda, C., Seoane, S., & Gil-Sotres, F. (1999). Dependence of mineralization of soil organic matter on temperature and moisture. *Soil Biology and Biochemistry*, *31*(3), 327-335. https://doi.org/10.1016/S0038-0717(98)00129-1

Li, J., Luo, J., Lindsey, S., Wang, S., Deng, F., & Wang, W. (2023). Changes in soil microbial communities in response to repeated application of nitrification inhibitors. *Applied Soil Ecology*, *182*, 104726. https://doi.org/10.1016/j.apsoil.2022.104726

Li, X., Li, B., Chen, L., Liang, J., Huang, R., Tang, X., Zhang, X., & Wang, C. (2022). Partial substitution of chemical fertilizer with organic fertilizer over seven years increases yields and restores soil bacterial community diversity in wheat–rice rotation. *European Journal of Agronomy*, *133*, 126445. https://doi.org/10.1016/j.eja.2021.126445

Li, X. G., Jia, B., Lv, J., Ma, Q., Kuzyakov, Y., & Li, F.-m. (2017). Nitrogen fertilization decreases the decomposition of soil organic matter and plant residues in planted soils. *Soil Biology and Biochemistry*, *112*, 47-55. https://doi.org/10.1016/j.soilbio.2017.04.018

Liu, J., Ding, C., Zhang, W., Wei, Y., Zhou, Y., & Zhu, W. (2022). Litter mixing promoted decomposition rate through increasing diversities of phyllosphere microbial communities. *Frontiers in microbiology*, *13* (1009091). https://doi.org/10.3389/fmicb.2022.1009091

Liu, N., Michelsen, A., & Rinnan, R. (2020). Vegetation and soil responses to added carbon and nutrients remain six years after discontinuation of long-term treatments.

*Science of The Total Environment*, *722*, 137885. https://doi.org/10.1016/j.scitotenv.2020.137885

Lladó, S., López-Mondéjar, R., & Baldrian, P. (2017). Forest Soil Bacteria: Diversity, Involvement in Ecosystem Processes, and Response to Global Change. *Microbiology and Molecular Biology Reviews*, *81*(2), 10.1128/mmbr.00063-00016. https://doi.org/10.1128/mmbr.00063-16

Loftmyndir ehf. (2022). https://www.map.is

Lopes, J. I., Goncalves, A., Brito, C., Martins, S., Pinto, L., Moutinho-Pereira, J., Raimundo, S., Arrobas, M., Rodrigues, M. A., & Correia, C. M. (2021). Inorganic Fertilization at High N Rate Increased Olive Yield of a Rainfed Orchard but Reduced Soil Organic Matter in Comparison to Three Organic Amendments [Article]. *Agronomy-Basel*, *11*(11), 15, Article 2172. https://doi.org/10.3390/agronomy11112172

Lumbanraja, J., & Evangelou, V. (1991). Acidification and liming influence on surface charge behavior of Kentucky subsoils. *Soil Science Society of America Journal*, *55*(1), 26-34.

Magdoff, F. R., & Bartlett, R. J. (1985). Soil pH Buffering Revisited. *Soil Science Society of America Journal*, *49*(1), 145-148. https://doi.org/10.2136/sssaj1985.03615995004900010029x

Magnusson, B. (2010). NOBANIS – Invasive Alien Species Fact Sheet – ***Lupinus nootkatensis***. *Online Database of the European Network on Invasive Alien Species – NOBANIS*. Retrieved November 26, 2023, from https://www.nobanis.org ; https://www.nobanis.org/globalassets/speciesinfo/l/lupinus-nootkatensis/lupinus_nootkatensis.pdf

Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2012). Nutrient Leaching in a Colombian Savanna Oxisol Amended with Biochar. *Journal of Environmental Quality*, *41*(4), 1076-1086. https://doi.org/10.2134/jeq2011.0128

Mankasingh, U., & Gísladóttir, G. (2019). Early indicators of soil formation in the Icelandic sub-arctic highlands. *Geoderma*, *337*, 152-163. https://doi.org/https://doi.org/10.1016/j.geoderma.2018.09.002

Männistö, M., Ganzert, L., Tiirola, M., Häggblom, M. M., & Stark, S. (2016). Do shifts in life strategies explain microbial community responses to increasing nitrogen in tundra soil? *Soil Biology and Biochemistry*, *96*, 216-228. https://doi.org/10.1016/j.soilbio.2016.02.012

Marteinsdóttir, B., & Stefánsson, J. H. (2020). *GróLind Stöðumat á ástandi lands og kortlagning beitarlanda* [Presentation]. GróLind Kynningarfundur, Iceland. https://grolind.is/wp-content/uploads/2020/06/Gr%C3%B3Lind-stodumat_beitarlond_18_06_2020.pdf

Martínez-García, L. B., Korthals, G. W., Brussaard, L., Mainardi, G., & De Deyn, G. B. (2021). Litter quality drives nitrogen release, and agricultural management (organic vs. conventional) drives carbon loss during litter decomposition in agro-ecosystems. *Soil Biology and Biochemistry*, *153*, 108115. https://doi.org/10.1016/j.soilbio.2020.108115

Massah, J., & Azadegan, B. (2016). Effect of chemical fertilizers on soil compaction and degradation. *Agricultural Mechanization in Asia, Africa and Latin America*, *47*(1), 44-50.

Matsuoka-Uno, C., Uno, T., Tajima, R., Ito, T., & Saito, M. (2022). Liming and Phosphate Application Influence Soil Carbon and Nitrogen Mineralization Differently in

Response to Temperature Regimes in Allophanic Andosols. *Agriculture*, *12*(2), 142. https://www.mdpi.com/2077-0472/12/2/142

Mbewe, E. C. (2015). *The efficacy of sunflower seed cake as an organic fertilizer.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/the-efficacy-of-sunflower-seed-cake-as-an-organic-fertilizer

Mdolo, P. (2016). *Sewage sludge and municipal waste: potential sources of phosphorus for land restoration.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/sewage-sludge-and-municipal-waste-potential-sources-of-phosphorus-for-land-restoration

Mekuria, W., Getnet, K., Noble, A., Hoanh, C. T., McCartney, M., & Langan, S. (2013). Economic valuation of organic and clay-based soil amendments in small-scale agriculture in Lao PDR. *Field Crops Research*, *149*, 379-389. https://doi.org/10.1016/j.fcr.2013.05.026

Meyer, O. (1994). Functional Groups of Microorganisms. In E.-D. Schulze & H. A. Mooney (Eds.), *Biodiversity and Ecosystem Function* (pp. 67-96). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-58001-7_4

Mirzabaev, A., Wu, J., Evans, J., García-Oliva, F., Hussein, I. A. G., Iqbal, M. H., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türkeş, M., Vázquez, R. J., & Weltz, M. (2019). Chapter 3 - Desertification. In P. R. Shukla, J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 249-344). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157988.005

Möckel, S. C. (2016). *Environmental changes and development of the nutrient budget of Histosols in North Iceland during the Holocene* [Master’s thesis, University of Iceland]. Reykjavik. http://hdl.handle.net/1946/26191

Möller, K., & Schultheiß, U. (2015). Chemical characterization of commercial organic fertilizers. *Archives of Agronomy and Soil Science*, *61*(7), 989-1012. https://doi.org/10.1080/03650340.2014.978763

Montanarella, L. (2015a). Agricultural policy: Govern our soils. *Nature*, *528*(7580), 32-33. https://doi.org/10.1038/528032a

Montanarella, L. (2015b). The Global Soil Partnership. *IOP Conference Series: Earth and Environmental Science*, *25*(1), 012001. https://doi.org/10.1088/1755-1315/25/1/012001

Montanarella, L., Pennock, D. J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Singh Aulakh, M., Yagi, K., Young Hong, S., Vijarnsorn, P., Zhang, G. L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henriquez, C. R., . . . Vargas, R. (2016). World's soils are under threat. *SOIL*, *2*(1), 79-82. https://doi.org/10.5194/soil-2-79-2016

Mosheim, R. (2019, October 30, 2019). *Fertilizer Use and Price*. Economic Research Service, U.S. DEPARTMENT OF AGRICULTURE. Retrieved September 24, 2023 from https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx

Murphy, K. L., Klopatek, J. M., & Klopatek, C. C. (1998). The Effects of Litter Quality and Climate on Decomposition along an Elevational Gradient. *Ecological Applications*, *8*(4), 1061-1071. https://doi.org/10.2307/2640961

Nakanyala, J. (2012). *Phosphorus availability following revegetation with Nootka lupine at two contrasting sites in Iceland.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/phosphorus-availability-following-revegetation-with-nootka-lupine-at-two-contrasting-sites-in-iceland

National Geographic Society. (2023). *The Development of Agriculture*. Retrieved August 25, 2023 from https://education.nationalgeographic.org/resource/development-agriculture/

Nearing, M. A., Xie, Y., Liu, B., & Ye, Y. (2017). Natural and anthropogenic rates of soil erosion. *International Soil and Water Conservation Research*, *5*(2), 77-84. https://doi.org/10.1016/j.iswcr.2017.04.001

Nicholls, R., Beaven, R., Stringfellow, A., Monfort, D., Le Cozannet, G., Wahl, T., Gebert, J., Wadey, M., Arns, A., Spencer, K., Reinhart, D., Heimovaara, T., Malagón Santos, V., Rodríguez, A., & Cope, S. (2021). Coastal Landfills and Rising Sea Levels: A Challenge for the 21st Century. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.710342

Nogalska, A., Krzebietke, S. J., Zalewska, M., & Nogalski, Z. (2017). The effect of meat and bone meal (MBM) on the nitrogen and phosphorus content and pH of soil. *26*(4), 181-187. https://doi.org/10.23986/afsci.64207

NRCC. (1983). *FARM ANIMAL MANURES IN THE CANADIAN ENVIRONMENT*. NRC Associate Committee on Scientific Criteria For Environmental Quality, National Research Council Of Canada (NRCC).

OECD/FAO. (2023). *OECD-FAO Agricultural Outlook 2023-2032*. OECD Publishing, Paris. https://doi.org/10.1787/08801ab7-en

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, D. J., & Stringer, L. (2019). Chapter 4 - Land degradation. In P. R. Shukla, J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 345-436). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157988.006

Oshima, H., Goto, D., Goto, I., & Maeda, Y. (2015). Effect of organic matter removal treatments and addition of aluminum-containing substances on incidence of Fusarium wilt of lettuce. *Soil Science and Plant Nutrition*, *61*(4), 613-619. https://doi.org/10.1080/00380768.2015.1014295

Óskarsson, H., Aradóttir, Á. L., & Halldórsson, G. (n.d.). *The Mt. Hekla afforestation project*. Icelandic Forest Service and the Soil Conservation Service of Iceland. Retrieved September 03, 2023 from https://hekluskogar.is/the-mt-hekla-afforestation-project/

Ouikhalfan, M., Lakbita, O., Delhali, A., Assen, A. H., & Belmabkhout, Y. (2022). Toward Net-Zero Emission Fertilizers Industry: Greenhouse Gas Emission

Analyses and Decarbonization Solutions. *Energy & Fuels*, *36*(8), 4198-4223. https://doi.org/10.1021/acs.energyfuels.2c00238

Padrón, R. S., Gudmundsson, L., Decharme, B., Ducharne, A., Lawrence, D. M., Mao, J., Peano, D., Krinner, G., Kim, H., & Seneviratne, S. I. (2020). Observed changes in dry-season water availability attributed to human-induced climate change. *Nature Geoscience*, *13*(7), 477-481. https://doi.org/10.1038/s41561-020-0594-1

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chapter-1 Chemical Fertilizers and Their Impact on Soil Health. In G. H. Dar, R. A. Bhat, M. A. Mehmood, & K. R. Hakeem (Eds.), *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs* (pp. 1-20). Springer International Publishing. https://doi.org/10.1007/978-3-030-61010-4_1

Pan, Y., Kang, P., Tan, M., Hu, J., Zhang, Y., Zhang, J., Song, N., & Li, X. (2022). Root exudates and rhizosphere soil bacterial relationships of Nitraria tangutorum are linked to k-strategists bacterial community under salt stress. *Front Plant Sci*, *13*, 997292. https://doi.org/10.3389/fpls.2022.997292

Panagos, P., Borrelli, P., & Poesen, J. (2019). Soil loss due to crop harvesting in the European Union: A first estimation of an underrated geomorphic process. *Science of The Total Environment*, *664*, 487-498. https://doi.org/10.1016/j.scitotenv.2019.02.009

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, *54*, 438-447. https://doi.org/10.1016/j.envsci.2015.08.012

Pascault, N., Ranjard, L., Kaisermann, A., Bachar, D., Christen, R., Terrat, S., Mathieu, O., Lévêque, J., Mougel, C., Henault, C., Lemanceau, P., Péan, M., Boiry, S., Fontaine, S., & Maron, P.-A. (2013). Stimulation of Different Functional Groups of Bacteria by Various Plant Residues as a Driver of Soil Priming Effect. *Ecosystems*, *16*(5), 810-822. https://doi.org/10.1007/s10021-013-9650-7

Paustian, K., Parton, W. J., & Persson, J. (1992). Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots. *Soil Science Society of America Journal*, *56*(2), 476-488. https://doi.org/10.2136/sssaj1992.03615995005600020023x

Pereira, P., & Martinez-Murillo, J. F. (2018). Editorial overview: Sustainable soil management and land restoration. *Current Opinion in Environmental Science & Health*, *5*, 98-101. https://doi.org/10.1016/j.coesh.2018.07.006

Pierzynski, G., & Brajendra (Eds.). (2017). *Threats to soils: Global trends and perspectives.* [Global Land Outlook Working Paper Series]. UNCCD Publication. https://www.unccd.int/resources/publications/threats-soils-global-trends-and-perspectives.

Pilbeam, C. J., Mathema, S. B., Gregory, P. J., & Shakya, P. B. (2005). Soil fertility management in the mid-hills of Nepal: Practices and perceptions. *Agriculture and Human Values*, *22*(2), 243-258. https://doi.org/10.1007/s10460-004-8284-y

Plante, A., & Conant, R. T. (2014). Soil Organic Matter Dynamics, Climate Change Effects. In B. Freedman (Ed.), *Global Environmental Change* (pp. 317-323). Springer Netherlands. https://doi.org/10.1007/978-94-007-5784-4_3

Poulsen, R. (2011). *The effect of fluoride pollution on soil microorganisms* [Bachelor thesis, University of Iceland]. Reykjavik. http://hdl.handle.net/1946/10396

Pushkareva, E., Baumann, K., Van, A. T., Mikhailyuk, T., Baum, C., Hrynkiewicz, K., Demchenko, E., Thiem, D., Köpcke, T., Karsten, U., & Leinweber, P. (2021).

Diversity of microbial phototrophs and heterotrophs in Icelandic biocrusts and their role in phosphorus-rich Andosols. *Geoderma*, *386*, 114905. https://doi.org/10.1016/j.geoderma.2020.114905

Qian, P., & Schoenau, J. J. (2002). Availability of nitrogen in solid manure amendments with different C:N ratios. *Canadian Journal of Soil Science*, *82*(2), 219-225. https://doi.org/10.4141/s01-018

Qiao, C., Xu, B., Han, Y., Wang, J., Wang, X., Liu, L., Liu, W., Wan, S., Tan, H., Liu, Y., & Zhao, X. (2018). Synthetic nitrogen fertilizers alter the soil chemistry, production and quality of tea. A meta-analysis. *Agronomy for Sustainable Development*, *38*(1), 10. https://doi.org/10.1007/s13593-017-0485-z

Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience*, *3*(5), 311-314. https://doi.org/10.1038/ngeo838

Quynh, H. T., & Kazuto, S. (2018). Title “Organic Fertilizers” in Vietnam’s Markets: Nutrient Composition and Efficacy of Their Application. *Sustainability*, *10*(7), 2437. https://www.mdpi.com/2071-1050/10/7/2437

Raghavendra, M., Sharma, M. P., Ramesh, A., Richa, A., Billore, S. D., & Verma, R. K. (2020). Soil Health Indicators: Methods and Applications. In A. Rakshit, S. Ghosh, S. Chakraborty, V. Philip, & A. Datta (Eds.), *Soil Analysis: Recent Trends and Applications* (pp. 221-253). Springer Singapore. https://doi.org/10.1007/978-981-15-2039-6_13

Ram, S., Singh, V., & Sirari, P. (2016). Effects of 41 Years of Application of Inorganic Fertilizers and Farm Yard Manure on Crop Yields, Soil Quality, and Sustainable Yield Index under a Rice-Wheat Cropping System on Mollisols of North India. *Communications in Soil Science and Plant Analysis*, *47*(2), 179-193. https://doi.org/10.1080/00103624.2015.1109653

Rashmi, I., Roy, T., Kartika, K. S., Pal, R., Coumar, V., Kala, S., & Shinoji, K. C. (2020). Organic and Inorganic Fertilizer Contaminants in Agriculture: Impact on Soil and Water Resources. In M. Naeem, A. A. Ansari, & S. S. Gill (Eds.), *Contaminants in Agriculture: Sources, Impacts and Management* (pp. 3-41). Springer International Publishing. https://doi.org/10.1007/978-3-030-41552-5_1

Reid, N. B., & Naeth, M. A. (2005a). Establishment of a Vegetation Cover on Tundra Kimberlite Mine Tailings: 1. A Greenhouse Study. *Restoration Ecology*, *13*(4), 594-601. https://doi.org/10.1111/j.1526-100X.2005.00076.x

Reid, N. B., & Naeth, M. A. (2005b). Establishment of a Vegetation Cover on Tundra Kimberlite Mine Tailings: 2. A Field Study. *Restoration Ecology*, *13*(4), 602-608. https://doi.org/10.1111/j.1526-100X.2005.00077.x

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., . . . Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9* (37), 16. https://doi.org/10.1126/sciadv.adh2458

Ritchie, H. (2017). *How many people does synthetic fertilizer feed?* Our World in Data. Retrieved September 24, 2023 from https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed

Runólfsson, S. (1987). Land Reclamation in Iceland. *Arctic and Alpine Research*, *19*(4), 514-517. https://doi.org/10.2307/1551418

Runólfsson, S., & Arnalds, A. (2004). Landcare at the top of the world Conservation strategies in Iceland. 13th International Soil Conservation Organisation Conference, Brisbane,

Ruppel, O. C. (2022). Overview of international soil law. *Soil Security*, *6*, 100056. https://doi.org/10.1016/j.soisec.2022.100056

S.Nickayin, S., Wilke, M., & Þrastardóttir, R. (2022). State of the art of Nature-based Solutions in Iceland. (LBHÍ nr. 159), 44. Retrieved December 10, 2023, from https://www.lbhi.is/university/about-the-school/news/state-of-the-art-of-nature-based-solutions-in-iceland?trk=public_post_main-feed-card_feed-article-content

Šarauskis, E., Naujokienė, V., Lekavičienė, K., Kriaučiūnienė, Z., Jotautienė, E., Jasinskas, A., & Zinkevičienė, R. (2021). Application of Granular and Non-Granular Organic Fertilizers in Terms of Energy, Environmental and Economic Efficiency. *Sustainability*, *13*(17), 9740. https://www.mdpi.com/2071-1050/13/17/9740

Savci, S. (2012a). An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development*, *3*(1), 73.

Savci, S. (2012b). Investigation of effect of chemical fertilizers on environment. *Apcbee Procedia*, *1*, 287-292.

Schjønning, P., Christensen, B. T., & Carstensen, B. (1994). Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *European Journal of Soil Science*, *45*(3), 257-268. https://doi.org/10.1111/j.1365-2389.1994.tb00508.x

Schlesinger, W. H. (2009). On the fate of anthropogenic nitrogen. *Proceedings of the National Academy of Sciences*, *106*(1), 203-208. https://doi.org/10.1073/pnas.0810193105

Scotti, R., Conte, P., Berns, A. E., Alonzo, G., & Rao, M. A. (2013). Effect of organic amendments on the evolution of soil organic matter in soils stressed by intensive agricultural practices. *Current Organic Chemistry*, *17*(24), 2998-3005.

SCSI. (n.d.-a). *Bændur græða landið*. Soil Conservation Service of Iceland (*Icelandic name: Landgræðslan*). Retrieved December 10, 2023 from https://land.is/heim/landnyting/baendur-graeda-landid/

SCSI. (n.d.-b). *Soil Conservation Service of Iceland (Icelandic name: Landgræðslan)*. Retrieved August 05, 2022 from https://land.is/

SCSI, & EFLA. (n.d.). *Reiknivél um áburð. Reiknivél um kostnað og kolefnisspor áburðarnotkunar*. Soil Conservation Service of Iceland (*Icelandic name: Landgræðslan)*. Retrieved December 09, 2023 from https://land.is/heim/landnyting/reiknivel-um-aburd/

Shah, N. W., Baillie, B. R., Bishop, K., Ferraz, S., Högbom, L., & Nettles, J. (2022). The effects of forest management on water quality. *Forest Ecology and Management*, *522*, 120397. https://doi.org/10.1016/j.foreco.2022.120397

Shaji, H., Chandran, V., & Mathew, L. (2021). Chapter 13 - Organic fertilizers as a route to controlled release of nutrients. In F. B. Lewu, T. Volova, S. Thomas, & R. K.R (Eds.), *Controlled Release Fertilizers for Sustainable Agriculture* (pp. 231-245). Academic Press. https://doi.org/10.1016/B978-0-12-819555-0.00013-3

Silva, G. (2018). *All fertilizers are not created equal*. Michigan State University Extension. Retrieved December 09, 2023 from https://www.canr.msu.edu/news/all_fertilizers_are_not_created_equal

Singh, B. (2011). The Nitrogen Cycle: Implications for Management, Soil Health, and Climate Change. In B. P. Singh, A. L. Cowie, & K. Y. Chan (Eds.), *Soil Health and*

*Climate Change.* (First ed., pp. 107-130). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-20256-8_6

Skemman. (n.d.). *A digital repository of academic and research documents*. Retrieved August 05, 2023 from https://skemman.is/

Smith, C., Hill, A. K., & Torrente-Murciano, L. (2020). Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. *Energy & Environmental Science*, *13*, 331-344. https://doi.org/10.1039/C9EE02873K

Smith, P., Nkem, J., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Hoang, A. L., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J.-F., & Taboada, M. A. (2019). Chapter 6 - Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In P. R. Shukla, J. Skea, E. C. Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 551-672). Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157988.008

Solís, J. D. Á., Niñez, J. A. M., Martínez, N. S. L., Albores, J. C., & Miceli, F. A. G. (2016). Effect of bokashi and vermicompost leachate on yield and quality of pepper (Capsicum annuum) and onion (Allium cepa) under monoculture and intercropping cultures. *Ciencia e investigación agraria: revista latinoamericana de ciencias de la agricultura*, *43*(2), 243-252.

Soumana, I. (2013). *Comparison of two ecological succession monitoring protocols on restored Andisol.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/comparison-of-two-ecological-succession-monitoring-protocols-on-restored-andisol

Stehlíková, I., Madaras, M., Lipavský, J., & Šimon, T. (2016). Study on some soil quality changes obtained from long-term experiments. *Plant, Soil and Environment*, *62*(2), 74-79.

Stewart, W. M., Dibb, D. W., Johnston, A. E., & Smyth, T. J. (2005). The Contribution of Commercial Fertilizer Nutrients to Food Production. *Agronomy Journal*, *97*(1), 1-6. https://doi.org/10.2134/agronj2005.0001

Stockholm Resilience Centre. (2023). *All planetary boundaries mapped out for the first time, six of nine crossed*. Retrieved September 24, 2023 from https://www.stockholmresilience.org/research/research-news/2023-09-13-all-planetary-boundaries-mapped-out-for-the-first-time-six-of-nine-crossed.html

Sun, Y., Wang, C., Yang, J., Liao, J., Chen, H. Y. H., & Ruan, H. (2021). Elevated CO2 shifts soil microbial communities from K- to r-strategists. *Global Ecology and Biogeography*, *30*(5), 961-972. https://doi.org/10.1111/geb.13281

Takahashi, S. (2014). Phosphorus Fractionation of Composted Crop Residues and Forms of Soil Phosphorus after 22 Years of Compost Application to Andosols. *Communications in Soil Science and Plant Analysis*, *45*(7), 1003-1010. https://doi.org/10.1080/00103624.2013.867057

Teferi, H. H. (2011). *Woodland restoration by natural regeneration and plantation (assisted regeneration) in Iceland.* United Nations University Land Restoration

Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/woodland-restoration-by-natural-regeneration-and-plantation-assisted-regeneration-in-iceland

Teng, Y., & Chen, W. (2019). Soil Microbiomes—a Promising Strategy for Contaminated Soil Remediation: A Review. *Pedosphere*, *29*(3), 283-297. https://doi.org/10.1016/S1002-0160(18)60061-X

The World Bank. (2023). *Food Security Update January 26, 2023*. World Bank Publications. https://thedocs.worldbank.org/en/doc/40ebbf38f5a6b68bfc11e5273e1405d4-0090012022/related/Food-Security-Update-LXXVII-January-26-2023.pdf

Tjilumbu, L. (2012). *Analysis of vegetation and selected soil properties in four different habitats at the Hekla Forest project area in Iceland.* United Nations University Land Restoration Training Programme [Final Project]. https://www.grocentre.is/lrt/moya/gro/index/publication/analysis-of-vegetation-and-selected-soil-properties-in-four-different-habitats-at-the-hekla-forest-project-area-in-iceland

Tripathi, S., Srivastava, P., Devi, R. S., & Bhadouria, R. (2020). Chapter 2 - Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In M. N. V. Prasad (Ed.), *Agrochemicals Detection, Treatment and Remediation* (pp. 25-54). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-103017-2.00002-7

United Nations. (2022). *Global Impact of war in Ukraine on food, energy and finance systems - BRIEF NO.1*. https://unsdg.un.org/resources/global-impact-war-ukraine-food-energy-and-finance-systems-brief-no1

United Nations Environment Programme. (2021). *UNEP Food Waste Index Report 2021*. https://www.unep.org/resources/report/unep-food-waste-index-report-2021

Verde, J. R., Arbestain, M. C., & Macías, F. (2010). Influence of Agricultural Practices on the Stability of Organo-Al Complexes in an Alu-Andic Andosol: A Laboratory Study. *Soil Science*, *175*(8), 390-397. https://doi.org/10.1097/SS.0b013e3181eb66bd

Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J., & Smith, C. J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, *94*(1), 23-38. https://doi.org/10.1016/j.earscirev.2009.02.003

Vilmundardóttir, O. K., Gísladóttir, G., & Lal, R. (2014). Early stage development of selected soil properties along the proglacial moraines of Skaftafellsjökull glacier, SE-Iceland. *CATENA*, *121*, 142-150. https://doi.org/10.1016/j.catena.2014.04.020

Walling, E., & Vaneeckhaute, C. (2020). Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *Journal of Environmental Management*, *276*, 111211. https://doi.org/10.1016/j.jenvman.2020.111211

Wang, Y., Zhu, Y., Zhang, S., & Wang, Y. (2018). What could promote farmers to replace chemical fertilizers with organic fertilizers? *Journal of Cleaner Production*, *199*, 882-890. https://doi.org/10.1016/j.jclepro.2018.07.222

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*(1), 3-17. https://doi.org/10.1079/AJAA200228

Wickramatilake, A. R. P., Kouno, K., & Nagaoka, T. (2010). Compost amendment enhances the biological properties of Andosols and improves phosphorus utilization from added rock phosphate. *Soil Science and Plant Nutrition*, *56*(4), 607-616. https://doi.org/10.1111/j.1747-0765.2010.00493.x

Wilhelm, R. C., Lynch, L., Webster, T. M., Schweizer, S., Inagaki, T. M., Tfaily, M. M., Kukkadapu, R., Hoeschen, C., Buckley, D. H., & Lehmann, J. (2022). Susceptibility of new soil organic carbon to mineralization during dry-wet cycling in soils from contrasting ends of a precipitation gradient. *Soil Biology and Biochemistry*, *169*, 108681. https://doi.org/10.1016/j.soilbio.2022.108681

Wilmoth, J., Menozzi, C., Bassarsky, L., & Gu, D. (2023). *As the World's Population Surpasses 8 Billion, What Are the Implications for Planetary Health and Sustainability?* UN Chronicle, United Nations. Retrieved August 25, 2023 from https://www.un.org/en/un-chronicle/world-population-surpasses-8-billion-what-are-implications-planetary-health-and

Withington, C. L., & Sanford, R. L. (2007). Decomposition rates of buried substrates increase with altitude in the forest-alpine tundra ecotone. *Soil Biology and Biochemistry*, *39*(1), 68-75. https://doi.org/10.1016/j.soilbio.2006.06.011

World Bank Group. (2023). *Commodity Market Outlook : Lower prices, Little Relief, April 2023*. World Bank. https://www.worldbank.org/en/research/commodity-markets

Xiao, R., Wang, J. J., Gaston, L. A., Zhou, B., Park, J.-H., Li, R., Dodla, S. K., & Zhang, Z. (2018). Biochar produced from mineral salt-impregnated chicken manure: Fertility properties and potential for carbon sequestration. *Waste Management*, *78*, 802-810. https://doi.org/10.1016/j.wasman.2018.06.047

Zaman, M., Cameron, K. C., Di, H. J., & Inubushi, K. (2002). Changes in mineral N, microbial biomass and enzyme activities in different soil depths after surface applications of dairy shed effluent and chemical fertilizer. *Nutrient Cycling in Agroecosystems*, *63*(2), 275-290. https://doi.org/10.1023/A:1021167211955

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., & Crowley, D. (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems & Environment*, *139*(4), 469-475. https://doi.org/https://doi.org/10.1016/j.agee.2010.09.003

Zheng, X., Zhang, B., Lai, W., Wang, M., Tao, X., Zou, M., Zhou, J., & Lu, G. (2023). Application of bovine bone meal and oyster shell meal to heavy metals polluted soil: Vegetable safety and bacterial community. *Chemosphere*, *313*, 137501. https://doi.org/10.1016/j.chemosphere.2022.137501

Zhou, S., Williams, A. P., Lintner, B. R., Findell, K. L., Keenan, T. F., Zhang, Y., & Gentine, P. (2022). Diminishing seasonality of subtropical water availability in a warmer world dominated by soil moisture–atmosphere feedbacks. *Nature Communications*, *13*(1), 5756. https://doi.org/10.1038/s41467-022-33473-9

# Appendices

# Appendix A. Soil properties for eight soil amendments.

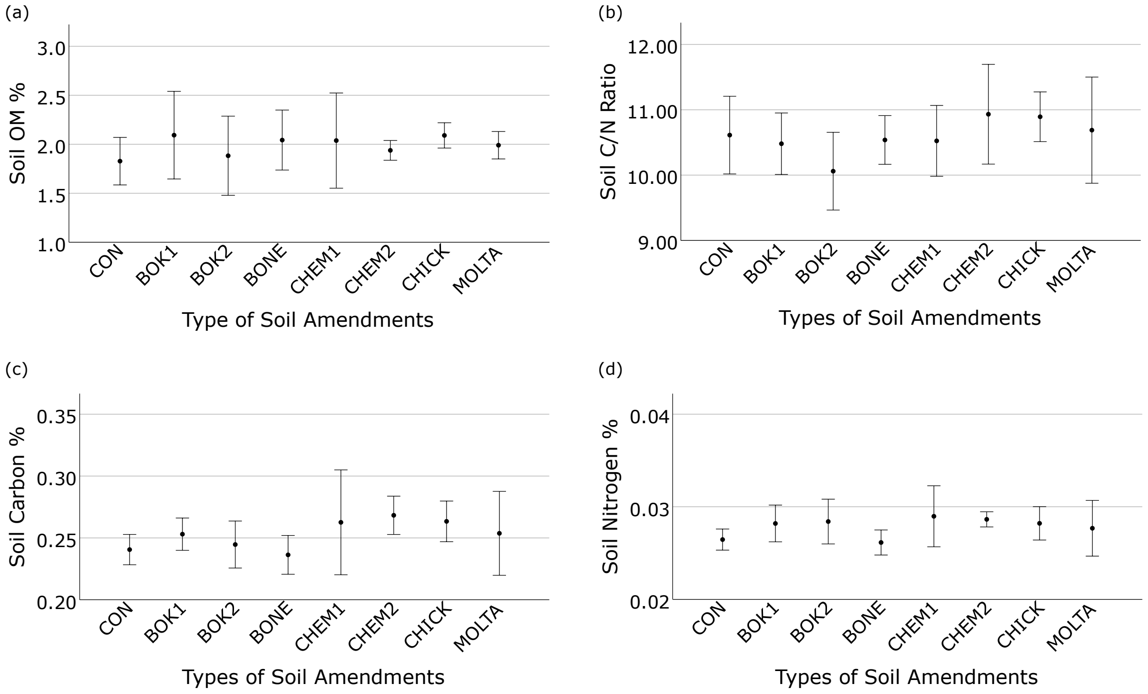


*Figure A.1 Soil properties presented as means ± standard deviations for the following soil amendments: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, and MOLTA = Molta compost. (a) Soil organic matter %, (b) Soil carbon to nitrogen ratio, (c) Soil carbon %, and (d) Soil nitrogen %. None of these soil properties were significantly different among soil amendments.*

# Appendix B. Vegetation survey data for five soil amendments in 2021.

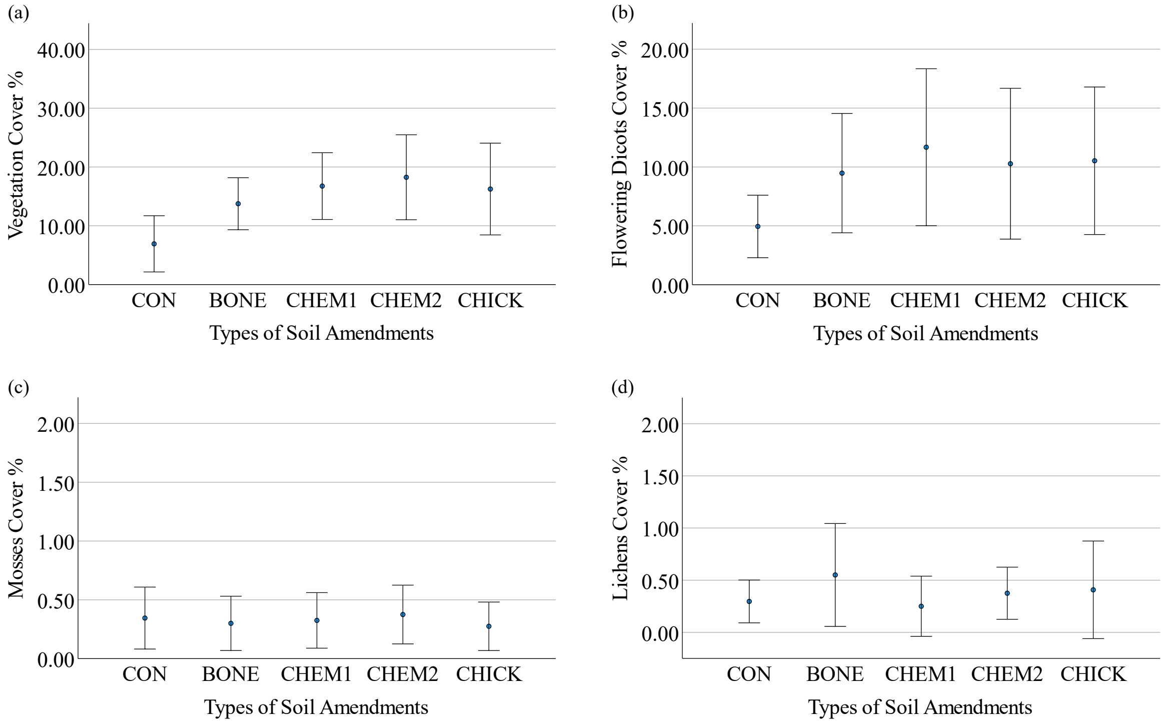


*Figure B.1 Vegetation survey data (mean ± standard deviation) for soil amendments in 2021. Five types of soil amendments were used: CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure. (a) Vegetation cover %, (b) Flowering dicots cover %, (c) Moss cover %, and (d) Lichen cover %. None of these vegetation parameters were significantly different among soil amendments for year 2021.*

# Appendix C. Vegetation survey data for eight soil amendments in 2022.

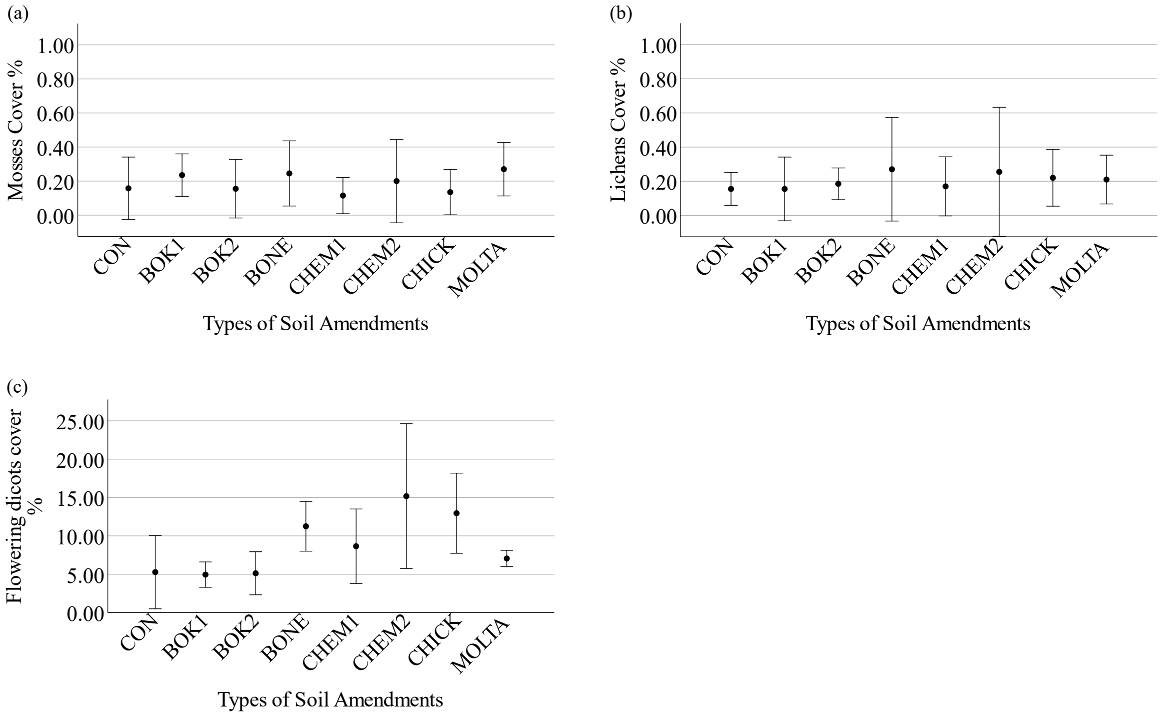


*Figure C.1 Vegetation survey data (means ± standard deviations) for soil amendments in 2022. The eight types of soil amendments were: CON = Control, BOK1 = Bokashi 1, BOK2 = Bokashi 2, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure, MOLTA = Molta compost. (a) Moss cover %, (b) Lichen cover %, and (c) Flowering dicots cover %. None of these vegetation parameters were significantly different among soil amendments for year 2022.*

# Appendix D. Vegetation survey data for five soil amendments in year 2021 and 2022.

*Table D.1 Vegetation parameters for soil amendments in 2021 and 2022. Five soil amendments were used: CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure. Means and Standard deviations (shown in parentheses) are presented. Note: CHEM2-2022 plots had significantly more vegetation cover than CON-2021 (p = 0.032) and CON-2022 (p = 0.039). Also, CHICK-2022 plots had taller vegetation than CON-2021 (p = 0.048) and CON-2022 (p = 0.032).*

| | **Vegetation Cover (%)** | | **Vegetation Height (cm)** | |
|---|---|---|---|---|
| **Amendments** | **2021** | **2022** | **2021** | **2022** |
| CON<br>(n=8) | 6.9 (4. 8) | 5.9 (3.6) | 2.19 (0.83) | 2.42 (2.31) |
| BONE<br>(n=4) | 13.8 (4.4) | 16.5 (2.6) | 2.85 (1.54) | 6.11 (1.95) |
| CHEM1<br>(n=4) | 16.8 (5.7) | 13.5 (5.1) | 3.99 (0.89) | 8.94 (5.73) |
| CHEM2<br>(n=4) | 18.3 (7.2) | 24.3 (8.6) | 5.42 (0.61) | 16.19 (7.57) |
| CHICK<br>(n=4) | 16.3 (7.8) | 18.8 (4.7) | 3.95 (0.68) | 15.41 (5.26) |
| Total<br>(n=24) | 13.1 (7.1) | 14.2 (8.2) | 3.43 (1.45) | 8.58 (7.07) |

*Table D.2 Vegetation taxa cover for soil amendments in 2021 and 2022. Five types of soil amendments were used (CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure). Means (Standard deviations) are shown. Note: CON-2021 plots had significantly less grass cover than CHEM2-2021 (p = 0.008) and CHEM2-2022 (p = 0.005); and CON-2022 plots had significantly less grass cover than CHEM2-2021 (p = 0.013) and CHEM2-2022 (p = 0.008). Also, the comparisons between individual soil amendments within years were not significantly different for moss cover, lichen cover, and flowering dicot cover.*

| | **Moss Cover (%)** | | **Lichen Cover (%)** | | **Grass Cover (%)** | | **Flowering Dicots Cover (%)** | |
|---|---|---|---|---|---|---|---|---|
| **Amendments** | **2021** | **2022** | **2021** | **2022** | **2021** | **2022** | **2021** | **2022** |
| CON (n=8) | 0.3 (0.3) | 0.2 (0.2) | 0.3 (0.2) | 0.2 (0.1) | 1.9 (1.1) | 1.9 (1.1) | 5.0 (2.7) | 5.3 (4.8) |
| BONE (n=4) | 0.3 (0.2) | 0.2 (0.2) | 0.6 (0.5) | 0.3 (0.3) | 4.0 (1.9) | 4.1 (2.1) | 9.5 (5.1) | 11.3 (3.2) |
| CHEM1 (n=4) | 0.3 (0.2) | 0.1 (0.1) | 0.3 (0.3) | 0.2 (0.2) | 5.5 (1.9) | 4.5 (1.5) | 11.7 (6.7) | 8.7 (4.9) |
| CHEM2 (n=4) | 0.4 (0.3) | 0.2 (0.2) | 0.4 (0.3) | 0.3 (0.4) | 10.3 (1.9) | 10.8 (2.6) | 10.3 (6.4) | 15.2 (9.4) |
| CHICK (n=4) | 0.3 (0.2) | 0.1 (0.1) | 0.4 (0.5) | 0.2 (0.2) | 5.7 (2.0) | 6.0 (1.4) | 10.5 (6.3) | 13.0 (5.2) |
| Total (n=24) | 0.3 (0.2) | 0.2 (0.2) | 0.4 (0.3) | 0.2 (0.2) | 4.9 (3.3) | 4.9 (3.4) | 8.6 (5.4) | 9.8 (6.4) |

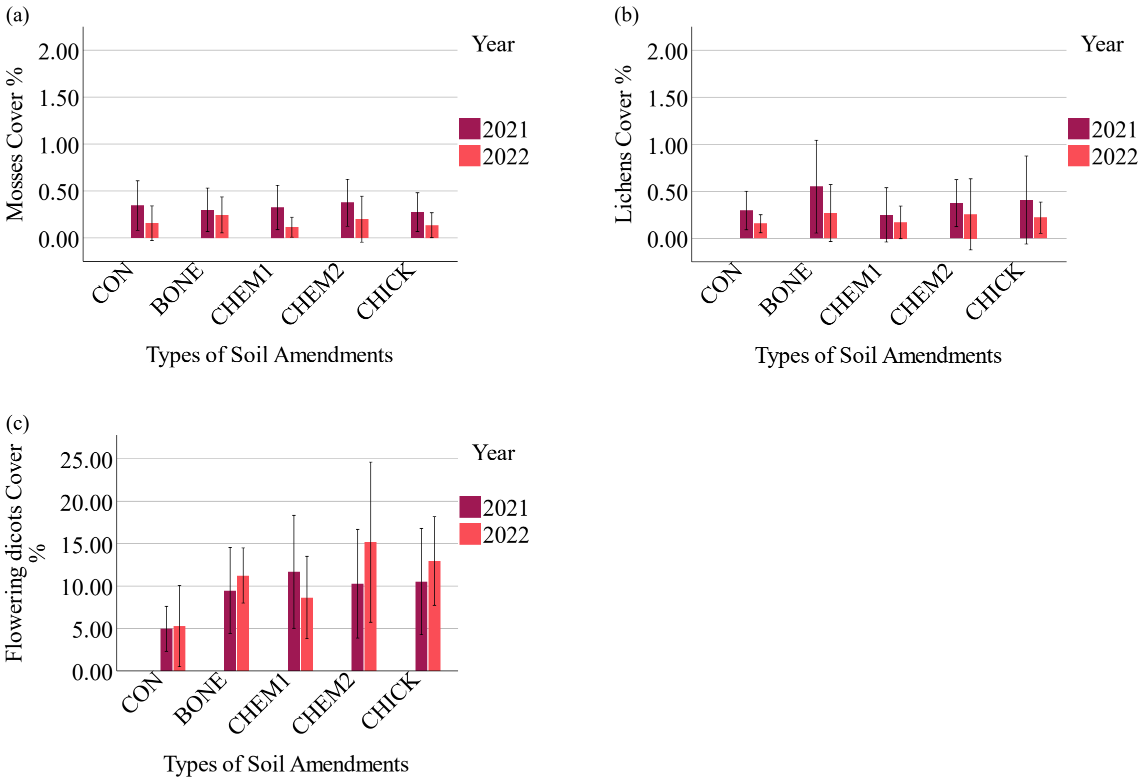


*Figure D.1 Vegetation survey data (mean ± standard deviation) for soil amendments in 2021 and 2022. Five types of soil amendments were used: CON = Control, BONE = Bonemeal, CHEM1 = Chemical fertilizer 1, CHEM2 = Chemical fertilizer 2, CHICK = Chicken manure. (a) Moss cover %, (b) Lichen cover %, and (c) Flowering dicots cover %. Note that comparisons between individual soil amendments within years were not significantly different for moss cover, lichen cover, and flowering dicot cover.*