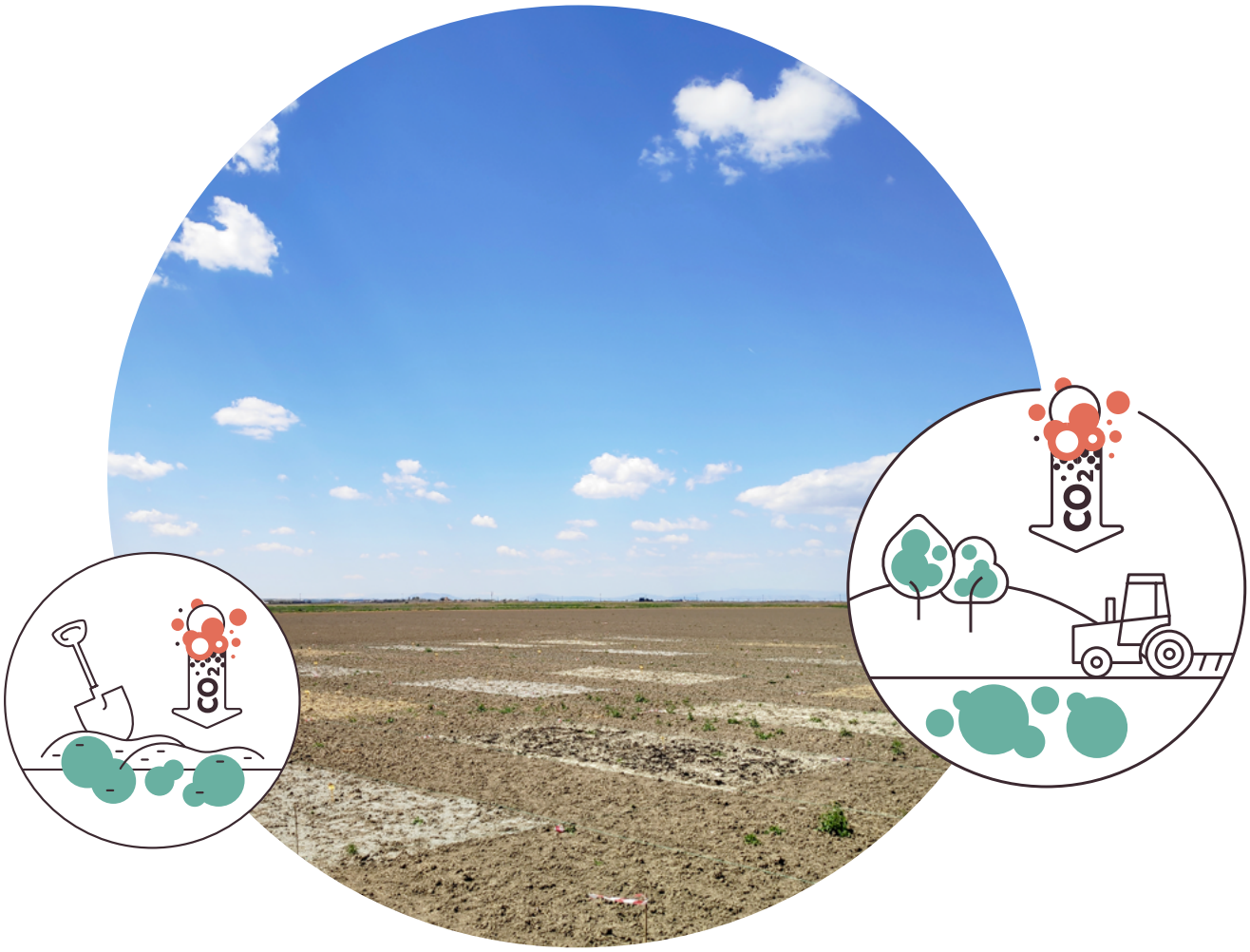
fieldcode



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The Olivine project 2021 progress report

Investigating the potential of olivine rich rocks for large-scale carbon dioxide removal from the atmosphere. This project tests the effectiveness of enhanced weathering in Greece, using local materials in combination with existing agricultural practices.

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Summary

The aim of the Olivine Project is to clarify the potential of carbon dioxide removal (CDR) through enhanced weathering (EW) and to contribute to scaling up this negative emissions technology into a relevant tool for climate change mitigation. Fieldcode thereby aims to offset all our customers' CO_2 emissions linked to usage of our product, and even remove a surplus 10% of carbon dioxide, through our own EW actions. The start of this project in 2021 represents the very first EW field trials in Greece and the first EW experiments globally with cotton and in a clay-rich, high pH, calcareous soil generally deemed less appropriate for EW.

The experimental area of these cotton trials focused on scientifically assessing the EW performance of 6 different olivine rich rock dusts and their potential effects on crop performance and soil quality. This part of the experiment had 4 replicates for each treatment, consisting of 4x8m sized plots onto which rock dust was manually applied at a dose of 40 ton/ha. In order to test the practical aspects of field-scale EW within existing local agricultural practices, a pilot area was additionally set up. In this part of the field two Greek olivine rich rock dusts were mechanically applied with the farmer's machinery at a dose of 1.2 ton/ha on single replicate plots of 21x100m. In both the experimental and pilot areas some olivine rich rock dust treatments were combined with biochar added at a dose of 3 and 2.6 ton/ha, respectively. In the period from rock dust application in early April through to cotton harvest in early October, soil, cotton and soil water were periodically sampled and analyzed.

This first year of the Olivine Project yielded a lot of practical knowledge on carrying out EW field experiments. Good communication and cooperation with the farmer are indispensable, both rock dust and soil should be dry prior to application and homogenization, the weather and natural open system setting greatly influence timing and sampling of the experiment, and biochar activation prior to application poses an additional practical challenge.

The first cotton harvest showed no negative effects on cotton yield or fiber quality. Addition of the olivine rich rock dusts did not have any impact on the plants' nutrient uptake – except in case of the Eifelgold basalt which seemed to yield higher P contents during flowering. Soil and soil water samples of both the pilot and experimental areas showed seasonal patterns that reflect the synergy of farmer management practices with the natural background of chemical, physical and biological processes throughout the cotton-growing season. Nitrogen fertilization in the irrigation water carried out in June-July might also have affected the soil and soil water's chemistry. The generally observed trend of the pilot area soil water data having a larger spread than the experimental area data is attributed to their lower statistical significance and to natural soil heterogeneity across a larger part of the field.

As no clear EW signal was observed during the first 6 months of this field experiment, we could not measure the progress of rock dust dissolution to calculate the amount of removed CO_2. The only sign of enhanced weathering was found 6 months after rock dust application in the soil of the 40 ton/ha olivine rich rock dust treatments, which had elevated Ni and Cr contents compared to the control and basalt treatments. None of the soil water parameters we hoped would reflect EW showed systematic differences between the treatments and controls. Interestingly, soil water from the pilot area often has higher Ni contents than that in the experimental area. As this is also the case for the control plots, this is likely not reflecting rock dust addition but rather a natural background signal. Biochar did not seem to have any effect on the cotton yield or quality but potentially had a positive effect on the plants' P uptake during flowering. Surprisingly, it seems that both in the pilot and experimental areas those olivine rich rock dust treatments combined with biochar have higher Ni contents in their soil water than their respective controls and rock dust or biochar only treatments.

The lack of a clear enhanced weathering signal during the first 6 months of the experiment is not surprising since closed system lab experiments already showed a delay in the EW signature traveling down into the soil column and appearing in the soil water chemistry. Gradual dissolution of a rock dust addition representing <1.35 weight% of the soil it was mixed into might take a while to become visible, especially in a complex open system such as an agricultural field. Although the cotton field soil of this first experiment is not beneficial for enhanced weathering, simultaneously carried out EW field experiments in a more appropriate soil in Germany reported a similar lack of EW signature in the soil and soil water samples in the first half year of experimentation.

All in all, this first half year of experimentation suggests that cotton cultivation could be a potential crop for EW as it seems unaffected by the olivine rich rock dust applications. More time and further research are however needed to identify a measurable EW signature as well as to ascertain appropriate application doses for different soil and climate conditions that are safe for both crops and the environment.

Based on the above preliminary results, we recommend continuing the cotton field experiment for a second year. On one hand because data of at least two growing seasons are needed to make sound conclusions on the effects of olivine rich rock dust additions on the plants' nutrient uptake and the cotton yield and quality. Continuation of this experiment, on the other hand, can show whether the patterns observed in the first half year persist and if perhaps over time an EW signature does emerge in the soil water data. Of great importance to be better understood are thereby the increasing amounts of Ni and Cr in the soils with higher rock dust application rates, and elevated soil water Ni concentrations in treatments that combine olivine rich rock dust with biochar.

This first EW field experiment turned out to be somewhat too complicated due to the use of 6 different rock dusts (and biochar) in an open system setting of commercial cotton cultivation. In order to better understand the processes of enhanced weathering in a natural open system, we suggest to conduct a second EW experiment in the field next to the Institute of Industrial and Forage crops in Larisa. This location provides a better soil for EW reactions and the freedom to decide when and how much irrigation and fertilization is carried out. Using alfalfa, a perennial livestock crop that does not require nitrogen fertilization, would allow the soil – and experimental equipment – to remain untouched for a couple of years. This new experiment would have a more simple design involving only one Greek olivine rich rock dust at two application doses (50 ton/ha and 100 ton/ha) and 5 replicates for each treatment. Besides the same sampling and analyses approach as was carried on the cotton field in 2021 we would also install soil sensors for continuous monitoring of pH, soil moisture and EC. This way we increase our chances to identify a clear EW signal which is needed to move forward to atmospheric CO_2 removal on a global scale.

Introduction

Introduction

Fieldcode initiated the Olivine Project in 2020 as another chapter in the company's commitment to sustainability. Climate positivity is Fieldcode's promise to its customers to help them turn their field service operations into CO_2 negative events. We therefore invest in different carbon dioxide removal techniques. Besides setting up our Olivine Project, we are also funding Australian research into direct air capture, planting trees in Zimbabwe, a founding member of the Negative Emissions Platform and cooperating with Project Vesta.

Hemmersbach supports the Olivine Project as an integral part of our Climate Force. As a social purpose company, we founded this third direct action so that our own environmental team can work towards the enabling of atmospheric CO_2 removal at a global scale. To bridge the time until this particular method is ready to be deployed, we plant trees and protect nature reserves in both Zimbabwe and Indonesia.

Carbon Drawdown Initiative focuses on the need for development of large-scale CO_2 removal technologies to mitigate climate change. We founded the Negative Emissions Platform and fund existing negative emission projects such as Climeworks, Project Vesta, 44.01, Carbonfuture, etc. In collaboration with Hemmersbach and Fieldcode, we started our own CO_2 removal project late 2020. The Olivine Project described in this report is part of our Project Carbdown, which also comprises other enhanced weathering research that ranges from lab experiments over greenhouse tests to field trials carried out in Germany and the Netherlands.

fieldcode

hemmersbach

Carbon Drawdown Initiative

Why remove CO_2

Climate change causes a global crisis that endangers all life on earth. Humanity released an immense volume of greenhouse gasses in the – geologically speaking – blink of an eye. Carbon dioxide (CO_2) is thereby the most significant as it represents about 75% of all greenhouse gasses. Since the start of the industrial revolution, a clear correlation can be observed between the global rise in temperature and the ca. 50% increase of CO_2 in our atmosphere.

Nature could not adjust to this sudden unbalance in the carbon cycle, resulting in the worldwide destabilization of weather patterns and ecosystems. Even if we become **carbon neutral** and put an end to all CO_2 emissions, the climate disruption will not be undone. In order to mitigate climate change, we must also remove large volumes of CO_2 that are already in the atmosphere. Removal of historically emitted CO_2 from the environment is known as "**negative (carbon) emissions**".

Climate positivity refers to activities that go beyond achieving net zero carbon emissions, creating an environmental benefit by removing additional CO_2 from the atmosphere. Such negative emissions can be achieved in many ways. Direct Air Capture (DAC) is a high tech approach where for example machines use filters to strip CO_2 from the ambient air they draw in. Other methods such as enhanced weathering (EW) focus on accelerating **carbon dioxide removal (CDR)** processes that are already present in nature.

Rock weathering

A mineral is defined as a solid with a distinct chemical composition and crystal structure (for example, quartz is SiO_2 in trigonal crystals). Natural rocks consist of countless grains of one specific mineral, or of a number of different minerals. When carbon dioxide gas reacts with water, it forms a weak acid (carbonic acid or H_2CO_3) that can dissolve minerals. So when a rock comes into contact with CO_2 and water, a chemical reaction occurs whereby the minerals inside the rocks are dissolved producing cations and anions. At the same time, the CO_2 is transformed into bicarbonate and carbonate anions (HCO_3^- and CO_3^{2-}, respectively). This process is one of the rock weathering mechanisms and it is similar to the breakdown of marble statues by acid rain caused by industrial emissions.

Natural rock weathering currently removes about 1.1Gton (one trillion or 1,000,000,000,000 kg) of CO_2 per year from the atmosphere, with the carbon mainly stored as bicarbonate in the oceans (Strefler et al, 2018). For comparison, in the last couple of years, human activities annually emitted over 40 Gton of CO_2. Rock weathering is an important reason why the earth's atmospheric CO_2 concentrations remained relatively low and within a certain range for millions of years. Both our neighbouring planets have a much hotter surface temperature than expected from their distance to the sun. On Venus,

evaporation of its surface water shut down all rock weathering and the subsequent unbridled increase in CO_2 pushed the change of this once earth like planet into the hottest one of our solar system.

Rock weathering does not only remove CO_2 from the atmosphere, it also initiates **permanent carbon storage**. In the natural carbon cycle, CO_2 emitted by plants, animals and volcanoes (carbon sources) is taken up in the soil, by growing plants, in the oceans and through the formation of carbonate rocks (carbon sinks). Carbon dioxide taken up in the soil, by plants and in the oceans can be released again from these sinks. Rock weathering turns carbon dioxide gas into (bi) carbonates and releases cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+},...) which are dissolved in the groundwater. These cations and anions may locally form carbonate minerals (for example calcite, $CaCO_3$) but mostly travel via rivers to oceans where they increase ocean alkalinity and can be used for organic carbonate mineral formation (sea shells, corals,...). Carbonate minerals are eventually incorporated into limestone or other carbonate rocks that represent a carbon storage for up to 100,000 or even millions of years

Enhanced weathering

Rock weathering offers a natural solution to our need for permanent carbon dioxide removal, but it acts on geological timescales of 1000s of years and is hence too slow. In order to create an effective tool for climate change mitigation, we need to speed up the snail-like breakdown of mountains. **Enhanced weathering (EW)** accelerates natural rock weathering through

- Using mainly the faster reacting minerals (calcium and/or magnesium silicate minerals, for example olivine)
- Increasing the rocks' surface area where the weathering reactions occur (crushing and grinding it to a powder)
- Spreading the highly reactive rock powder in an environment that further expedites its chemical dissolution (weathering occurs faster at higher temperatures and in the presence of sufficient water and CO_2 - which combine into carbonic acid)

When Seifritz first suggested to use silicate minerals for carbon dioxide removal in 1990 (Seifritz, 1990), his idea was quickly put aside because preliminary lab experiments indicated that the enhanced weathering process is too slow to be effective. As years passed by and the urgency of the global climate crisis became more apparent, his idea was revisited about a decade later. By then it was clear that humanity needs to investigate all possible ways of CO_2 removal to have a chance of turning the tide.

Prof. Schuiling was a strong advocate of the potential role for olivine in combatting climate change, stating that it will dissolve much faster in the natural

environment than in laboratory tests. He was also one of the first to suggest mixing olivine rich rock powders into the soil of agricultural fields on a global scale as a potentially significant CDR technique (Schuiling & Krijgsman, 2006). Soil microorganisms and plant roots generate weak organic acids and higher levels of CO_2 that enhance the chemical reactions of rock weathering.

In the past 15 years, scientific interest in different applications of enhanced weathering for CDR increased exponentially and resulted in many new studies and publications. Studies into the combination of EW and agriculture, however, are mainly laboratory experiments, theoretical models, feasibility studies and pot experiments in greenhouses. Very few trials have been carried out 'in the real world' because of the complexity of such a setting. The Olivine Project described in this report is therefore **among the first field trials** of enhanced weathering globally.

Soil carbon sequestration

Weathering of rocks results in the formation of soils, thereby playing a central role in controlling a soil's inherent fertility status through the supply of many of the nutrients that enable plants to grow. Besides representing the natural product of rock weathering, soils also play a vital role in the global carbon cycle as both a carbon sink and a carbon source. Rock weathering, soils and carbon sequestration - the process of storing CO_2 in a carbon pool – are thus closely linked to one another.

Total soil carbon stocks consist of both organic carbon and inorganic carbon. The quantities and proportions of these types of soil carbon depend on climate, geology and land management practices. Plants transform CO_2 into organic carbon through the biological process of photosynthesis. This carbon partially returns to the atmosphere through the respiration of plants and oxidation of organic material whilst about 50% of it ends up in the soil as **soil organic carbon** (SOC). Whereas formation of soil organic carbon is a common terrestrial process, the right conditions to form **soil inorganic carbon** (SIC) through abiotic precipitation of carbonate minerals are less commonly met. Inorganic soil carbon, however, is a more stable carbon pool: the mean residence time of SIC is thousands of years, while that of SOC is generally tens of years.

It is important to stress that **inorganic carbon** present in soils is mostly primary carbonate minerals from the soil parent material besides secondary carbonate minerals formed from **natural rock weathering**. As mentioned before, rock weathering involves CO_2 dissolving in water and producing carbonic acid, which in turn dissolves calcium and magnesium silicate minerals. The resulting Ca^{2+}, Mg^{2+} and HCO_3^- ions are mostly leached through groundwater into rivers and finally to the ocean, where they precipitate to form solid inorganic carbonates. However, under the right chemical soil conditions these

inorganic carbonates can also form as secondary minerals within the soil itself. Some estimates indicate that less than 10% of total SIC stored globally to 1 m depth come from atmospheric carbon dioxide sequestration through weathering (Eswaran et al, 2000).

As soil inorganic carbon pools are rather fixed over geologically short time intervals, **soil carbon sequestration** usually refers to the biological process where CO_2 is removed from the atmosphere through photosynthesis by plants and stored as **soil organic carbon**. Carbon is rarely, if ever, present in soils in its elemental form (C), but rather in the form of soil organic matter (SOM) which besides carbon contains significant amounts of hydrogen (H), oxygen (O) and nitrogen (N). Plant nutrients, biomass productivity, the type of vegetation, water availability and climate are just some of the major factors that constrain the amount of carbon sequestration possible in a given soil. Stabilization and decomposition of SOM builds up soil organic carbon through different processes. SOC can therefore be located in different carbon pools, each with distinct turnover times, and changes in land use and agricultural management may have different effects on these C pools. For example, labile pools may accumulate much faster but are also more prone to carbon losses than stable pools.

Soils can act as **both carbon sinks and carbon sources** depending on soil management, biomass input, micro-climatic conditions and bioclimatic change. Substantially more carbon is stored in the world's soils than is present in the atmosphere. Lal (2010) states that the soil carbon pool to one-meter depth is estimated at 2500 Gton, consisting of 1550 SOC and 950 Gton SIC. The total pedogenic carbon pool is thereby more than 3 times the size of the atmospheric carbon pool (780 Gton) and over 4 times that of the terrestrial biomass carbon pool (living organisms and detritus, 620 Gton).

Agriculture has had - and continues to have – a profound **influence** on the **global carbon cycle** because it affects vegetation and soils worldwide. Since the start of agricultural practices ca. 12,000 years ago, an estimated one third of the soil organic carbon stored in the top meter of soil was released into the atmosphere due to clearance of natural vegetation and soil cultivation. Globally about 525 Gton carbon (357 Gton pre-1850 and 168 Gton post-1850) may have been released by agricultural land use changes, contributing significantly to the increase of atmospheric greenhouse gas concentrations and thus accelerating climate change (Lorenz & Lal, 2018).

This huge amount of carbon released from the soils also shows that there is a **significant potential of soils to sequester carbon dioxide** by restoring depleted soil organic carbon stocks. Improved soil management in agro-ecosystems can substantially reduce greenhouse gas emissions whilst simultaneously sequestering some of the atmospheric CO_2. In order to increase the amount of soil organic carbon, protection measures of the soil organic matter are required. Increased soil carbon can improve soil structure, enhance water

filtration and make the soil more fertile. This results in healthier soils that have a higher ecosystem resilience to climate impacts, more biodiversity, and better resistance to disease.

Application of enhanced weathering on agricultural soils may alter soil nutrients, structure and chemistry which in turn influences soil organic carbon sequestration. So besides permanent CO_2 capture through long-term EW of olivine rich rocks, the current project also looks into short-term improvement of soil quality which potentially affects more temporary CO_2 removal and storage as soil organic carbon.

Olivine and cotton in Greece

In this project we assess the carbon dioxide removal potential of enhanced weathering of olivine rich rocks combined with existing agriculture. Olivine is the name of a mineral group that consists of magnesium-iron-silicates ($(Mg,Fe)_2SiO_4$) which make up the majority of the earth's mantle but are also commonly found on the earth's surface. The purely magnesium silicate end member (Mg_2SiO_4 – forsterite) is the fastest dissolving. When it comes in contact with water and CO_2 the following chemical reaction occurs

$$Mg_2SiO_{4(s)} + 4\,H_2O_{(l)} + 4\,CO_{2(aq)} \rightarrow 2\,Mg^{2+}{}_{(aq)} + H_4SiO_{4\,(l)} + 4\,HCO_3^-{}_{(aq)}$$

Mountainous areas across Greece contain **olivine rich rocks** that are extracted at **two** locations. At both these **active quarries** the olivine rich rocks are being crushed, making their product an excellent enhanced weathering starting material. To minimise CO_2 emissions related to transport of the crushed olivine rich rocks, the project site is chosen to be in central Greece.

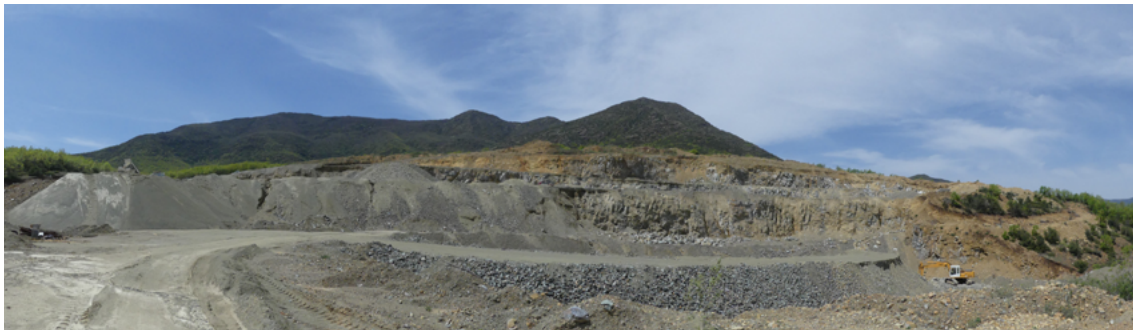


Figure 1.1. Quarry near Skoumtsia, Greece, where the company Vitruvit extracts their olivine product.

High temperatures are another advantage of Greece for enhanced weathering experiments. However, the semi-arid climate means that high temperatures coincide with little to no precipitation during the summertime. As the weathering reaction can only happen in the presence of water, and it is not feasible to use large amounts of freshwater solely for CDR, the crushed rock powder needs to be spread on already **irrigated land**.

Cotton is a crop that needs a lot of irrigation during the summer time, amounting to about 5000 mm per hectare. Greece produces about 80% of

all EU cotton and annually grows this crop on ca. 250,000 ha. Combining our enhanced weathering experiments with cotton cultivation thus represents a significant **potential for scaling up** at a later stage. But the choice of Greece and cotton for our first EW trials has another advantage besides the benefits listed above.

All minerals have so-called impurities in their crystal structure, specific elements present in very small amounts that are not part of the mineral's chemical formula. For example, colourless mineral quartz (SiO_2) can be pink if small amounts of manganese (Mn) are present (rose quartz). Similarly, **olivine** ($(Mg,Fe)_2SiO_4$) has trace amounts of heavy metals such as nickel (Ni) and chromium (Cr). Consequently, when the crystal structure of olivine is dissolved these heavy metals are also released.

On the one hand, plants need certain amounts of nutrients including metals to grow regularly, making olivine rich rock powder a **natural fertilizer containing metals**. On the other hand, one needs to avoid that weathering of olivine releases **too high** amounts of metals some of which are potentially toxic such as **nickel or chromium**. For example, Dalton (2019) showed that whereas nickel is essential for the growth of many plant species and microorganisms, at high levels it may become toxic to plants or to the consumers of their products. Since cotton is not consumed as a food, any increased levels of Ni or Cr that might arise from our trials will not present an issue for the industrial use of the cotton.

Besides elevated levels of Ni and Cr, there is another potential health issue linked to the use of olivine rich rocks that needs to be addressed. When olivine rich mantle rocks are pushed up from the earth's mantle to its surface, this involves intense geological processes at elevated temperatures and in the presence of fluids. **Olivine** can thereby react with water and **alter to** another Mg-Fe rich silicate called **serpentine** ($(Mg,Fe)_3Si_2O_5(OH)_4$). This new mineral removes CO_2 through weathering at a somewhat slower pace than olivine and hence can still be used for CDR. However, in certain settings it will form as needle like crystals that might be asbestiform. It is therefore important to check any olivine rich rock candidates for EW for the presence of **asbestos**.

The Olivine Project represents the first large-scale enhanced weathering experiments in Greece, applying local olivine rich rocks to existing agriculture. In 2021 we started out with adding 6 different European rock dusts on a clay rich cotton field in Thessaly. This 2 ha large field trial comprises two experimental set-ups with different rock dust application rates in order to investigate a variety of practical and scientific questions. Besides the dynamics of rock dust dissolution and CO2 removal, we also look into any effects the rock dust application might have on the soil and crop.

This report presents a **detailed overview** of all the work we carried out throughout **2021**, in chronological order. All scientific data obtained from a range of analyses are provided in the appendices, but also shortly presented and discussed in the relevant chapters. A bold font indicates the highlights in a chapter section at the end of which a summary is presented against a greenish background. We hope that in this way the 2021 Progress Report is a reference work interesting to readers from many different backgrounds.

First, the current scientific knowledge on enhanced weathering is summarized in Chapter 2. Chapter 3 then offers more information on the specific study area along with a report on the reconnaissance trip to the cotton field in January 2021. Chapter 4 subsequently describes the main materials involved in this EW field trials such as the different olivine rich rock dusts, the soil of the cotton field, etc. Chapter 5 covers the details of the design of the cotton field EW experiment and Chapter 6 discusses all the steps we took in the spring of 2021 to set them up. Chapter 7 details how we collected soil, soil water, plant and cotton samples throughout the summer of 2021 as well as the field observations we made during that time. Chapter 8 introduces the different analytical methods applied to the samples at the Institute of Industrial and Forage Crops (IIFC) in Larisa. Chapters 9 and 10 present the soil, soil water, cotton and plant data obtained for the two different set-ups of these field experiments. Finally, there is a brief discussion of the initial results along with recommendations for the continuation of this research project in 2022.

Literature background

Literature background

Because there is a large variety of EW starting materials, environments and applications, the scientific literature on enhanced weathering is quite diverse. A growing portion of EW publications is thereby research on **terrestrial enhanced weathering** as a potentially important CDR technique for climate change mitigation. Those studies however, are mainly laboratory tests, greenhouse pot experiments, numerical modelling and theoretical life cycle assessments. Only very few EW **field experiments** have been published so far. There are, however, a multitude of agricultural field experiments in which silicate rock powders (SRPs) were tested as natural fertilizers for soil (re) mineralization.

In this chapter, we summarize the scientific publications that discuss the effects of SRPs on crop yield and on the removal of carbon dioxide from the atmosphere. First, we discuss the main insights from agricultural field studies of SRPs applied to crops. The following section gives an overview of EW studies with (ultra)mafic rocks applied to agricultural soils, focusing on carbon dioxide removal. Finally, we briefly discuss relevant EW field trials that are currently being carried out.

Main factors controlling weathering of silicate rock powders

Apart from nitrogen (N), all macro- and micronutrients essential for plant growth and health (P, K, Ca, S, Mg, Fe, B, Cl, Mn, Zn, Cu, Mo, Ni) can be present in silicate rocks. The main benefits of applying SRPs to agricultural land could be increasing crop yields, improving soil health, and carbon sequestration through enhanced weathering. Potential co-benefits are reduction of nitrous oxide emissions and (a)biotic stress resistance in plants. Below we summarize the main factors controlling the success of SRP application in an agricultural setting. This section is based on the review by Swoboda et al (2022).

Silicates are a group of minerals with a large variety of chemical compositions and a range of different structural integrities. The specific **mineral composition** of a silicate rock powder will therefore determine its theoretical EW potential with regards to both how much CO_2 it can remove from the atmosphere, and how fast. Field observations suggest that plant and microbiological processes can increase these theoretical weathering rates up to several orders of magnitude.

The **grain size** of applied SRP is also important as a smaller grain size is usually linked to a larger surface area where the chemical weathering reaction can take place. In general, the more a rock is crushed, the faster it will weather. The energy and cost involved with milling silicate rocks, however, puts limitations on the achievable grain size. Whilst farmers are already applying lime

and certain mineralizing rock dusts at rates of 0.5-6ton/ha, **application rates** tested in various studies range from less than 1ton/ha to well above 100ton/ha. In principal, higher application rates mean potentially higher CO_2 removal and nutrient release. But apart from being impractical to apply to a field, very high application rates (up to 100ton/ha) might lead to nutrient imbalances and are therefore best avoided.

Soil type and **climate** are two other – interrelated - factors that greatly determine the weathering of a silicate rock powder. High temperatures accelerate the weathering process and intense rainfall is crucial since water is necessary for the chemical reaction to take place as well as to transport the reaction products off site. The (sub-) humid tropics thus represent favorable climatic conditions for the application of silicate rock powders. Similarly, the soils in these regions are also well suited for soil mineralization through SRP as they are depleted in nutrients and have relatively low pH.

For the European region where, in general, soils have higher reserves of weatherable minerals and a higher pH compared to tropical soils, it is important to consider the **mineralogy of soils in relation to the mineralogy of applied SRPs**. The soil pore water is in equilibrium with the soil minerals and dissolution of added material occurs more easily when there is ionic non-equilibrium between the SRP surface and the soil solution. Simply put: adding SRP of the same mineralogy as the soil is thought to result in limited weathering, introduction of different minerals into the soil changes its chemical balance which favours SRP weathering.

Within a specific climate, weather conditions fluctuate according to the seasons and annual variability. This needs to be taken into account when deciding on the **duration of enhanced weathering field trials**. Agronomic trials with SRP typically range from several months up to two years. Whereas this can render sufficient insights into effects on crop yields and short-term nutrient supply, it might be too small of a time window to adequately capture the medium to long-term soil changes and CO_2 removal. In order to assess the efficiency of relatively slow enhanced weathering and the full extent of its potential long-term effects on the soil, field trials lasting 2-10 years seem more appropriate.

Particular **plant species** can considerably increase the weathering rate of applied silicate rock powders. Chemical, physical and biological conditions of the soil are very different near plant roots – the zone referred to as rhizosphere. The release of certain major cations from basaltic rock dust increases up to 100-fold in the presence of specific plant species compared to the same soil without plants. The degree to which weathering is enhanced by plants varies from species to species. This is linked to the morphology of their root systems, the weak acids and other metabolites they release, and their symbiosis with root fungi, rhizobia … Soil **(micro) organisms** can also facilitate the physical and chemical breakdown of silicate grains.

Finally, **modification** of the SRPs might help to further improve their naturally slow dissolution rates. Physical modification is milling the rock to dust, chemical modification could be acid treatments to corrode the mineral structure. Less technical and energy demanding, however, are biological modifications such as adding silicate dissolving microorganisms, or mixing SRPs with compost or manure. The last one proved to be especially successful with yields matching, or even exceeding, those obtained with only compost/manure or traditional fertilizers. However, besides the release of macro- and micronutrients, the addition of SRP to cattle slurry also effects its GHG emissions (Swoboda et al., 2021).

Swoboda et al. (2022) present literature data they gathered on **48 crop trials using SRPs** ranging from minerals (feldspars, feldspathoids, micas) to igneous rocks (granites, intermediate rocks, (ultra)mafic rocks). Their focus was thereby on agricultural benefits, namely the effects on yield, nutrient supply and soil properties. In general, significant **yield increases** were achieved on acidic (low pH) soils such as oxisols. Results **on temperate soils** (as the European ones) were mostly **insignificant**, although all trials with mafic and ultramafic rocks improved yield. The **best** nutrient supply was observed from application of **mafic and ultramafic rocks** to **acidic soils**. In some cases, very high application rates (>100ton/ha) resulted in imbalance of nutrients. Soil pH increased in most cases, sometimes even similarly as when lime would have been added. The **combination of rock powder and compost** generally causes an increase in soil biology. Care has to be taken when using SRPs from mine tailings or ultramafic rocks as these might release heavy metals.

Section summary

Various agricultural studies assess the effects of silicate rock powders (SRPs) applied to soils. They identify the following factors as decisive for the optimum weathering of these SRPs:

- the specific minerals the SRP consists of, and how they differ from the minerals in the soil
- smaller SRP grain sizes weather faster
- higher SRP application rates are better only up to a certain point due to nutrient imbalances
- (sub-)tropical climates and intensely weathered soils with low pH have highest EW potential
- longer field trials (>2 years) are needed to estimate long-term SRP effects on soil
- whereas weathering is generally faster in the root zone of plants, specific plant species can further speed up SRP weathering – soil (micro)organisms can also facilitate weathering
- SRP modifications can further enhance their weathering (physical: milling to dust; chemical: corroding with acid; biological: mixing with manure or compost)

Mafic and ultramafic rocks

The review paper of Swoboda et al. (2022) mentions that most nutrient supply from silicate rock powders to the soil is observed when mafic and ultramafic rock dusts are applied. The term "**mafic**" relates to the **presence of** dark-coloured, mainly **ferro-magnesian (Fe-Mg) silicate** minerals such as olivine and pyroxene. From an enhanced weathering point of view, the fastest dissolving minerals are calcium and magnesium silicates. Olivine is thereby both the most commonly found and the fastest weathering magnesium silicate. This means that olivine-containing rocks have the highest potential for both carbon dioxide removal and soil fertility improvement.

There is, however, an important difference in the mineral assemblage of mafic and ultramafic rocks. **Ultramafic rocks** (peridotite, dunite, harzburgite, kimberlite…) consist **mostly** of **olivine** (and its alterations such as serpentine) along with some other Fe-Mg silicate minerals. These rocks have the highest CDR potential (up to 0.8ton CO_2 per ton of applied ultramafic rock dust), but they contain limited plant nutrients and high amounts of Ni and Cr which can be an environmental risk (Strefler et al., 2018). **Mafic rocks** (**basalt**, gabbro, diabase…) have a lower CDR potential (about 0.3ton CO_2 per ton of applied basalt) as they contain less olivine and Fe-Mg silicate minerals (Strefler et al., 2018). However, they contain a range of other minerals that release Ca, Na, K and P upon dissolution, making them excellent natural fertilizers – and they do not have the high Ni and Cr contents as ultramafic rocks do.

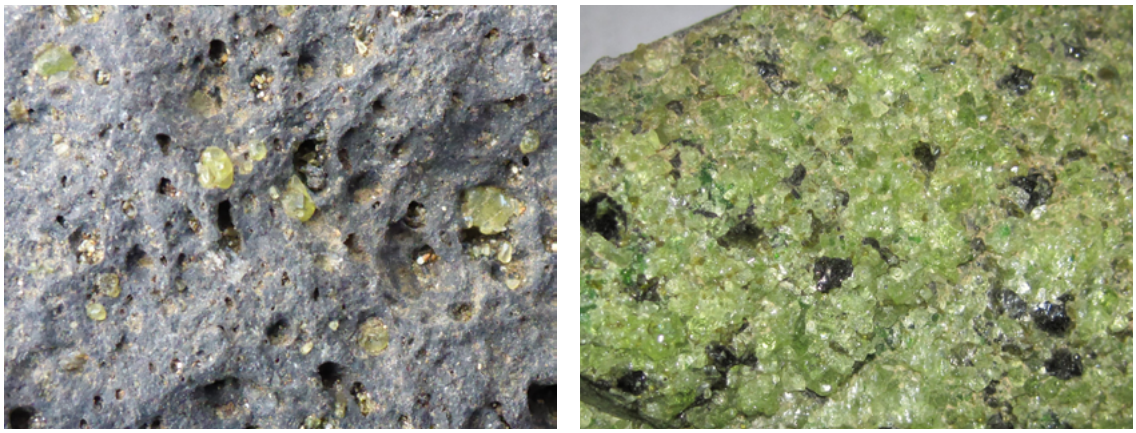


Figure 2.1. Comparison of mafic rock (basalt) from Hawaii on the left with an ultramafic rock (peridotite) from Arizona, USA, on the right. The light green grains in both rocks are up to 5mm large olivine crystals. Peridotite image on the right courtesy of James St. John (Ohio State University, Newark, US).

Both mafic (basalt) and ultramafic (olivine rich) rock dusts have been applied to agricultural soils to study their potential for CDR. In **lab experiments** (ultra) mafic rock dust is added to columns filled with soil that are continuously irrigated. As water flows through the soil column with mixed in rock dust, water samples are collected from various column depths as well as the eluate at the bottom. Analyses of these water samples then show how the chemistry of the soil water in the column changes over time due to weathering of the added rock dusts. At the end of such a lab experiment, soil samples can be taken to

assess how the soil chemistry might have changed over time.

In order to assess the effect that plants might have on enhanced weathering of (ultra) mafic rock dusts, **pot experiments** are conducted under greenhouse conditions. Large pots contain rock dust mixed in with soil and sustain the growth of specific crops. They are a type of mesocosms - enclosed environments that allow a small part of a natural environment to be observed under controlled conditions. Besides collection of water and soil samples as done in lab experiments, the crops themselves are also analysed to evaluate the effects that the rock dust might have on them.

Although closer to the real-life agricultural environment than lab experiments, pot experiments still don't represent all the complexities of chemical, physical and biological processes going on in the soil of farming land. **Field experiments** in actively farmed agricultural land replicate the exact conditions in which terrestrial enhanced weathering can take place, thus giving the most accurate insight of the CDR potential of EW. It is however very challenging to obtain representative samples in these natural conditions, or to monitor the EW process against the background of so many naturally occurring processes.

Section summary

Both mafic and ultramafic rocks contain olivine. As ultramafic rocks mainly consist of olivine they have a high EW potential, but they don't contain many plant nutrients other than Mg and their high Ni and Cr contents might cause environmental and toxicity issues. Mafic rocks such as basalt have a lower EW potential as they contain less olivine, but they contain a range of other minerals that can be used by plants and they don't have very elevated Ni and Cr concentrations.

Enhanced weathering upon addition of (ultra) mafic rock dusts to an agricultural soil is studied in different ways:

- Lab experiments represent maximum control over the system and best estimates of CO_2 removal, but it does not take into account the effects of plants, micro-organisms or seasonal fluctuations in temperature and precipitation.
- Field experiments in farmed agricultural land represent the real environmental system in which CDR through EW can take place, but the complexity of this natural system is a major challenge for measuring the CO_2 drawdown solely due to EW.
- Pot experiments are in between lab and field experiments: they assess the effects of plants on EW within the controlled environment of a greenhouse and with some micro-organism activity.

EW lab and pot experiments with (ultra)mafic rock dusts

The table below summarizes the main set-up and results from **scientific publications** on enhanced weathering studies with (ultra) mafic rock dusts applied to agricultural soils. To the knowledge of this report's authors, there are only **five** unique ones to date (April 2022): two lab experiments and three pot experiments.

Renforth et al (2015) carefully extracted cores from a calcareous soil which contains a 10-15cm organic rich plough layer. They mixed olivine rich dunite in the top 20 cm of this core and carried out a 5 month lab experiment with water continuously flowing through the cores. In this period of time they observed that the olivine dissolution signature did not travel down below the mixing zone and that most released trace elements were retained within the soil instead of leached out with the eluate (water collected at the bottom of the column). Ni concentrations in the eluate water were not measurable, but they did observe increased Cr concentrations.

Pogge von Strandmann et al. (2021) studied the Mg and Li isotopes of the soil and water samples from the above Renforth et al. (2015) experiment. They observed that olivine dissolution changes both Li and Mg isotope signatures of the drainage water over time. This EW signature, however, is significantly delayed by the exchangeable cation pool in the soil: as Mg and Li is released through ultramafic rock dust dissolution, it is temporarily adsorbed to minerals and organics in the soil. Only when this exchangeable soil pool is in equilibrium with the newly introduced olivine dissolution reaction, does the soil water fully reflect the EW signature. These findings caution for initial underestimation of added SRP dissolution as retardation of the EW signature by the exchangeable soil pool will likely occur in most soils.

Reference	Soil type (country) Climatic conditions	Crop	Rock type Origin, olivine content Grainsize	Application dose / Duration	CO_2 removed (Method)	Comments
Laboratory experiments						
Renforth et al, 2015 (Pogge von Strandmann et al, 2022)	Calcareous soil with 10-15cm organic plough layer (UK), pH>7, 19°C (4°C), 15mL/hour of fertilizer alike liquid	none (prior farming of broad bean, wheat)	'olivine' (dunite) from Åheim, NO (80% is forsterite) 65% <212µm	12.7 kg/m² 133 days (6 months)	2 ton/ha/y (Mg, Si in leachate) (0,3ton/ha/y)	- Mg^{2+} suggests quick increase in EW at start, then stabilization - Mg increase only in top 10cm of soil column - Rate of olivine dissolution 10-100 times slower than lab derived kinetic rates - Elevated Cr in water leached from experiment
Dietzen et al, 2018	Sandy podzol (DK), organic rich, acidic, pH 3.5(!), on glacial sands, 20-25°C, 'soil moisture as field conditions'	none (no farming since 1980s)	'olivine' (dunite from Åheim, NO?) 50% <20µm	1kg/m² 5kg/m² 97 days	12-16 ton/ha per year (final exchangeable Mg in soil)	- In 3 months' time, ca 27% of the 1kg/m² olivine weathered whereas only ca 7% of the 5kg/m² did - Replacing lime with olivine SRP also increases soil pH but with reduced CO_2 emissions & extra CDR - Increased pH also increases SOM decomposition
Pot experiments						
ten Berge et al, 2012	Sandy soil (NL) low bioavailable Mg and K, pH 4.9, 6-25°C, water in tray below pot + 130mm water/230days	Ryegrass	'olivine' (dunite) from Raubergvik, NO, forsterite dominated, 73% <50 µm	0.16kg/m², 0.82kg/m², 4.1kg/m², 20kg/m² 230 days	0.46-4.27 ton/ha per year (plant Mg & soil exchangeable Mg)	- In 230 days, ca 15% of the 0.16kg/m² olivine weathered whereas only ca 1% of the 20kg/m² did - Negative feedbacks in soil at high application rates: Mg-induced Ca deficiency and lower P in crop - Although Ni more bioavailable in soil and elevated in water and crop, still below phytotoxic threshold
Amann et al, 2020	Sandy loam soil (BE) pH 7.1, 7-25°C, water irrigation 800mm/year	Wheat, barley, none	Dunite from Åheim, NO (90% olivine) <50µm, <1.1mm	22kg/m² 340 days	23-49 kg/ha per year (Mg in leachate)	- More weathering observed for fine (<50µm) than coarse (<1.1mm) SRP - No difference between daily or weekly irrigation - Elevated Ni & Cr from fine SRP; pH always higher - Increase in DIC, Mg & Si only observed in top 13cm - Lower Si with plants only difference for crop/no crop
Kelland et al, 2020	Clay-loam soil (UK), pH 6.6, low TOC, oil seed rape field 17-25°C, water irrigation 77mm/120days	C_4 cereal Sorghum (Sorghum bicolor)	Basalt (US) (25% glass, 58% feldspar, 11% pyroxene, 1% olivine) 80% <1250µm	10kg/m² 120 days	2-4 ton/ha 1-5 years (elemental budget of plants/soil / leachate)	- 21% yield increase & 26% Si increase in shoots - no cations or TA increase in leachate, only pH - Mg, Si, Ca mostly taken up in soil (clays, secondary minerals) and by plants - root assisting mycorrizal fungi corrode rock grains - model shows 10X finer SRP does not remove significantly more CO_2, it mainly does it faster

Additional soil cores that were drilled for, but not used in, the above Renforth et al (2015) study were utilized by Pogge von Strandmann et al. (2022) to carry out the exact same EW experiment at a significantly lower constant temperature (4°C instead of 19°C). They found that although olivine dissolution rates start out similar in both experiments, the rate at 4°C is two orders of magnitude smaller after >100 days. This may indicate that EW will be considerably less efficient as a CDR method in low temperature climates. In both experiments Ni and Cr concentrations were well below drinking water standards and soil limits, but caution is warranted as annual application of ultramafic rock dust might result in a buildup of heavy metals in the soil over time.

Over a period of three months, **Dietzen et al. (2018)** assessed the effects of very fine olivine rich dunite dust on the overall CO_2 flux of an uncommonly acid (pH 3.5) and organic rich soil. In this incubation experiment, they observe that the olivine dissolution rate does not correlate directly with the olivine application rate: whereas ca 27% of the 1kg/m² applied olivine dissolved, only ca 7% of the 5kg/m² applied olivine dissolved. They do find a positive correlation with olivine application rate and pH increase, which in turn results in an increased decomposition of SOM at higher pH. However, the rise in CO_2 emissions due to increased SOM decomposition is overcompensated by the CO_2 removal through olivine weathering. They conclude that fine olivine rich rock dust is an effective replacement for lime as it comparably increases soil pH. But whereas lime dissolution releases CO_2, olivine dissolution removes CO_2.

Ten Berge et al. (2012) set up a 32 weeks long pot experiment using sandy soil to which 4 different olivine rich rock dust doses are applied. They primarily establish an upward water flow (placing a tray with water below each pot) to avoid nutrient losses through leaching, and use ryegrass as test crop. They find that olivine quickly increases soil water pH and alkalinity and, at high doses (20kg/m²) also boosts concentrations of Mg, Si and Ni in the soil water. Low to medium olivine application doses (0.16-4.1 kg/m²) result in increased plant uptake of Mg, Si, and Ni, as well as more bioavailable Mg and Ni in the soil. At higher rates of olivine application (20kg/m²), the increased input of Mg^{2+} to the soil makes it release K^{+} so that at high doses plants show higher K concentrations and a larger yield. However, high olivine doses also cause negative feedback such as Ca imbalance in the soil and a decrease of Ca and P contents in the plants. Although Ni contents increase in plants (from 0.531 to 2.67 ppm with 20kg/m²) they remain below the phytotoxic threshold of 10 ppm. Concerning EW, 15% of the lowest olivine rich rock dust application dose dissolved over the course of the experiment in comparison with only about 1% of the highest application dose.

The 340 days long pot experiment of **Amann et al. (2020)** involves application of an olivine rich rock dust to a sandy loamy soil in which they grow wheat and barley. No differences are observed when the same amount of water is applied on a daily or weekly basis. For both fine and coarse-grained ultramafic

rock dust, they describe a quick increase of pH from 7 to more than 8 which then stabilizes to 8. Overall, the olivine weathering signal moves slowly downward in the soil. Elevated concentrations of Ni and Cr are measured in the soil water when using very fine (<50µm) olivine rich material, but remain within the recommended limits for agricultural irrigation water. As the Mg^{2+} released from olivine dissolution is partially taken up by plants, precipitated in secondary minerals and absorbed by clays and organic material, the amount of Mg^{2+} measured in soil water is not representative of the amount of enhanced weathering that took place. They therefore suggest that dissolved inorganic carbon (DIC) and total alkalinity (TA) are better soil water parameters to calculate CO_2 consumption through EW of (ultra) mafic rock dusts.

The pot experiment of **Kelland et al. (2020)** involves the application of a rather coarse-grained basalt to a clay loam soil in which the cereal sorghum is grown. After a period of 120 days with continuous low rate drip irrigation they find significant increases in yield and Ca, Mg, K, P and Si contents in the plants. Silicium benefits the plant as it increases its defense to biotic (pests, diseases) and abiotic (draught, salinity, heat) stresses. Over the course of the rather short experiment, the water leached from the pots only shows an increase in pH, no significant changes in cation concentrations or total alkalinity. The basalt weathering products (Ca, Mg, Si) are mostly taken up by the soil (clay minerals, formation of new minerals) and plants. The increase of soil exchangeable Mg and Si indicates fertilization potential for depleted agricultural soils. Root excluding weathering bags embedded in the rhizosphere show extensive colonization by mycorrhizal fungi that made the olivine grains' surface rougher through bioweathering. Based on the data from their experiment, Kelland et al. created a model which confirms that olivine and pyroxene are the fastest weathering minerals. Model calculations furthermore indicate that 10 times more fine-grained rock dust would indeed speed up the weathering process but not result in a significantly larger CO_2 drawdown within the first five years.

Section summary

The main observations from previously published studies on EW with (ultra)mafic rock dusts on agricultural soils are:

- Enhanced weathering rates observed in identical experiments are significantly slower at 4°C than at 19°C, suggesting low efficiency for EW in low temperature climates.
- Although Ni and Cr contents in soil and eluate remain well below soil limits and drinking water standards, repeated annual application of ultramafic rock dust could still result in a buildup of heavy metal concentrations in the soil.
- In highly acidic and SOM rich soils, olivine rich rock dust is comparatively efficient to increase soil pH as lime, but whereas lime dissolution emits CO_2 olivine rich rock dust removes CO_2.
- Lower olivine application rates obtain higher dissolution percentages than (significantly) higher application rates, suggesting that the amount of olivine rich rock dust is not the main limiting factor of the dissolution speed.
- Too high rock dust application rates (>10kg/m^2) do not only result in lower weathering fractions but may also create nutrient imbalances such as Mg induced Ca deficiency (and Ni or Cr contamination in case of olivine rich rock dust).
- In a pot experiment with mafic basalt rock dust, soil exchangeable pools of Mg and soluble Si increase which is positive for depleted agricultural soils.
- Mycorrhizal fungi are found to play an active role in disrupting and "roughing up" the surface of Mg-Ca-Fe silicate grains through bio-weathering, which makes them more vulnerable to dissolution and thus enhances chemical weathering with CO_2 removal.
- Products of (ultra)mafic rock dust weathering are in first instance taken up by the soil (clay, organic material, secondary minerals) and plants – leaving only a fraction of them in the soil pore water or leachate. It thus takes quite some time for the EW signature to be visible in soil water and for it to move down in the soil.
- Estimates of removed CO_2 are often based on changes in the Mg concentration in the soil and/or in plants and/or in soil water collected throughout the experiment. As the products of (ultra)mafic rock dissolution are partially retained by soil minerals and organics, it seems better to estimate CO_2 removal from an entire elemental budget and/or soil water DIC and TA and/or CO_2 fluxes and/or specific isotope ratios.

EW field trials

Low et al. (2022) identify four, currently ongoing, early-stage field experiments of terrestrial enhanced weathering worldwide:

- They describe Project Carbdown, a European program that started late 2020, as the only terrestrial EW project in continental Europe. The Olivine Project is part of Project Carbdown, which besides other field trials in Germany and the Netherlands includes lab and pot experiments of the application of basalt and ultramafic rocks to agricultural soil.

- The Working Lands Innovation Centre started large-scale EW field trials in 2019, applying metabasaltic rock dust to different types of crops across 100 acres of land in the state of California (USA). They focus on stakeholder engagement and actively involved researchers, state agencies, industry, farmers, ranchers, tribes and small-businesses from the very start of their project.

- The international Leverhulme Centre for Climate Change Mitigation was established in 2016 to objectively investigate enhanced rock weathering with croplands as a CDR strategy. Their 10-year multi-disciplinary program includes pot experiments in the UK (Kelland et al., 2020) and field trials with basalt in Australia, the USA and Malaysian Borneo besides theoretical modelling and assessment of environmental and socio-economic impacts.

- The Guelph wollastonite trials seem to be the only completed large-scale EW field experiments so far. Between 2015 and 2018, agricultural researchers from the University of Guelph added the calcium silicate mineral wollastonite to both pot experiments and agricultural fields in Ontario, Canada (Haque et al. 2019; Haque et al. 2020).

To our knowledge, there are no scientific papers to date (April 2022) that describe the outcome of enhanced weathering field experiments involving application of (ultra)mafic rock dusts to agricultural soils. Our literature research uncovered EW field experiments with calculations of the observed CO_2 capture only for wollastonite applications.

Calcium-magnesium silicates are the fastest weathering minerals when in contact with CO_2 and water. Whereas forsterite olivine (Mg_2SiO_4) represents the optimal magnesium silicate for enhanced weathering, **wollastonite** ($CaSiO_3$) is the most optimal calcium silicate for the job. An advantage of wollastonite is that when it dissolves it releases many Ca^{2+} cations which may react immediately with the CO_2 bound in (bi)carbonate anions to form the secondary mineral calcite ($CaCO_3$). Permanent storage of removed CO_2 as carbonate minerals hence occurs faster for wollastonite dissolution – within the **soil** itself as **inorganic carbon** – than for olivine dissolution where the

weathering products mostly travel by water to form carbonates elsewhere. This in situ formation of pedogenic carbonates during wollastonite dissolution allows for a more direct estimation of CO_2 removal rates through soil inorganic carbon (SIC) measurements. And, just like (ultra)mafic rock dusts, wollastonite is an efficient and climate positive replacement of lime commonly used to increase soil pH. The downside to wollastonite, however, is that this mineral is **much less widespread than olivine**.

Haque et al. (2020) applied wollastonite (at least 90% <84µm) on potato and soybean fields with sandy loam soils and a pH 5.9 and 6.6, respectively. Application doses varied from 1.25 to 5 tons per hectare (0.125 to 0.5kg/m^2) and soil samples were collected for analyses about 5 months after application, right after crop harvest. They found statistically significant increases in soil inorganic carbon over this short period of time, reflecting CO_2 capture and storage through wollastonite weathering. The highest application dose thereby sequestered 0.4 ton CO_2 per hectare over 5 months. In a longer running field trial Haque et al. (2020) applied wollastonite to the same field for three consecutive years and accordingly observed continuously greater accumulations of SIC. These field trial results confirm the findings of their earlier pot experiments (Haque et al., 2019), which show that wollastonite amendments lead to CO_2 sequestration and promote enhanced plant growth of beans and corn.

The main reasons for the **current absence** of **agricultural EW field trials with (ultra)mafic rocks** in literature are likely (1) the duration needed for such trials (> 1 year) to allow the chemical-physical-biological soil system to find a new balance; (2) the even longer testing period needed to adequately assess any side effects on crops and the environment (> 2 years); (3) the challenge of monitoring a dissolution process within a complex open system where many other chemical reactions take place (partially interacting with the enhanced weathering process).

However, the large range of CO_2 removal rates estimated from lab and pot experiments so far (see table above) shows that we need to undertake real-life EW field trials to gain insight into the CO_2 sequestration potential under specific climate, soil and crop conditions. Besides the 4 agricultural EW programs mentioned by Low et al. (2022), a growing number of international research projects are being devoted to this topic, giving prospects for crucial insights and publications in the near future. The Olivine Project wants to contribute to the build-up of this much needed knowledge as the first and so far only EW field experiment in Greece.

Section summary

Worldwide, there are only a few research programs on the CDR potential of EW in agriculture which include large-scale field experiments. From these, only the results on application of the calcium silicate mineral wollastonite are published.

No CO_2 removal rates estimated from field trials with (ultra)mafic rocks have been reported so far. EW lab and pot experiments, representing less complex and more controlled environments, reveal a large variability of CO_2 sequestration potential with (ultra)mafic rock dusts.

Conducting real-life EW experiments on field scale brings many new challenges due to higher complexity and longer durations. Nevertheless, field trials in different climates, soils and crops are urgently needed to adequately assess the climate change mitigation potential of agricultural EW with (ultra) mafic rocks.

The olivine project

The olivine project

To contribute towards a better understanding of the real Carbon Dioxide Removal (CDR) potential of Enhanced Weathering (EW) outside labs and greenhouses, we started to design an agricultural field experiment in September 2020. Multiple papers suggest that crushed olivine rich rocks spread over large areas of land can help fight climate change impacts. Our main aim is therefore to test this hypothesis within the framework of existing agriculture so that any positive results are directly relevant to local farmers.

The Olivine Project started with field experiments in a cotton field in central Greece, in the agricultural area of Thessaly. On the one hand, we test the large-scale application of realistic amounts of rock powder using practical farming tools. On the other hand, we study enhanced weathering of different olivine rich rock materials applied at higher concentrations to smaller plots. We thereby want to identify the chemical fingerprint of EW so we can eventually work out a straightforward way to calculate the amount of CO_2 removed through rock dust dissolution. But we also evaluate any effects that the addition of olivine rich rock powder might have on the soil quality, soil water composition, and cotton yield and quality.

Context of the study area

As soils are the products of the combined action over a long time of the parent material, climate, topography and vegetation of an area, we present a brief description of these factors below.

Geological & geographical setting

The geology of Greece is structurally very complex due to its location in the convergence zone of Europe and Africa. About 150 million years ago, tectonic forces started pushing the heavier African plate northwards underneath the less dense Eurasian plate. As it sunk into the olivine rich mantle rocks beneath Eurasia, the sediments on top of the African plate were scraped off and piled up. Around 65 million years ago, continued collision between the two plates after closure of the ocean in between them started deformation of the southern edge of the Eurasian continental crust, forming **mountain ranges** such as the Alps and the Balkans.

The Greek orogenic belt is the southern continuation of the Balkan mountains and constructed from a mixture of Eurasian and African **crustal rocks**, including scraped off **ocean sediments** as well as **parts of the olivine rich mantle**. The present-day Thessaly plain developed from a large basin between the Pindus Mountains, Greece's largest mountain chain, and the southern continuation of Mt Olympus, Greece's highest peak. For millions of years this basin was a huge lake, sustained by rainfall and water run-off from the surrounding mountains. Only about 1 million years ago,

the Pineios river started to form its delta along the Aegean coast (Caputo et al, 1994).

Figure 3.1. Simplified geographical map of Greece obtained from www.freeworldmaps.net. The present day Thessaly plain is a large flat area between the Pindus Mountains and the Mt Olympus range, with the Pineios river and its tributaries as main hydrological features.

The subsequently developed riverine network largely drained this intra - mountain basin with the only remaining lake in the **plain of Thessaly** being **Lake Karla**, located at its northern end. This 180 km^2 lake was the site of a unique fishing culture but completely drained in 1962 to gain land for agri-culture. As agriculture wasn't so successful in the saline (with high electrical conductivity) soils of the former lakebed and the local population wanted to restore the original fishing tradition, about 50km^2 of the former lake was recently reflooded.

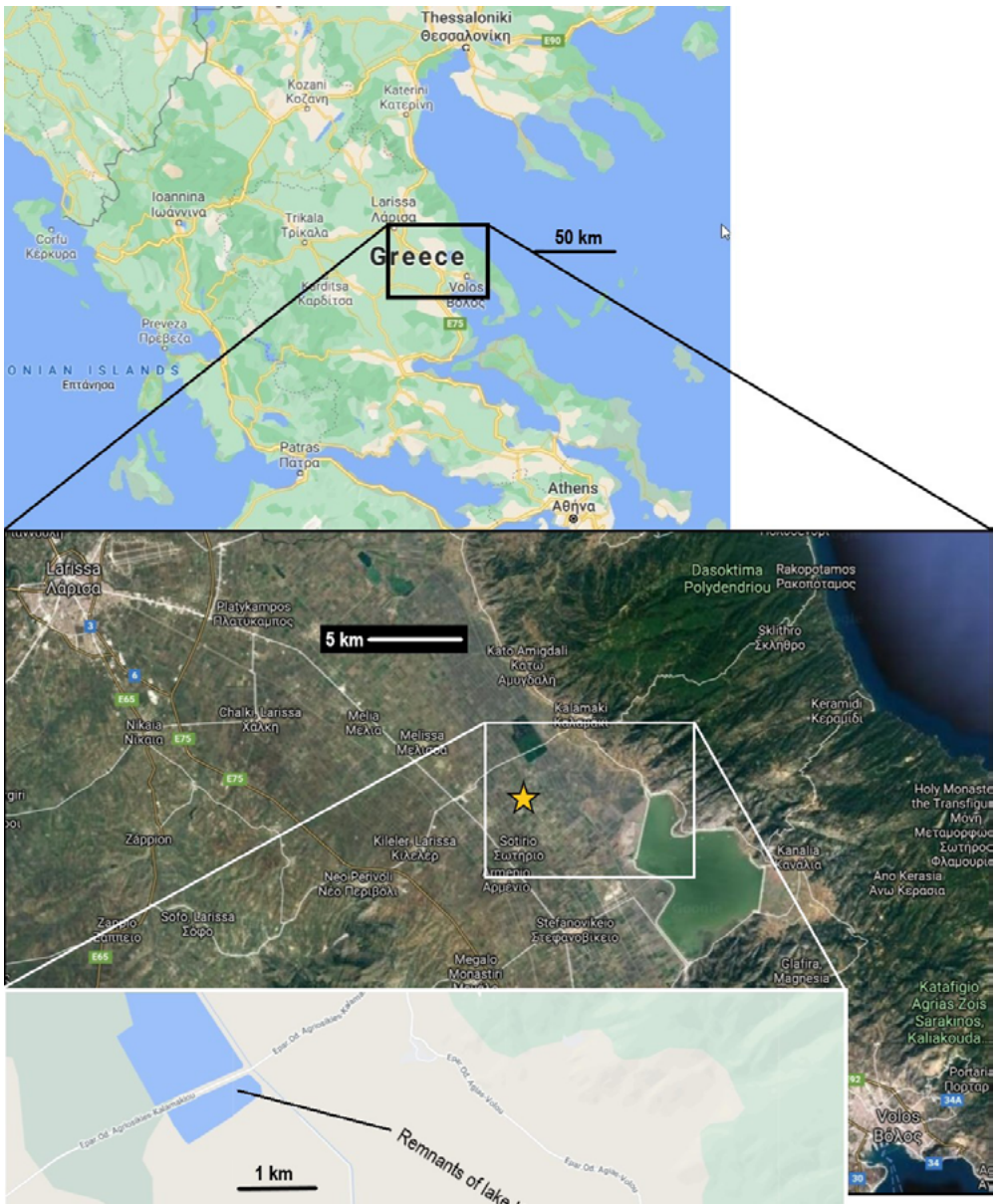


Figure 3.2. Series of Google Maps images showing the location of the field for the EW experiments (yellow star) and the geography of the wider area.

Our field is situated in a part of the Thessaly plain that used to be lake Karla. It is near the small farmers' village of Niki (postal code 41500), 25 km SE of Larissa and about 30km NE of Volos. The parent material of the **soil** of this area is comprised of **lake sediments** that settled at the bottom of the former basin, with **components derived** from the natural weathering of the **mountains surrounding the Thessaly plain**. These mountains are made up from very different types of rocks such as limestone, silicate rocks and olivine rich mantle material. This is reflected in the mineralogy and chemistry of the soil summarized as rich in carbonates, high silicate clay content and elevated levels of nickel and chromium. Overall, Central Greece is one of the regions within Europe where natural soils have elevated background levels of Ni and Cr, a heavy metal signature inherited from the chemical composition of their parent rock material (Lado et al., 2008).

Climate

The climate of the area is typically continental with **cold and wet winters** and **hot and dry summers**. Daytime temperatures can drop below zero on some winter days, whereas in summertime they occasionally rise above 45 °C. The mean annual precipitation in the region is about 560 mm, but this rainfall is distributed unevenly in both space and time. The mean annual potential evapotranspiration is about 775 mm and the mean annual temperature is 14.3 °C (Vasiliades et al, 2009).

Satellite images and soil variability

Satellite imagery can assist in obtaining soil information from a synoptic point of view, giving a general insight into soil's properties. **Bare soil reflectance**, for instance, can serve as a tool to assess the **soil variability** in a field. A time series of bare soil satellite images of a field can thereby give a reliable first indication of soil homogeneity. Detailed knowledge of any observed variability, or of the main soil properties that cause it, can however not be determined from satellite data. This information is only obtained by a soil survey including sampling of the soil from different parts across a field and subsequent analysis of its main soil properties.

The field for our EW experiments does not show soil variability in the panchromatic **satellite imagery** derived from Google Earth. Analysis of soil samples collected from different areas in **our field** did not reveal significant differences in soil properties, confirming a rather **homogenous** nature of the soil.

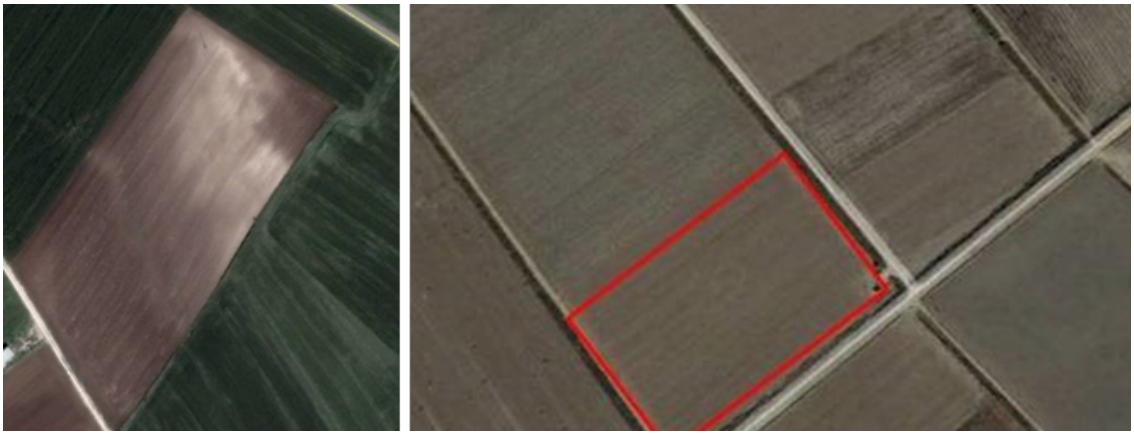


Figure 3.3 Left: Google Earth bare soil reflectance image of a field where patchy colours suggest variable soil properties. Subsequent soil analysis showed that the light coloured part of the field represents soil with significantly less soil organic matter and clay than the darker areas of the field

Right: Google Earth bare soil reflectance image of the field of which we use the bottom 2 ha (red rectangle) for our EW experiments. The uniform shade of brown across the entire field suggests rather homogenous soil properties in this field, which is confirmed by soil analyses

Soil survey

The area of the field and its surroundings is covered by **alluvial soils** which developed recently on a parent material which is the **sediments of** the drained **lake** Karla. The main characteristics of these soils are their heavy texture, medium to poor water drainage, high calcium carbonate content along the entire soil depth coupled with high pH values and often high electrical conductivity. These soils are classified as Vertic Xerofluvent and their chemical and physical characteristics make them not so efficient for carbon dioxide removal (CDR) through the application of silicate rock powder (SRP).

Due to their short time under atmospheric conditions, the soils of the drained lake could not yet develop soil genesis horizons. Soils without diagnostic horizons, basically unaltered from their parent material (unconsolidated sediment or rock), are also known as Entisols.

Plant species

The main cultivations in the area of our EW field experiment are cotton, wheat, maize, and alfalfa. We decided to start our trials with cotton because of the importance of this crop in Greece, its need for intense summer irrigation and the fact that it is not consumed as human or animal food.

Research published so far on the **application of SRP in agriculture** includes maize, grasses (Lolium multiflorum, Lolium perenne), rapeseed (Brassica campestris), eucalyptus, holy basil, black oat (Avena strigosa), soybean (Glycine max), alfalfa (Medicago sativa), scots pine (Pinus sylvestris) and buffalo grass (Bouteloua dactyloides). But there does **not** seem to be **any literature** related to the effect of SRPs application **on cotton** crops.

Positive results for the yield of tested crops are mostly in acidic soils (Oxisols) and/or in (sub)tropical climates. Although most studies in temperate (e.g. European) soils reported no effect on yield, significant yield increase was recorded in some cases for maize and soybean.

Section summary

The field for the EW experiments is located in the plain of Thessaly, in an area that used to be lake Karla. The soil of this field reflects the geological and geographical context of this location. On the one hand, it has fine-grained silica rich lake sediments. On the other hand, its elevated Ni and Cr contents reflect the chemical composition of the mountains which surround the plain and include olivine-rich rocks.

The local climate combines hot and dry summers with cold and wet winters. Temperatures can range from below 0 to over 45°C and annual precipitation is 560mm.

Satellite images of the field for our EW experiments suggest that there is no significant soil variability within the field.

Soil survey information of the area describes young, relatively undeveloped soils (Entisols) with a heavy texture, high calcium carbonate content and poor water drainage that are far from optimal for EW.

There are no studies yet on the effects of silicate rock dusts applied to cotton cultivation.

Reconnaissance field trip 21-22 January 2021

Late January 2021, there is a preliminary visit of the cotton field along with the first meeting of

- the owner, **Gregory Xiros**
- the farmer who works this field, "**Doris**" Dritan Xhaja
- the soil scientist researcher at the Institute of Industrial and Forage Crops (IIFC) in Larisa, **Elefterios Evangelou**
- the retired soil scientist and former director of ELGO Dimitra, **Christos Tsadilas**
- the geologist hired by Fieldcode to start this project, **Ingrid Smet**

Figure 3.4.
From left to right: Doris, Gregory Xiros, Lefteris Evangelou, Christos Tsadilas.

During this visit, the farmer shared practical details of cotton growing on this field (timing, distances between rows, fertilization, irrigation ...). We discussed the main aim of the project and a draft design for the first trials in 2021. Together we decided where we can store tons of rock dust and biochar, how we can best apply these products both manually and with the available farming equipment, when and how deep he will plough and harrow the soil...

At the time of our visit, the soil was wet and sticking very much to our footwear due to its high clay content. The reason for this clay is that nearby Lake Karla used to extend all over this area, but the 180 km^2 large lake was drained in 1962 to gain land for agriculture. The high clay content of the fields in these lake sediments results in soils with poor water drainage and high pH. Enhanced weathering of olivine is however optimal in better draining, more sandy soils with low pH.

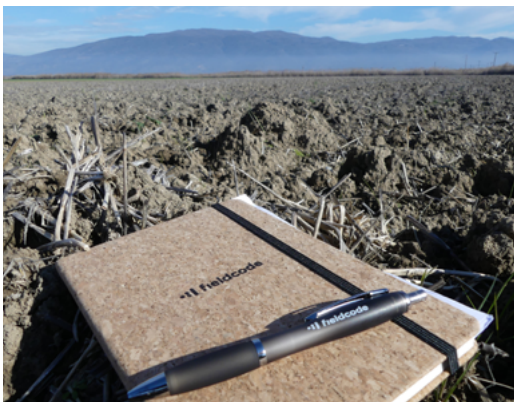


Figure 3.5. The clay rich soil of the field with remnants of the previous crop (wheat) and distant mountains enclosing the Thessaly plain.

On 21 January we took soil cores at two depths at two different locations with a simple soil-sampling auger to have an initial idea about the soil's characteristics. In order to have a more in depth understanding of this soil, we arranged a JCB mechanical excavator to open up a full soil profile the next day, January 22.

Figure 3.6. Cores taken with soil-sampling auger already showing the clay rich content of the soil.

Figure 3.7. JCB digger opening up a full soil profile for more detailed soil characterization and sampling.

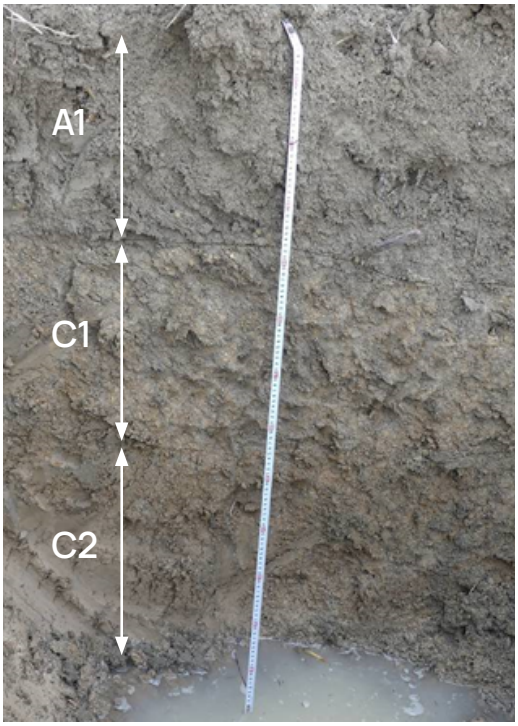


Figure 3.8. Soil profile opened up on the cotton field on 22 January 2021.

The soil's top layer (down to ca. 0.4m) is the **plough horizon A1** which has a greyish brown colour, more organic content and a different texture due to decades of crop growing and ploughing.

Beneath it is a **mixed zone** (0.4-0.8m – **C1**) showing orange yellow spotted oxidation zones due to the seasonally changing level of the water table.

From about 0.8m down we find the orange brown coloured **lake sediments** that did not yet evolve into a soil horizon (**C2** –recent alluvial deposits).

As this thick layer of clay is nearly impermeable for water, we found the groundwater table to be rather shallow at about 1.3m depth.

Figure 3.9. Christos Tsadilas taking samples from the different soil horizons.

We took samples from each of these three soil horizons (layers) revealed in the soil profile. Together with the soil cores sampled the previous day with the auger, they were analyzed at the Institute of Industrial and Forage Crops (IIFC) in Larisa for the characteristic soil parameters. The data of these preliminary analyses are presented in **Appendix A**.

The main results from these analyses are that the soil at Gregory's field has

- a high clay content of around 50%
- a high pH of 8.4
- a significant amount of carbonate minerals, around 24% $CaCO_3$-equivalent

Drawdown and removal of CO_2 through enhanced weathering of olivine rich rocks is shown to work best within sandy, well-draining soils with low pH (below 7) and little to no carbonate minerals. Therefore, our **initial field visit indicated** that **this soil** is **not optimal for** the **chemical dissolution of olivine** due to its high pH, high clay content and many carbonate minerals.

This type of soils, however, is more common for cotton cultivation in the area and both the farmer and owner are exceptionally cooperative – vital for such field trials. We furthermore had no chance of finding a more suitable soil on short notice during what would turn out to be a 6 months long strict Covid19 lockdown. Therefore, we decided to carry out our first trials in this not optimal soil as this allowed us to start our enhanced weathering project in 2021 and gather practical experience and useful knowledge either way.

Section summary

A first visit to the cotton field shows that both farmer and owner are very interested in the EW experiments we want to carry out and want to be as cooperative as possible.

Studying a soil profile opened up with a JCP digger confirms that the field is situated in lake sediments that did not yet fully develop soil horizons besides a more organic rich plough layer on the top.

Soil samples indicate that that the soil has a high pH, contains about 50% clay and has a lot of carbonate minerals.

The soil properties suggest that this field is not optimal for enhanced weathering trials. Because of exceptional cooperation with the farmer and restrictions due to a Covid19 lockdown, however, we decided to proceed with this particular soil for our first EW experiments.

Starting materials

Starting materials

The main parameters determining the efficiency of enhanced weathering are the mineral content, chemical composition and grain size of the rock powder, the chemical and physical characteristics of the soil, the type of plants and micro-organisms in the soil, the climate and the amount of available water and CO_2. In 2021, six different olivine rich rock powders were applied to the clay rich soil of a cotton field in central Greece.

Greek olivine rich rocks

Across Greece there are many areas where olivine rich mantle rocks occur and there are currently two locations where these rocks are excavated (Figure 4.1). Olivine rich rocks are increasingly in demand for a variety of industrial processes where they replace more traditional, less environmentally friendly products. They are, for example, used as a refractory material, as slag conditioner in the steel industry, for sand blasting, as foundry sand…

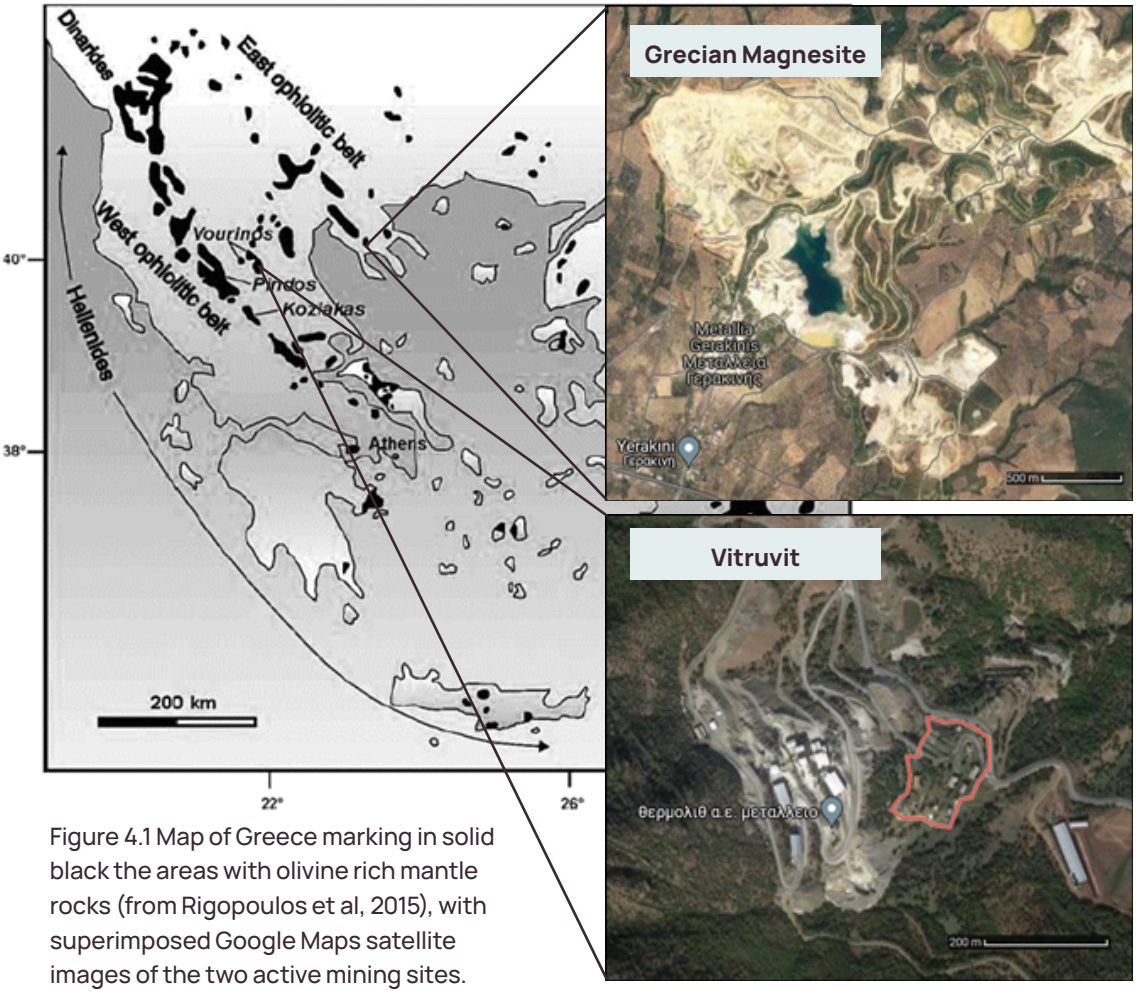


Figure 4.1 Map of Greece marking in solid black the areas with olivine rich mantle rocks (from Rigopoulos et al, 2015), with superimposed Google Maps satellite images of the two active mining sites.

Grecian Magnesite S.A. has a quarry near the village of Yerakini (Gerakini) in Greece's northern region of Halkidiki. Their core business is extraction of the mineral magnesite from the olivine rich rocks which at this location are some-

what altered through geological processes. They also sell the olivine rich rock itself as "olidun", a product that is gaining importance due to increased demand from metallurgy.

Vitruvit S.A. excavates olivine rich rocks in northern mainland Greece, near the village of Skoumtsia, at the location of a former chromium mine. The less altered olivine rich rock represents the company's main product from this quarry and is sold as "thermo olivine" for a range of industrial applications.

Both companies offer their olivine rich product in varying grain sizes and sent us a few kilograms of sample for initial characterization (Figure 4.2). Three of these samples were sent to the Qmineral laboratory in Belgium late November 2020. The following preliminary analyses were carried out on these Greek olivine rich rocks:

- Mineralogical composition with XRD to assess how much olivine they contain, and how much of the other CO_2 reactive minerals such as pyroxene, serpentine (hydrated olivine), amphibole …
- Chemical composition with XRF to assess how much heavy metals such as Ni and Cr they contain.
- Grain size distribution with laser to see how much small material is in the finer fractions.
- Asbestos screening to ensure that none of the serpentine minerals occur as asbestiform crystals.

The Qmineral report of these preliminary analyses is presented in **Appendix B**.

Figure 4.2. Photographs of larger rock pieces and 2-6 mm olivine rich "dunite" provided by Grecian Magnesite, as well as the three grainsize fractions of "olivine" provided by Vitruvit, in the autumn of 2020.

The main results from the preliminary analyses shows that the two Greek olivine rich rock dusts:

- → do not contain any asbestos.
- → are mainly composed of olivine, serpentine (altered olivine) and pyroxene, three minerals that capture CO_2 through enhanced weathering of which olivine is the most efficient.
- → from Vitruvit have more pure olivine (65%) and less serpentine (9%) than the more altered ones from Grecian Magnesite (43% olivine, 33% serpentine).
- → have similar amounts of SiO_2 (42-44wt%), MgO (41-43wt%), Ni (2280-2530ppm) and Cr (2800-3000ppm).

Section summary

Olivine rich mantle rocks are present across the Greek mountain ranges. Two companies, Vitruvit S.A. and Grecian Magnesite S.A., are actively mining them on mainland Greece and sent us sample materials for preliminary characterisation.

Our analyses show that both Greek olivine rich rocks are safe to use with respect to asbestos and that they contain the usual elevated amounts of Ni and Cr. The main difference is that Vitruvit rocks retain more olivine in its original form, whereas in Grecian Magnesite more olivine has been geologically altered to the mineral serpentine.

However, both rocks seem to be safe and suitable for our enhanced weathering experiments.

European olivine rich rocks

Networking with other climate positive scientists and enhanced weathering pioneers led to the kickoff of "**Project Carbdown**" late 2020. Funded by the Carbon Drawdown Initiative, Hemmersbach and Fieldcode, this is the umbrella project for our Greek EW field trials alongside similar field trials, greenhouse and laboratory experiments in Germany and the Netherlands.

The main people actively involved in Project Carbdown are:

- Dirk Paessler & Ralf Steffens (Carbon Drawdown Initiative, DE)
- Prof. Dr. Jelle Bijma (Alfred Wegener Institut, DE)
- Prof. Dr. Jens Hartmann (Universität Hamburg, DE)
- Dr. Mathilde Hagens (Wageningen University, NL)
- Dr. Ingrid Smet (Fieldcode, GR)

Eifelgold basalt is an olivine containing rock in **Germany**, extracted and sold by RPBL. Compared to olivine rich mantle rocks, this volcanic rock has only 10% olivine and thus a lower CDR potential but also less Ni. It however has other minerals with important plant nutrients such as P, K, Ca ..., which are very limited in olivine rich mantle rocks, making it more suitable for application in combination with crops. Project Carbdown's EW research in Germany and the Netherlands is focused on this local Eifelgold basalt rock dust which is already certified as a mineral soil fertilizer.

An **olivine rich rock from Norway** is also applied in some of the German EW field trials to allow comparison with the German basalt. With the idea to assess the CO_2 removal potential of the same rock types within a different environment (climate, soil and crops), we decided to also include the German basalt and Norwegian olivine rich rock in our Greek cotton field trials. Different mining companies quarry the olivine rich rock location in Norway and we purchased rock dust through the Dutch company greenSand.

A recent scientific paper (Kremer et al, 2019) discusses promising rocks for CDR through enhanced weathering in Europe. It identifies two more locations besides the one in Germany, the one in Norway and the two in Greece which are already mentioned. These are both **olivine rich rocks** derived from the mantle that are currently quarried by **Novo Cives in Italy** and by **Pasek in Spain** for the same industrial applications as described above. To have a chance at testing the EW potential of all olivine rich rocks currently available in Europe, we decided to also include these two rock types in the Greek olivine project.

All six rock dusts were provided to us **<250 µm** - a standard grain size for some mining companies and still feasible to prepare for the other ones (Figure 4.3). Smaller grains might be better as they theoretically weather

faster, but the energy required – and hence CO_2 emissions and price – for further grinding increases too much. Apart from the Norwegian product, we purchased all rock dusts directly from the mining companies who delivered them dry in properly closed big bags. The Norwegian olivine rich rock dust purchased through greenSands, however, was delivered in an open big bag and partially wet. This created issues both with the manual application of the Norwegian rock dust and its homogenous incorporation into the soil (see below).

Figure 4.3. Photographs of the 6 different rock dusts applied on the cotton field, identified by the name of the company we obtained them from and the country code of their origin. Notice the clotting in the partially wet Norwegian rock dust on the bottom right.

A sample of each of the six rock dusts was sent to the Qmineral laboratory in Belgium to obtain a full characterization of these materials. The exact composition of the EW starting materials needs to be known as it is required for any calculations and experiment interpretations at the end of the project. For example, these data are relevant to understand any differences in enhanced weathering behaviour, or side effects on plants or soil, that we might observe during the experiment. The analyses carried out are:

- Mineralogical composition with XRD to assess how much olivine they contain, and how much of the less CO_2 reactive minerals such as pyroxene, serpentine (hydrated olivine), amphibole …
- Chemical composition with XRF to assess how much heavy metals such as Ni and Cr they contain.
- Grain size distribution with laser to see how much small material is in the finer fractions.
- Cation exchange capacity (CEC) to measure the rock dusts' ability to hold positively charged ions.
- BET analysis where N_2 gas is used to measure the physical adsorption of gas molecules onto the rock dusts to derive their specific surface area.

The Qmineral report on the analyses of these six EW starting materials is presented in **Appendix C**, below follow the main insights regarding these rocks' EW potential.

Contact area available for chemical reaction with water and CO_2

Eifelgold basalt has the largest surface area, the 2nd finest grains and the best capability to hold positively charged ions. This rock dust's physical qualities therefore suggest that, theoretically, it has **most** opportunities for **dissolution** reactions to happen.

Despite having the second largest grains, **Grecian Magnesite** rock dust has the **second highest surface area**, suggesting it also has a large contact area for enhanced weathering. The specific surface area of the other olivine rich rock dusts is less than 50% of the above two rock dusts. The **Pasek** rock dust has the largest grains, smallest surface area and lowest capability to hold on cations – so it theoretically has the **smallest contact area** for EW.

Mineralogical composition

As expected, **Eifelgold** has the lowest amount of the most EW efficient mineral **olivine (12%)**. It has however the highest amount of **pyroxene (43%)**, another Ca-Mg silicate with good EW potential. And this basalt has about **23%** of **Ca, K** and **P rich minerals** that are absent in the five other olivine rich rocks, but which are advantageous for soil fertilization.

Pasek olivine rich rock dust has only **24% of olivine** as most of it seems to have been altered into **serpentine (46%)**. Its third main component is **pyroxene (19%)**.

The four other olivine rich rock dusts mainly consist of olivine (48-64%), serpentine (10-29%) and pyroxene (6-26%). **Vitruvit** rock dust thereby represents the mineral assemblage with the **highest EW potential (64% olivine**, 10% serpentine) and **Grecian Magnesite** with the **lowest (48% olivine**, 29% serpentine). The Italian and Norwegian rock dusts have a mineralogical composition in between these two Greek rocks.

Chemical composition

The five olivine rich rock dusts have a similar chemical composition which is set apart from that of the **Eifelgold basalt**. The latter has significantly **less Mg**, but significantly **more Al, Ca, Na, K and P**. This once again shows the **potential** application of this basalt as a (partial) **fertilizer** replacement.

As expected, the five olivine rich rock dusts have elevated amounts of total Nickel (2300-2650 ppm) and Chromium (1750-3050ppm). In contrast, the **Eifelgold basalt** has over 10 times **less** of these heavy metals (ca. 205 ppm for both **Ni and Cr**).

Section summary

Eifelgold basalt dust shows the best physical properties for enhanced weathering, but has the least olivine suggesting a lower CDR potential. Its chemistry, however, has the combined advantages of more than 10 times lower Ni & Cr, and the presence of plant nutrients such as Ca, K & P.

All five olivine rich rock dusts have more olivine than the basalt, but consequently also much more Ni & Cr. Among them, Pasek seems to have the lowest EW potential on all accounts. Greek rock dusts Grecian Magnesite and Vitruvit show elevated EW potential, in physical properties and mineralogy respectively. Their mineral compositions furthermore represent two end members of a range in which the Novo Cives and greenSands mineral compositions fall.

Cotton field soil

The cotton field soil through which we mix the above-mentioned six EW rock dusts is another starting material whose characteristics influence the CDR productivity of our field trials. As discussed above, a preliminary site investigation showed that this soil is **not the most suitable** one **for EW** due to it having about 50% of clay, a high pH of 8.4 and already significant amounts of calcium carbonate minerals.

To further characterize the soil's original properties, we sampled it at several locations before application of the rock dusts. Five soil samples taken across the field, together with a composite sample made from equal amounts of those 5 samples, were sent for analyses to Qmineral in Belgium. There they analyzed the 5 individual samples for their TIC & TOC to see how much total (in)organic carbon is already present in the soil. The initial composite soil sample was analyzed for:

- Mineralogical composition with XRD to see what minerals this soil consists of.
- Chemical composition with XRF to see how much Ni and Cr it contains.
- Grain size distribution with laser to understand the sizes of its different grains.
- Cation exchange capacity (CEC) to measure its ability to hold positively charged ions.
- BET analysis with N_2 gas to derive the soil's specific surface area.

The results of these soil analyses are presented in **Appendix C**.

At the start of the 2021 EW field experiment, we furthermore took soil samples from the specific plots and areas where we would add rock dusts and repeat soil sampling at a later stage. These initial soil samples represent the controls, or background, against which soil samples taken at a later stage can be compared. Our colleagues at the IIFC in Larisa (Institute of Industrial and Forage Crops) analysed the basic soil parameters of these samples, the results of which are presented in **Appendix D**.

Mineralogical composition

XRD analyses show that the soil of Gregory's field is mainly composed of **clay minerals (42%)**, calcium carbonate minerals (22.5%), quartz (21%) and feldspars (12%). Clay minerals are characterized by **small crystal sizes** (reflected in the overall small grainsize of the soil, see below) and the ability to **absorb** many **cations, anions and water**. Their abundant presence will have an important influence on the soil chemical reactions and enhanced weathering. Another soil mineral that will play a role in enhanced weathering dynamics is

calcite ($CaCO_3$), which represents **21%** of this soil's 22.5% carbonate minerals. Analyses of the initial soil samples at the IIFC confirms that the amount of carbonates in the soil expressed as $CaCO_3$ is on average 23%. **Quartz and feldspar**, third and fourth most common minerals respectively, together represent about 33% of the soil mineralogy. These minerals can be regarded as chemically inactive within the soil environment within the timeframe of our experiments. They will not affect the enhanced weathering reactions as much as the clay and carbonate minerals.

TIC, TOC and physical properties

As expected from the high amount of carbonate minerals, the total inorganic carbon (**TIC**) of this soil is **high** (2.57 wt% of C). The soil's total organic carbon (**TOC**) content is somewhat **low** at 0.84 wt% of C. Texture analysis of the soil at the IIFC shows that about 47% of its grains are smaller than 0.002 mm (so called clay fraction), 29% have a size between 0.05 and 0.002 mm (silt fraction) and the remaining 25% of soil grains are larger than 0.05 mm (sand fraction). This overall **fine-grained texture** of the soil is confirmed by the more detailed grain size distribution analysis. Whereas the maximum grainsize occurring in the soil is similar to the rock dusts' largest grains (about 250µm), the grains become smaller more quickly than the rock dusts so that 80% of the soil has a grainsize smaller than 30µm. The soil's clay texture and small grain size reflect its high amount of clay minerals. This is also the reason for the soil's **high specific surface area** (BET of 51m^2/g) and **high cation exchange capacity** (CEC of 24.40meq/100g), respectively 4 and 5 times higher than the basalt rock dust. The highly abundant small grains of clay minerals represent a large mineral surface onto which water, cations and anions can be adsorbed.

Chemical composition

The soil contains about **471 ppm** of **nickel** and **411 ppm** of **chromium** – more or less double the amounts present in the basalt rock dust but over five times less than is present in the olivine rich rock dusts. These relatively high heavy metal concentrations in the soil are not unusual in Greece. The country's plate tectonic position reflects a complex geological history involving the creation of mountain ranges with mantle rocks. This is why the mountains surrounding the Thessaly agricultural plane contain olivine rich rocks. Physical breakdown and chemical weathering of these mountains thus releases their heavy metal content and transports it through rivers down into the plane.

The initial soil sample analyses carried out at the IIFC confirm the soil's **high pH** of **8.4**, in line with its high calcium carbonate mineral content. The soil's **electrical conductivity** (EC), a measure of the available cations and anions in the soil, is somewhat **low** (420-650µS/cm). This is surprising given the generally high EC values of most soils in the surrounding area. The low cation and anion content is also reflected in rather **low amounts** of nutrients such as **Mg, K, P and N**.

Section summary

The soil's texture is very fine-grained as it consists for up to 42% of clay minerals. Therefore, the soil can hold a lot of water and has a large surface area that can adsorb many cations and anions. These characteristics might have a negative influence on our attempts to monitor the EW process based on the reaction products in the soil water, as they will be partially adsorbed to the soil.

Carbonates are the second most common mineral; the soil contains about 23% of $CaCO_3$ equivalent. In combination with its high pH of 8.4, this makes the soil a chemically not so optimal environment for enhanced weathering.

The soil is rather poor in plant nutrients such as N, P, K and Mg probably due to intense farming practices. Basic levels of Cr and Ni within this soil are already elevated due to the region's local geology.

Biochar

A simplified definition of biochar is 'charcoal for application to soils'. Biochar is artificially created through **pyrolysis** - heating under limited supply of oxygen – **of organic matter**. The chemical, physical and biological properties of biochar can vary greatly as they depend on the type of biomass (the 'feedstock') that is used and the temperature, duration and conditions at which pyrolysis takes place. Generally speaking, it is a carbon-enriched material that represents a **stable storage for carbon**. A dead tree lying on the forest soil will decompose and release again the carbon which it stored during its lifetime as CO_2. However, if the wood of the tree is turned into biochar, the majority of its carbon is stored in a new and more stable form. Biochar is much more resistant to decomposition, so the residence times for biochar-carbon in the soil are in the range of 1,000 to 10,000 years (Lorenz & Lal, 2018).

But biochar may represent other soil benefits besides more stable carbon storage of biomass. It is a **highly porous material** and hence has a large specific surface area where reactions can take place. Biochar's chemically active surfaces can **retain nutrients** and **water** that might otherwise be washed out of the soil and hence lost for plants. Because of its high porosity, biochar also has a very low density. Addition of biochar to the soil may therefore decrease the soil bulk density and increase soil porosity, which in turn can benefit plant growth. Biochar can thus induce chemical and physical changes in the soil that lead to **better plant health** and **crop yield**.

A **combination** of **biochar and enhanced weathering** is proposed as a promising co-deployment of negative emission technologies to mitigate climate change (Amann & Hartmann, 2019). Enhanced weathering produces mineral nutrients that can be retained by biochar to keep them available for plants. Biochar also stores water which is needed for both enhanced weathering and plant growth. Increased plant growth leads to more CO_2 captured into biomass as well as more roots whose weak organic acids enhance rock weathering. **Biochar** may furthermore be a **habitat** and/or a **food source for soil biota** such as bacteria and mycorrhizal fungi which also enhance mineral weathering. Finally, **biochar** can **immobilize** heavy metals such as **nickel** and **chromium** whose release during EW of olivine could be hazardous.

Discussing the above information with the Project Carbdown team we enthusiastically decided to also include biochar in our enhanced weathering experiments. As there is currently no biochar sold in Greece, we used the same material as applied in the parallel German field experiments. We purchased this from the **European Biochar Certified** company Carbon Cycle Gmbh & Co. KG (Germany) (Figure 4.4). Each ton of their product binds about 3.6 tons of CO_2 for at least some centuries. They produce this high quality biochar from untreated woodchips from regional and sustainably managed forests (FSC/PEFC), resulting in very low levels of trace elements and metals (3 ppm Ni; 5 ppm Cr).

Figure 4.4. Transferring biochar into a fertilizer spreader for mechanical application onto the pilot plots.

There have been numerous laboratory and field experiments worldwide on the effects of biochar on crop yields – the main drive for farmers to apply it – but results vary greatly. According to Kroeger et al. (2021) application doses usually range from 2 to 100 tons/ha and no biochar experiments so far involved a clay soil similar to ours. It has been suggested that sandy soils may respond better to biochar addition than clayey soils (Sohi et al., 2009). Generally, yield increase linked to biochar addition is expected in highly weathered tropical soils rather than in richer soils of temperate climates such as in Europe (Jeffery et al., 2017).

Since Crane-Droesch et al. (2013) estimate an average crop yield increase of approximately 10% in the first year for **3 ton/ha** of biochar addition, we decided to use this application rate. The biochar product we acquired has a grain size of about 3-5 mm and a specific density of 233 kg/m^3. For our initial project design we wanted 3 tons of this material, but due to miscommunication we received only 4m^3 which amounts to a little less than 1 ton. We decided to keep the 3ton/ha application dose for the treatment in the **experimental area**. Adding the remaining biochar to about halve of the area originally designed to be treated with biochar, we could achieve an application dose of **2.6 ton/ha** in the **pilot area**.

Section summary

Biochar is a stable form of carbon produced through pyrolysis of organic material. It is capable of storing CO_2 10 to 100 times longer than otherwise decomposing biomass. When applied to agriculture it can improve soil quality as well as retain water and nutrients, which in turn increases crop yield.

Biochar in combination with enhanced weathering is thought to be beneficial as biochar (1) increases the amount of roots and soil micro-organisms, (2) may provide water needed for the chemical reaction and (3) can retain heavy metals such as Ni and Cr that are released during EW of olivine.

To test the effects of biochar on both enhanced weathering productivity and crop yield, we applied it to some of our experimental and pilot plots at a dose of about 3ton/ha and 2.6ton/ha, respectively.

Design of the 2021 experiments

Design of the 2021 experiments

In the first EW experiments of the Olivine Project, the above described 6 olivine rich **rock dusts** are **mixed into the top 30 cm of the soil**. This is done after soil preparation for cotton cultivation and just before the cotton seeds are sown. Soil samples are taken before addition of the rock dust in order to know the soil's initial characteristics.

After sowing, we install water-sampling equipment (macrorhizons and lysimeters) to collect **soil water samples** throughout the cotton growth season. Multiple chemical analyses are carried out on these samples to try identifying any changes that reflect the enhanced weathering process.

Another set of **soil samples** is taken from the different rock dust – soil combinations (treatments) at the cotton's blooming stage and right before harvest. These samples are analysed to assess any effect the rock dust treatments might have on the nutrient content of the soil and overall soil quality.

Plant samples are taken at the cotton's blooming stage in order to determine if the added rock dust influences the plants' nutrient contents. Right before the harvest in early October, we **sample cotton** from the different rock dust treatments to check if they affect in any way the cotton yield or quality.

Our approach for these initial experiments is twofold. On the one hand, we want to test the **practical feasibility** of enhanced weathering combined with local agriculture. This part of the experiment takes place in the '**pilot area**'. Six 0.21 ha (100m by 21m) pilot areas are treated with the two Greek olivine rich rock dusts. Greek regulations stipulate that one may not add more than 3kg of Ni per hectare per year, which translates in a **rock dust** application rate of **1.2 ton/ha**, or 0.12kg/m^2 assuming the rock dust contains 2,500mg/kg Ni. This amount is similar to the ca 0.5 to 2 ton/ha of lime dust that farmers worldwide add to acid soils to increase their pH and is therefore a realistic rate for annual application. The Greek olivine rich rock dust is added to the pilot plots by tractor and machinery available to the local farmer.

On the other hand, we want to **scientifically assess** the capacity of the different olivine rich rock types to capture CO_2, as well as the potential effects of olivine rich rock dusts on cotton and soil. For this purpose, we design an appropriate experiment that allows statistical comparison between observations for different treatments. A smaller part of the field is organised as '**experimental area**' where thirty-two 32m^2 (4m by 8m) plots are arranged in 4 rows with a distance of 4m in between them. This allows four replicates of eight different treatments, including one untreated control and application of the six different EU rock dusts at the rate of 40ton/ha (4kg/m^2). This higher amount of rock dust is chosen to make the chemical fingerprint of the EW process more identifiable in the soil water chemistry and to allow comparison with the EW field trials in Germany where the same application rate is used. It

is, however, still within the nickel addition limits within the whole experimental area due to the large untreated zones separating the treatment plots. In the experimental area, all rock dusts are manually applied to the soil.

As **biochar** is beneficial to soil quality and might retain heavy metals derived from dissolution of olivine rich rock dusts, we include it in some of the pilot and experimental treatments at a rate of 2.6ton/ha (0.26kg/m^3) and 3 ton/ha (0.3kg/m^2), respectively.

Layouts of the experimental and pilot areas are shown in detail in the following illustrations.

Layout of the 2 hectare of cotton field allocated for the 2021 Olivine Project

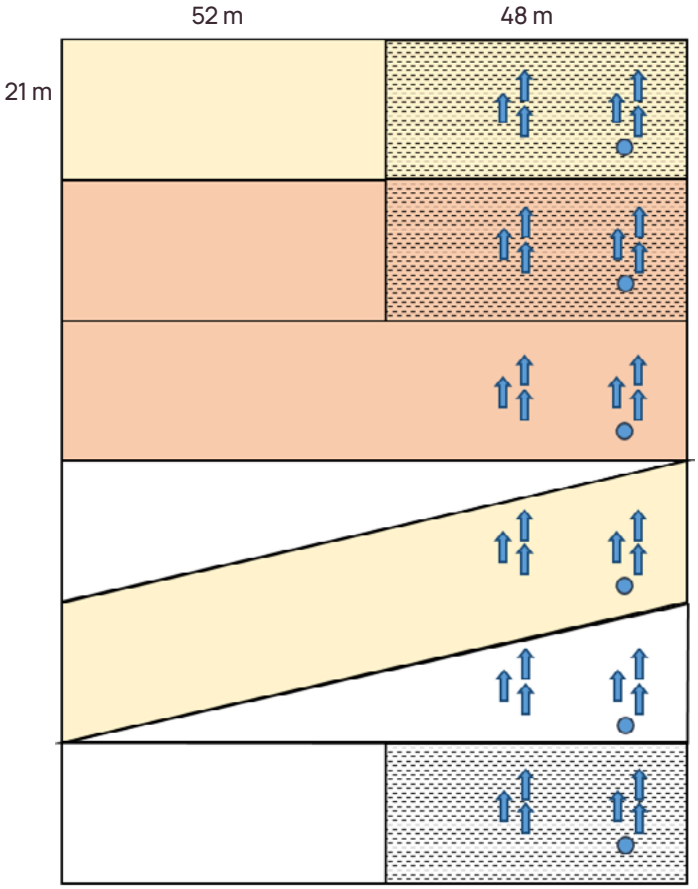
Pilot area (1.26 ha) - General design and lay-out

Pilot plots

- 1 plot = 21mx100m, 2100m²
- no buffer needed between plots due to their size

6 Treatments

- → Greek "olivine" from Grecian Magnesite (GM)
- → Greek "olivine" from Vitruvit (VV)
- → Control
- → Greek "olivine" from Grecian Magnesite + biochar
- → Greek "olivine" from Vitruvit + biochar
- → Control + biochar



Application rates: 0.12 kg/m² rock dust, and 0.26kg/m² biochar

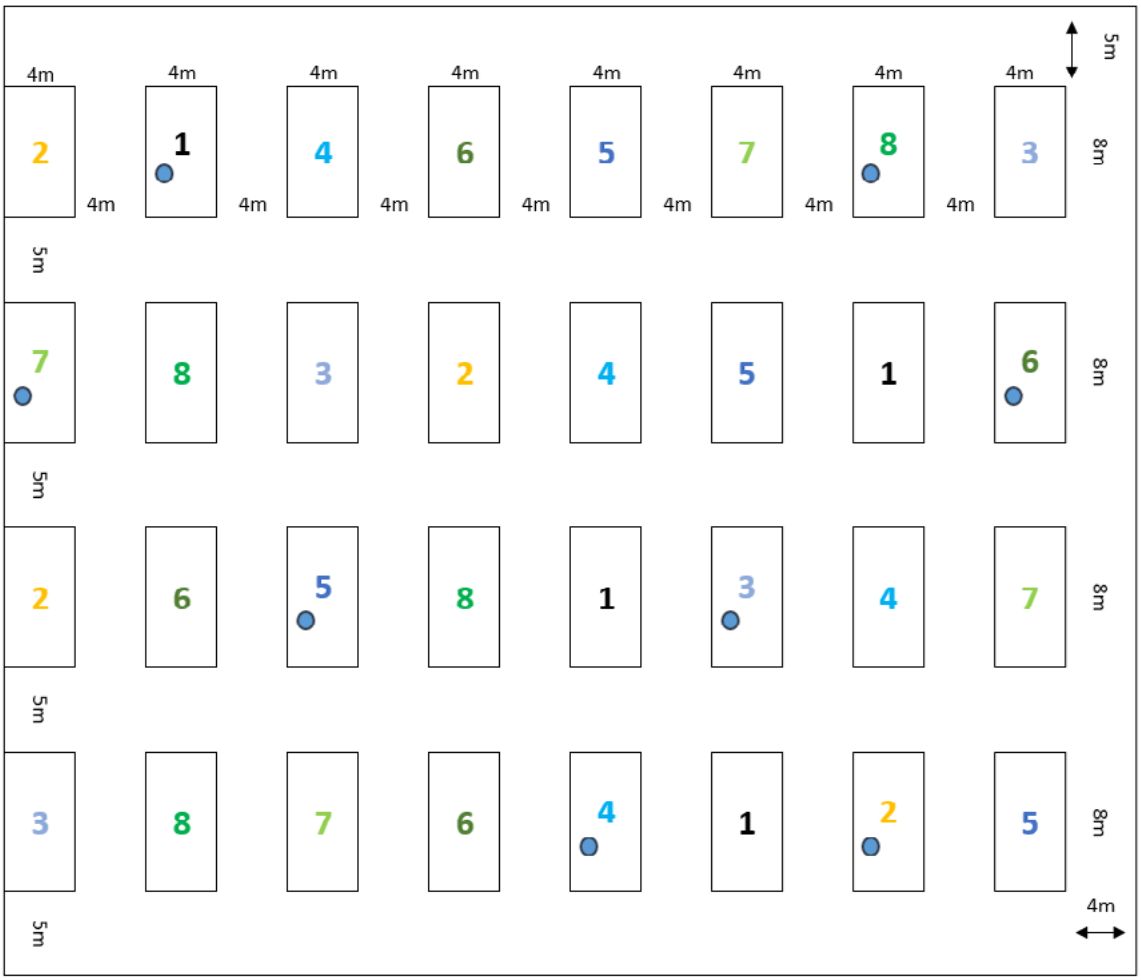
(biochar added to only 48% of a plot due to limited amount)

1 Replicate (a first small test on practical farming scale)

36 Microrhizons
6 per plot

6 Lysimeters
1 per plot

Experimental area (0.36 ha) - General design and lay-out



Experimental plots

- → 1 plot = 4mx8m, length along cotton rows, 32m²
- → parallel to cotton rows, 5m buffer between plots
- → perpendicular to cotton rows, 4m buffer

8 Treatments

1 Control

2 DE (German) Basalt

3 NO (Norway) olivine

4 ES (Spanish) olivine

5 IT (Italian) olivine

6 GR (Greek) olivine GM

7 GR (Greek) olivine VV

8 GR olivine VV + biochar

4 kg/m² rock dust
0.3kg/m² biochar

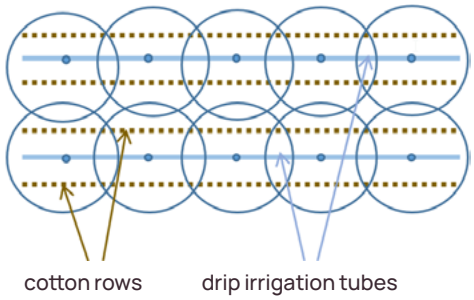
4 Replicates

For statistical reasons
(www.randomizer.org)

160 Microrhizons
5 per plot

8 Lysimeters
1 per treatment, spread across the experimental area

Experimental area (0.36 ha) - Details & specifications



Cotton sowing

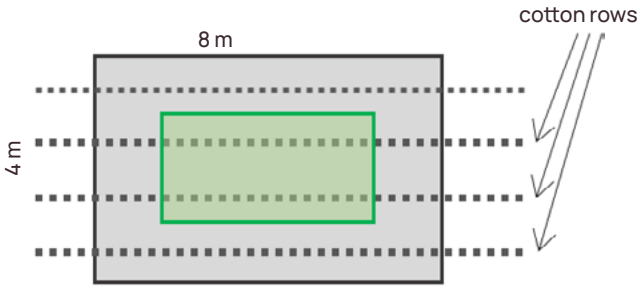
- 20 seeds/m so one seed every 5 cm
- 90 cm between 2 cotton rows
- drip irrigation in the middle of every other space between 2 rows
- 80 cm between two irrigation points along the tube
- irrigated soil shows wet circles on surface which downward into the soil widen like cones

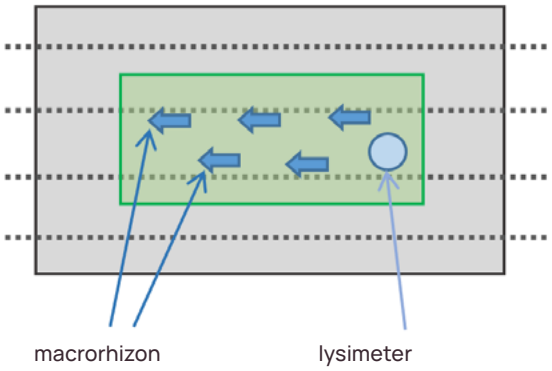
Target area within one plot

- 1 experimental plot of 4m x 8m includes 4 cotton rows
- safety perimeter of 1.5 - 2m all around

Only central 2 cotton rows for:

- macrorhizon/lysimeter installation
- cotton / soil water / soil sampling





Lysimeters/macrorhizons within one plot

5 macrorhizons for each of the 32 plots

- inserted at ca. 35 degrees down to about 25 cm depth
- right next to a cotton line to avoid tractor damage and target water in root zone
- zig zag within the target area between the two inner cotton rows

1 lysimeter for each of the 8 treatments, spread across the entire experimental area

- located in between 2 rows in one corner of the target area
- soil profile as good as possible recreated
- soil column inside 30 cm deep

Materials and Quantities

Experimental area

1 plot = 32m², so 1 treatment of 4 replicates = 128m²
Rock dust = 4 kg/m² (40 ton/ha) → 128 kg/plot and 512kg/treatment
Biochar = 0.3 kg/m² (3 ton/ha) → 10 kg/plot and 40kg/treatment

2. DE basalt	3. NO olivine	4. ES olivine	5. IT olivine	6. GR olivine GM	7. GR olivine VV	8. GR olivine VV + biochar
512kg	512kg	512kg	512kg	512kg	512kg	512kg +40kg

Lysimeters: 8 (2 per row, all treatments once)
Macrorhizons: 5 for each plot so 160

Pilot area

1 plot = 0.21 ha, 6 treatments (no replicates) = 1.26 ha
Rock dust = 0.12 kg/m² (1.2 ton/ha) → 0.25 ton for each of 4 rock dust treatments, total of 1 ton
* **Biochar** = 0.3 kg/m² (3 ton/ha) → 0.63 ton for each of 3 biochar treatments, total of 1.89 ton

2. Biochar	3. Biochar + GM olivine	4. Biochar + VV olivine	5. GM olivine	6. VV olivine
* 0,63 ton	* 0.63 ton 0.25 ton	* 0.63 ton 0.25 ton	0.25 ton	0.25 ton

Lysimeters: 6 (1 per pilot plot)
Macrorhizons: 6 for each plot so 36

Total quantities of materials for set up of field

NEEDED:

DE Basalt	NO olivine	ES olivine	IT olivine	GR olivine MG	GR olivine VV	Biochar	Lysimeters	Macrorhizons
0.512 t	0.512 t	0.512 t	0.512 t	1.012 t	1.512 t	* 1.93 t	16	196

ORDERED:

DE Basalt	NO olivine	ES olivine	IT olivine	GR olivine MG	GR olivine VV	Biochar	Lysimeters	Macrorhizons
± 1 t	± 1 t	± 1 t	± 1 t	± 1.5 t	± 2 t	* ± 3 t	20	200

* **Biochar delivered** was 4 m³ with a density of about 0.23kg/L, so turned out to be a total of **ca. 920 kg** – less than half of what we needed for the original project design. In the experimental plots of treatment 8 we added biochar at the planned rate of 0.3kg/m². In order to roughly maintain the same application rate, the pilot areas to be covered with biochar were subsequently reduced so that in the end each had an application rate of about 2.6 ton/ha.

Experimental set-up

Experimental set-up

Between 15 March and 30 April 2021, we set up the experiment design described in Chapter 5. It was the first time for us to undertake an enhanced weathering experiment with tons of rock dust, or a field experiment on this scale and of this complexity. We thus spent quite some time figuring out how to best implement our so far theoretical experiment with the tools and time available to us. Crucial in this phase was the fact that Doris, the cotton farmer, was extremely collaborative. He took care of the logistical challenges of getting tons of rock dust and biochar where they need to be and helped us find practical solutions to carry out the different steps as well as to meet the cotton sowing deadline.

As we learned many practical things along the way that might be useful for other enhanced weathering field trials, we describe every step of the way in detail below.

Measuring & outlining the experimental and pilot areas

Clear delineation of the plots is necessary when applying the rock dusts as well as for installation of the water sampling equipment. Any delineation put on the field needs to be removed after rock dust application to allow tractors to mix up the soil and sow the cotton. After this, the delineation needs to be put back again to know where macrorhizons and lysometers need to be installed. For this reason, we have designed a system of bamboo sticks and ropes that after initial installation can be taken down and then reinstalled with more ease.

Equipment

- 100m long surveyors measuring tape
- bamboo sticks & wooden markers
- rope & red-white flagging tape
- large plastic plant labels
- 2 people / 3 days

Figure 6.1. Field marking of the experimental plots.

Method

(Please see the first 3 figures in 'Design of the 2021 enhanced weathering experiments' to better understand the below descriptions)

Upon entering the cotton field from the access point (bottom left corner), our 2ha of field starts from the left 207m long side. With the surveyors measuring tape we define the right border of our playground by placing bamboo sticks

with red-white tape 100m to the right of this left border.

Sowing of the cotton rows, and all subsequent tractor movement, is done parallel to the ca 200m long left and right borders. About 12m maneuvering space is necessary at the top and the bottom to allow tractors to turn. Hence we mark this maneuver area, 12m inwards from the top and from the bottom, with another bamboo stick.

The **experimental area** contains 4 rows with each 8 plots, separated from one another by 4m wide buffers, and is started from the bottom right corner of our 2ha field. Along the right hand border, we trail a single long rope starting from a fixed marker on the bottom edge of the field upwards. In this rope we create loops with a red-white ribbon that mark the 12m maneuver zone followed by the first 5m buffer zone. Then we mark the alternating 8m plot and 5m buffer lengths for four times (see full red line in figure below).

The width of both the plots and buffer is 4m, so we put an identically marked rope 16m left of the one along the right field border. (see red dotted line in figure). Bamboo sticks are placed next to the loop markings of these two vertical main ropes. Between the bamboo sticks along these two main lines, we now put 16m wide ropes with loops and red-white ribbon every 4m (see green dotted horizontal lines in figure).

The final step is to place three vertical ropes from the top of the experimental area down to the bottom buffer zone, marking the boundaries of the plots and buffer zones between them. (see light blue lines in figure). If needed, readjust the bamboo sticks in the outer two vertical ropes (red) so that the intersection markings in the inner horizontal (green) and vertical (blue) ropes are more or less on top of each other and orthogonal.

One quarter of the experimental area is now marked; complete the remaining three quarters one after the other moving towards the left boundary of this area. Once the entire grid is marked out by ropes and bamboo sticks, large yellow plant labels are placed within each of the experimental plots (grey boxes). Each label shows the number of the treatment that will be put there preceded by the row number.

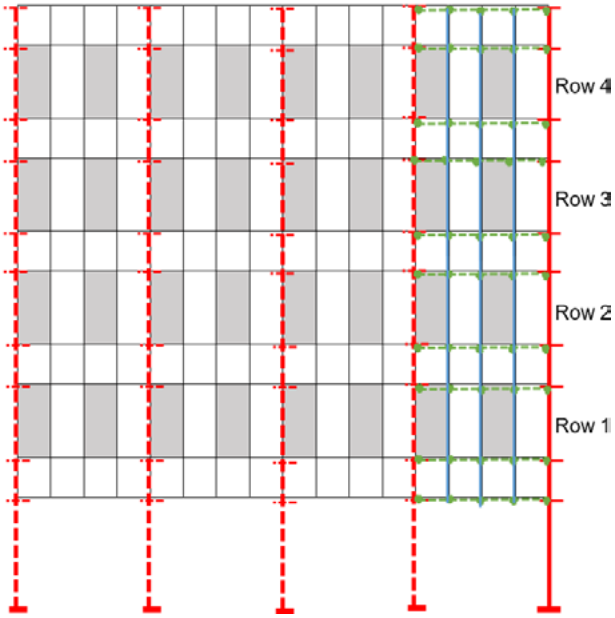


Figure 6.2. Illustration of the layout of the experimental area and the build up of marking it on the field. Grey boxes represent treatment plots. Rope markings visualized this on the field one quarter at a time from right to left, thereby first putting the red vertical main lines, followed by the green horizontal lines and finally the blue secondary vertical lines.

When this grid needs to be removed, first the minor vertical ropes (blue lines) are rolled up onto the wooden sticks that held them in place. Then the horizontal ropes (green lines) are collected and stored on bamboo sticks on the side of the field. Lastly, the major vertical ropes (red lines) are rolled onto a wooden stick from the top down to the bottom of the field where they are stored next to the 5 bamboo sticks that remain in place. Finally all bamboo sticks, apart from the ones along the bottom and the right hand side border of the field, as well as the labels, are removed.

Figure 6.3. Part of the experimental area marked out onto the cotton field. Yellow labels indicate treatment plots seperated from one another by buffer zones in a grid made up of bamboo sticks, green gardening wire and red-white flagging tape.

The **pilot area** is situated right above the experimental area up to the top 12m wide maneuver zone. In its original design it is divided into 6 equal blocks of 100m (horizontal) by 21m (vertical) which are marked solely by tall bamboo sticks with red-white ribbon placed along the right and left field boundaries. The final diagonal block within the lower part of the pilot area resulted from directing the tractor wrongly from the right boundary towards the left one (see later).

Section summary

A considerate amount of time and effort was needed to mark out the experiment design in the cotton field.

In order to visualize and outline the 32 experimental plots and the buffer zones that separate them, we designed a rope and bamboo system where specific distances are marked in the ropes with a knot and red-white flagging tape.

After applying the rock dusts and biochar, these bamboo sticks and ropes need to be removed to allow mixing the materials into the soil irrigation and cotton sowing with large farming machinery.

The rope and bamboo system was then put back to allow installation of the macrorhizon and lysimeter water sampling devices in the correct locations.

Manual application of rock dust on experimental plots

The big bags in which the 6 different rock dusts were delivered are placed onto a tractor trailer and brought onto the field close to the experimental area. Except for the control, **all treatments** require **4kg of rock dust per square meter**. Each of the 32 experimental plots is 4m wide by 8m long. This means that each plot has a surface of 32m² which needs to be evenly covered by 128kg of rock dust.

Equipment

- hanging scale
- plastic buckets & metal hand shovels
- rope & wooden markers
- dust masks & gloves
- 6 people/2 days

Figure 6.4. Weighing 8kg of rock dust into the plastic buckets.

Method

On the trailer, 2 persons are continuously filling plastic buckets with rock powder. When starting a new rock dust type, each bucket is weighed with the hanging scale to have 8kg of rock powder. The level of rock dust that this weight corresponds to is then indicated inside the bucket with a permanent marker. This way filling up the following buckets with the same rock powder can happen faster as the buckets do not need to be weighed, merely filled up to that marked level.

Two persons are continuously walking between the trailer and the experimental plot that is being prepared at that time. Bringing full buckets of rock powder to the experimental plot, and returning the empty ones to the trailer to be refilled.

With rope and 4 wooden markers we make a 4m by 8m movable grid that divides a plot into 8 equal areas of 4m² (2m by 2m each). Once this grid is placed over an experimental plot, two persons apply the rock dust on that particular plot, one of the 8 subplots at a time. Each subplot of 4m² is manually covered with 2 buckets of 8kg of rock dust. While emptying the buckets onto a subplot, we try to do this in a fluent movement to spread out the rock dust as evenly as possible across the 4m². Eventually, 16 buckets of 8kg rock dust are added to each 32m² experimental plot, resulting in an application rate of 4kg/m².

There was an issue with the **Norwegian rock dust** because we received it **partially wet** in an open big bag. As it arrived at the very last moment, we had to apply it immediately without knowing exactly how much dry weight we were adding to the plots of this treatment. We estimated the Norwegian rock

dust to have about 20% of moisture and therefore added 5kg per m^2. Due to its moisture content, this rock dust was clotting and could not be spread out so easily as the other completely dry rock dusts.

Afterwards at the IIFC, multiple samples of the wet Norwegian rock dust were weighed before and after drying them at 105 degrees C for about 12 hours. This showed that its initial moisture content was about 14.6%. We hence applied a **rate of 4.25kg/m^2** for the Norwegian olivine rich rock dust instead of the intended 4kg/m^2 that was applied for the other 5 rock dusts.

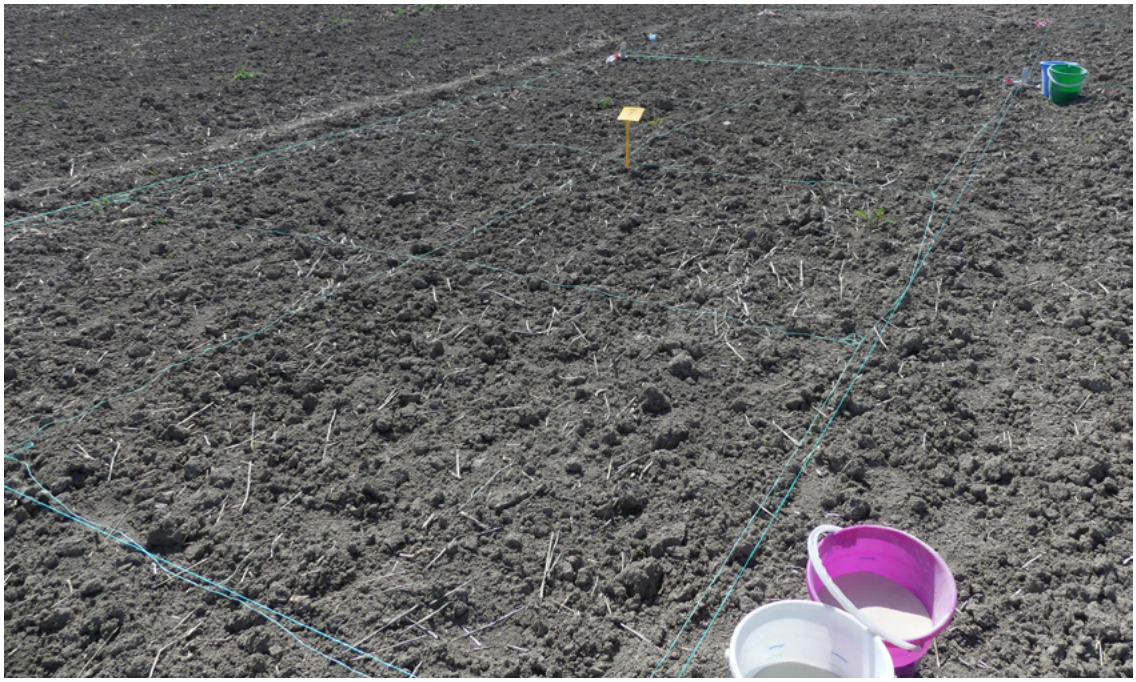


Figure 6.5. Experimental plot overlaid by movable grid of 8 subplots each 4m^2, ready for rock dust application.

Figure 6.6 Manually applying 2 buckets of 8kg rock dust to each of the eight 4m^2 subplots, as evenly as possible.

Figure 6.7. Filling buckets with rock dust up to the marked level and manually applying it to the (sub)plots.

Figure 6.8. Transporting the movable subplot grid to the next experimental plot where rock dust will be applied.

Figure 6.9. Manual application of olivine rich rock dust to the experimental area.

Figure 6.10. Comparison of the Norwegian (left) and Grecian Magnesite (right) treatments after manual application of 4kg/m² on the experimental plots. Note the granular texture of the Norwegian rock dust, resulting from its moisture content, as opposed to the blanket of powder of the Grecian Magnesite material, representative also of the application of the 4 other rock dusts.

Figure 6.11. Overview of the experimental area after manual application of the six olivine rich rock dusts

Section summary

For a more even spread of the rock dust by manual application, we divide the 32m² experimental plots into 8 subplots of each 4m². The 4kg/m² application rate is then easily achieved by spreading 2 buckets of each 8kg rock dust on each subplot.

To make the manual application of 3600 kg of rock dust as efficient as possible, we had dedicated 2 person teams to fill up buckets with 8kg rock dust, to transport full/empty buckets between the field and the trailer, and to evenly spread out the rock dust onto the plots. Four people moved the rope frame of the eight subplots from a finished plot to the next one to be treated.

Because of the higher amount added to the soil (4.25kg/m² instead of 4kg/m²), data gathered from the Norwegian rock dust can not be directly compared to data from the other five rock dust applications.

Mechanical application of rock dust on pilot areas

The big bags in which the Greek olivine rich rock dusts were delivered are placed onto a tractor trailer and brought onto the cotton field.

Equipment

- hanging scale
- plastic buckets & metal hand shovels
- dust masks & gloves
- tractor with wheat sowing machine
- 4 people/1 day (testing and calibration: 4 people/half a day)

Method

For the practical testing of enhanced weathering in combination with agriculture, we use the available farming equipment to apply rock dust in the pilot areas. Doris takes care of a small-scale farm that only grows cotton and wheat and therefore has only limited agricultural machinery. Works that need specific tractors or equipment, such as sowing and harvesting of cotton for example, are subcontracted to other farmers who have these tools as they work much larger fields.

As Doris has access to a **wheat-sowing machine**, we test this piece of equipment for mechanical application of the rock dust. It has 18 seeding rows over a width of 3m and the amount of seeds that is distributed is manually adjustable by opening the feeders more, or less. In comparison to wheat seeds, the olivine rich rock powder is much finer and heavier.

Figure 6.12. Initial testing of the wheat-sowing machine for mechanical rock dust application. Left adding weighed buckets of rock dust to the seed container and evenly spreading it out. Right for homogenous application of the rock dust to the field, it is important that all 18 seeding feeders continuously receive rock dust through the top openings.

For the pilot area the maximum amount of olivine rich rock dust that we may add annually to the soil is **1.2ton/ha or 0.12kg/m²**. If we distribute rock dust over a length of 10m, we cover an area of about 30m² to which 3.6kg of rock dust needs to be distributed. Over a length of 30m, we would need to spread 10.8kg of rock dust with this machine. We start out testing the wheat-sowing machine by loading it with 11kg of rock dust, spread evenly across the seed container box. As the tractor pulls it to discharge the rock dust, three to four people are standing on the wheat sowing machine to ensure that rock dust is continuously going into the seeding openings.

Figure 6.13. Testing and calibrating the wheat sowing machine for mechanical rock dust application on the pilot plots.

Although it works – the rock dust is falling down onto the ground in 18 continuous rows – it takes about 70m for all the rock dust to be used up. This means that the application rate achieved is only about 0.5ton/ha. We further improve the rock dust application rate by completely opening the seed feeders, and continue testing suitability of the machine for this practice by gradually adding more rock powder. It becomes clear that the correct distribution rate cannot be achieved by one run. But it is important to minimize the amount of tractor movement on the field as this compacts the soil, which has a negative effect on crop growth.

Figure 6.14. Evenly filling the seed container with 125kg of rock dust for one of the two rounds needed to apply the equivalent of 1.2ton/ha to one of the 100m by 21m large pilot plots.

Figure 6.15. Mechanical rock dust application on the pilot area with a wheat-sowing machine. Snow covered Mt Olympos in the background.

Eventually, calibration of the wheat-sowing machine with the Greek olivine rich rock dusts results in **two spreading rounds for each pilot** area of 100m by 21m. For **each round, 125kg of rock dust** is added to the seed container of the machine by filling it with 12kg heavy plastic buckets. At the start of each spreading round, the weight of the rock dust makes it fall down easily.

Figure 6.16. At the start of a mechanical rock dust application round, the weight of the rock dust itself is sufficient for continuous spreading down the seed feeders. The field already has application traces, indicating this is the second and last round.

But as the seed container starts to become more empty, at least three people need to stand on the back and continuously push the remaining rock dust into the seed feeders.

Figure 6.17. Towards the end of a round, four people on the back of the wheat-sowing machine push the remaining rock dust towards the sowing feeders to assure continuous application. Note the traces in the centre and the left part of the photo: this is the end of a first application round; each round is done by driving concentrically inward of the pilot plot.

Whilst spreading the rock dust on the pilot plots, an error was made at the start when we were applying the Grecian Magnesite material. Doris was wrongly directed from the top right corner of this plot to the top left one. The material of the first round was hence applied in a parallelogram shape instead of a rectangle (see pilot area design). We remedied this situation by appoint-

ing the triangle parts of the field above and below as the pilot control areas. This way, the top three pilot plots remained as planned, and the bottom pilot plot became the one with only biochar. A further adjustment of the original pilot area design arose from the smaller amount of biochar delivered than we originally requested. In order to maintain the planned biochar application rate, we needed to more or less half the pilot areas treated with biochar.

Figure 6.18. Mechanical rock dust application traces showing the error that was made with the Grecian Magnesite plot (left) resulting in a triangular control plot (middle) to maintain a rectangle Vitruvit plot (right).

Figure 6.19. It's a dusty business, but someone's got to do it... From left to right: Gregory Xiros, Christos Tsadilas, Lefteris Evangelou, Ingrid Smet and Doris driving the tractor.

Section summary

The wheat-sowing machine is an adequate tool for mechanical application of olivine rich rock dust to the field. Some initial calculations and calibrations are necessary to optimize the amount of rock dust added to the soil whilst minimizing tractor movement on the field.

In order to achieve an application rate of 1.2ton/ha, we needed to cover the 210m^2 large pilot plots two times, each time adding 125kg of rock dust.

Biochar addition to the experimental plots

Addition of **biochar** to the soil can enhance mineral weathering and increase crop yield due to its retention of water and plant nutrients. But in order to have these benefits, it **needs to be 'charged'** prior to application. Biochar can be compared to a battery: to get the best out of it, one should mix it with nutrients, water and microbes - a process known as charging (or activating). If freshly produced biochar is added to the soil **without activating**, it will **take up nutrients and water from the soil** – stealing it away from plants and EW - for the first few months and only start giving these back once it is charged.

Biochar activation methods include **soaking** it for a few days in **compost liquid** or mixing it with 10% finished compost and leaving it for **up to two weeks** prior to soil application. Other options are mixing the sterile biochar with liquid manure, dung or aqueous biomass such as liquid seaweed and letting it rest for a while. Due to the rather last minute arrival of the biochar and its 4m² large volume, it was **not practically possible** to mix it with any kind of organic fertilizer and let it settle for a few weeks.

Equipment

- hanging scale & plastic buckets
- graduate cylinders (for example 250mL, 1L, ...)
- field & crop appropriate liquid fertilizer
- larger plastic container to mix liquids
- 2 people/half a day (not including laboratory analysis of the biochar on beforehand)

Method

In the experimental area we have 1 treatment which combines the Greek olivine rich rock dust from Vitruvit with biochar. As the biochar application rate is 3ton/ha (0.3kg/m²) and each plot has a surface area of 32m², we need 9.6kg per plot. Due to time restraints we could not have the biochar settle in organic liquids for a prolonged time, so we opted to **saturate** it with a mixture of **liquid fertilizer and water** prior to application on the field. Although being more practical and fast, this method does not include any (micro) organisms, which are important to soil and plant health.

The 9.6kg of biochar to be applied to each plot of treatment 8 represents dry material. So back in the lab we weighed small amounts of biochar before and after drying it in an oven at 105 degrees C for about 12 hours. This indicated that the biochar's initial moisture content was about 12.2 wt%. So in order to have a dry weight of 9.6kg of biochar, we need 10.77kg of the biochar as we received it. The next information we need is how much liquid the biochar can maximally absorb. We estimated water-holding capacity of biochar in the lab. The table below contains the results of this test, indicating a water holding capacity of the totally dry biochar to be less than 200% of its weight. Knowing that our biochar already has at least 12.2% moisture, it will not be able to take up more than 170% of its weight.

Oven dry biochar (g)	Max water absorbed (mL)	Water holding capacity (%)
21.9	41	187
22.0	40.5	184
39.0	85.5	219

Table with the data of the laboratory estimation of the biochar's water holding capacity.

Figure 6.20. Pouring the fertilizer-water mixture over the biochar

Figure 6.21. Liquid fertilizer activated biochar ready for soil application..

We eventually decide to saturate up to 11kg of biochar with 18L of water diluted liquid fertilizer before spreading it onto a plot. This is prepared in 4 large plastic buckets. In each bucket we weigh about 2.75kg of biochar. In a separate container, we mix 1.25L of liquid fertilizer with 2.25L of water. This 4.5L solution is then slowly poured over the biochar and the mixture given some time to settle so that the biochar can absorb it all. The amount of liquid fertilizer and water is calculated from the NPK concentration of the liquid fertilizer and the specific needs of the soil and cotton crop. Four such biochar – fertilizer buckets are then manually distributed over each of the four experimental plots of treatment 8.

Figure 6.22. Four buckets of biochar having soaked up water and a liquid fertilizer are manually distributed on one plot.

Now that the experimental treatments are done, we systematically remove all the ropes and bamboo sticks that delineated the experimental plots. We thereby first roll up the secondary vertical ropes that were put in place last. Then we remove the horizontal lines and stack them atop bamboo sticks along the field's border. Last we roll back the primary vertical ropes which are kept alongside the main bamboo sticks on the bottom of the field.

As the rest of the cotton field will be treated with solid fertilizer grains, we purchase large plastic sheets to cover the 4 experimental plots that already received liquid fertilizer through the biochar application.

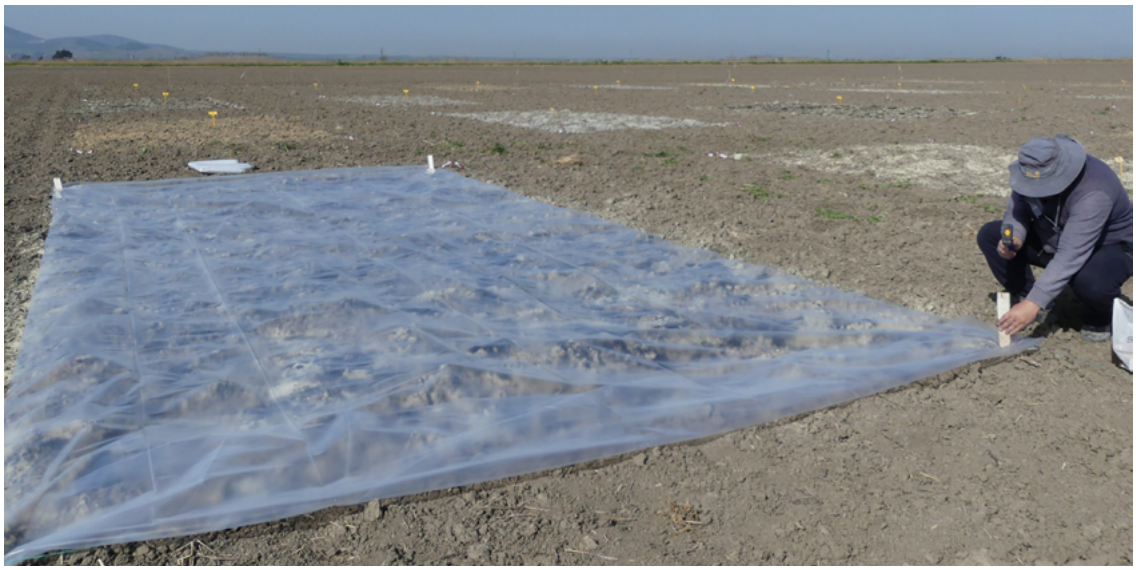


Figure 6.23. To avoid that the experimental plots treated with biochar will also receive the fertilizer generally applied to the cotton field, we temporarily cover these plots with large plastic sheets.

Section summary

Freshly produced biochar needs to be mixed with water and soil nutrients before soil application. Without this so-called activating or charging, biochar will initially steal water and nutrients from the soil and away from plants. Optimum charging of biochar involves mixing it with organic liquids and letting it settle before application.

Due to time constraints and practical considerations, our best option was to let the biochar absorb a mixture of water and liquid fertilizer in plastic buckets before manually spreading it on the designated experimental plots.

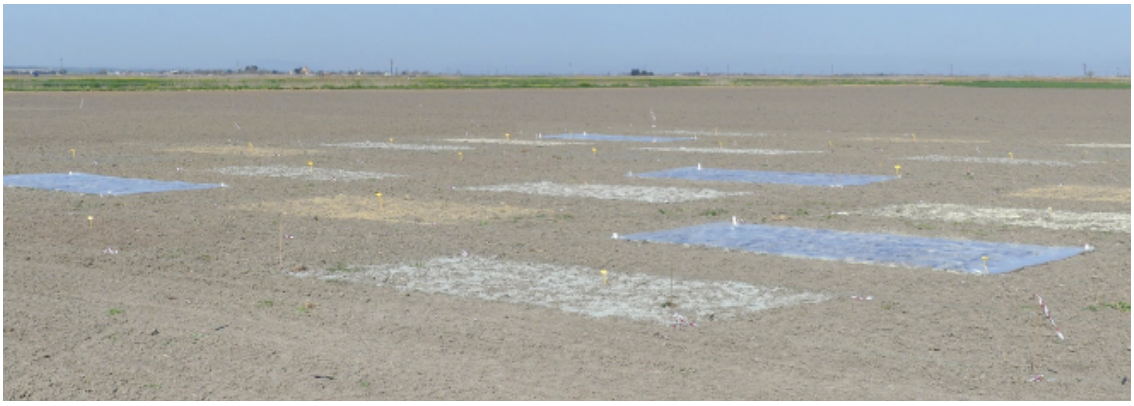


Figure 6.24. Overview of the experimental area after application of the 8 different treatments, ready for fertilizer distribution.

Biochar addition to the pilot areas

Besides the high price of liquid fertilizer, it is not practically possible to mix large volumes of biochar with a water-liquid fertilizer solution prior to application on larger areas of the field. Hence, we decide our best option is to apply a **granular fertilizer** that **dissolves easily in water** right after the biochar application, **and** then **irrigate** the field.

As we received less biochar than we would need to apply to three entire pilot areas at a rate of 3ton/ha, we calculated how much we needed to reduce the treatment areas to maintain a similar application rate. As manual application is not an option on such large areas, we also needed to test available tractor equipment to **apply** the biochar **mechanically**.

Equipment

- hanging scale
- plastic buckets & metal hand shovels
- dust masks & gloves
- tractor with fertilizer distributor
  (wheat-sowing machine tested but did not work, see below)
- 3 people/1 day

Figure 6.25. Biochar application tools.

Method

A bucket volume of 11L can hold 2.5kg of the biochar, meaning it has a density of ca. 230kg/m^3. The 4m^3 biochar we received thus had a total weight of about 920kg. We already used some 44kg for application on the experimental area, leaving us with ca. 876kg to distribute over three pilot areas at a rate of 0.3kg/m^2. This means we have about 292kg for each pilot area with a width of 21m and a length of 100m. As the exact weight of the remaining biochar is un-

known and for more easy calculations, we round up the **biochar** to **300kg**. We then reduce the length of the pilot plots to be covered with biochar to 48m, making its **area about 1000m²**.

In **first instance** we use the **wheat-sowing machine** for mechanical application of the biochar as it had proven very useful for the rock dust application. About 2.75kg of biochar fills up a bucket to its rim, so 54 full buckets represent a little less than 150kg of biochar. This is about 50% of the biochar amount needed for one pilot treatment and can just fit the seed container of the wheat-sowing machine. Hence we are hopeful that we can also do the mechanical biochar application with two rounds of the wheat sowing machine per pilot plot.

Figure 6.26. Completely filled up, the wheat-sowing machine container holds 150kg of biochar.

However, as Doris drives around the completely full wheat-sowing machine on the first pilot plot to be treated with biochar (the bottom one directly above the experimental area), the **biochar** material is **barely falling out**. Due to the combination of its very low density and relatively large size – in comparison to wheat seeds or rock dust – gravity is not successful at dispersing the biochar at a reasonable rate. Although **driving across** the entire **plot** more than 10 times – thereby **compacting** the soil which is negative for the crop as we will see later on – less than half of the biochar in the machine was applied. We can thus only conclude that the **biochar can not be** mechanically **applied** with this wheat-sowing machine.

Figure 6.27. Despite many rounds across the pilot – which result in the bad effect of soil compaction - the biochar is barely falling from the wheat-sowing machine. Another piece of equipment is needed for mechanical application of the biochar.

Doris proposes a **second attempt** with the simple **fertilizer disperser** he uses to distribute granular fertilizer material. Coincidentally, 54 buckets of biochar (about 150kg) fill up this container to a level just below its rim. So the biochar could potentially be applied in two runs per pilot. This time the biochar gets easily and evenly distributed. The fertilizer disperser is **the right tool** for **mechanical application of biochar** across larger field areas.

Figure 6.28. Half the amount of biochar needed for one pilot plot fits within the fertilizer disperser which turns out to be an efficient tool to evenly apply the biochar on the pilots.

The final biochar application rate in the pilot area is somewhat lower than in the experimental area: about 2.6ton/ha (0.260kg/m^2) of dry biochar. After biochar application, the same fertilizer disperser distributes solid fertilizer granules all over our 2 hectares of cotton field. This fertilizer was somewhat more expensive than the classic granules as it is much more water-soluble, but still significantly cheaper than the liquid fertilizer. Once this is done, the plastic sheets covering the 4 experimental plots with biochar and liquid fertilizer are removed.

Section summary

The large amount of biochar to be added to the pilot area (ca 900kg) makes it impossible to saturate it with a liquid fertilizer-water mixture prior to application. The best way to somewhat activate this biochar is therefore to disperse it together with a very water-soluble granular fertilizer, and do one irrigation round of the field straight after.

A first trial of mechanical biochar application with the wheat-sowing machine failed as even after many runs across the pilot plot little biochar had fallen out. This action heavily compacted the soil in that part of the field, which we will later on observe to have a negative effect on the crop.

Eventually a simple fertilizer disperser was the best tool for efficient mechanical application of biochar material across the larger pilot areas of the field.

Figure 6.29. Bright blue granules of a very water-soluble fertilizer are spread all across our field, in accordance with the nutrient needs of the soil and expected cotton crop. The experimental plots with biochar already received liquid fertilizer in similar proportions and are therefore covered with a plastic sheet.

Figure 6.30. The variety in the density of biochar grains and fertilizer granules after mechanical application onto the pilot area is similar to the heterogeneity you normally have on an agricultural field. And upon incorporation into the soil these materials will be more homogenously distributed throughout the top 30cm soil layer.

Mixing rock dust, biochar and fertilizer into the soil

Prior to **addition of rock dusts, biochar and fertilizer**, Doris ploughed our 2ha of the cotton field. He thereby mechanically digs up the soil to about 50cm depth, forcefully overturning and mashing the topsoil. As this results in an uneven terrain of large soil clumps, he also carried out some tilling afterwards to break the big soil clumps into smaller pieces and make the field more level.

Once all experimental treatments are applied onto the field, the farmer can continue preparing the soil for the cotton sowing. This is done by **tillage of the top 30cm of the soil**: breaking the soil apart mechanically by "combing" or "raking" the ground to sift and stir through the chunks and bits of the soil. This produces a finer topsoil layer by smoothing out the large clumps of soil, and levels the surface. It also improves aeration of the soil and its water holding capacity. Doris tills the field with a series of tools that work the soil increasingly more shallow, from 30cm, to 25cm to about 15cm. Finally, he carries out a special **irrigation** event across our entire 2ha part of the field to

allow the **fertilizer** we previously added **to be dissolved** and **taken up by the biochar** applied to the pilot area.

Figure 6.31. The two final tools pulled behind the tractor to prepare the soil for sowing by breaking up and 'raking' through the top soil layer.

Tillage incorporates the rock dusts, biochar and fertilizer somewhat homogeneously into the top 25-30cm of the soil. The parts of the field where we added biochar are still recognizable. The lower rock dust application rates of the pilot area mean that the added rock dust is no longer visible. In the experimental area, however, the plots with a more differently coloured rock dust can still be recognized. Inspecting the experimental plots reveals that the **Norwegian olivine rich rock dust** treatment is easily recognizable as the only one with (up to 7cm large) pure rock dust **clumps**. The initially wet rock dust was more difficult to manually spread out and formed clots which could not be worked into the soil as **homogeneously** as the other 5 rock dusts. This observation, and the higher application rate, means that we can **not directly compare data** from the Norwegian material **with** the **other rock dust treatments**.

Figure 6.32. White arrows point out rock dust clots in the Norwegian olivine treated experimental plots (left) and an indication of their average size (right). The moist condition into which we received this material hindered its homogenous incorporation into the soil. Any data gathered from these plots are therefore not directly comparable to results from plots where the other 5 rock dusts could be more evenly distributed throughout the soil.

Figure 6.33. Overview of the experimental area (from the bottom of the pilot area) after soil tillage in final preparation.

Figure 6.34. Irrigation of the field to allow the water-soluble fertilizer to dissolve and be absorbed by biochar where this was added.

Section summary

Conventional field preparation for sowing through ploughing and tilling can homogeneously distribute the olivine rich rock dusts into the top ca. 25cm of the soil. An intense irrigation event was carried out to allow the fertilizer to dissolve and be taken up by the biochar in the pilot area.

The initially moist Norwegian material could not be incorporated into the soil as homogeneously as the other rock dusts and formed up to 7cm large clots. Any data gathered from this treatment can therefore not be directly compared to results from the other 5 rock dusts.

Cotton sowing, irrigation & agricultural chemical treatment

As a specific machine is needed, another farmer is subcontracted to do the cotton sowing. The cotton is sown at a rate of about 20 seeds per meter (about one seed every 5cm) and simultaneously in 4 rows about 90cm apart from one another. The sowing machine pulled by the tractor cuts a trench of a few cm depth, drops in the seeds and then covers them with soil.

Figure 6.35. Handful of cotton seeds.

Figure 6.36. Cotton being sown on our part of the field.

Right after the cotton was sown on 23 April, heavy rains came which provided the moisture needed for them to sprout about a week later. The heavy rainfall events that occasionally occur in springtime are usually sufficient for the initial cotton growth. Towards summer there is however little to no precipitation, so up to June any irrigation required is carried out with the mechanic irrigating system that was used to dissolve the fertilizer grains. It is a delicate tradeoff between **stressing the plant to make many flower buds** due to **limited water** supply and allowing healthy plant growth.

From June onwards, however, regular irrigation (about every 5-6 days) is needed up **to the end of August**. A **drip irrigation system** is set up with tubes between every other 2 rows of cotton plants. These tubes have irrigation holes every 80cm and are connected to a larger pipeline along the bottom border of the field. An electric pump takes up the groundwater that is dispersed throughout a specific part of the drip irrigation network. In order to maintain a flow rate of about 3.8L of water expelled at each irrigation point per hour, the entire field (including Doris' part where regular cotton farming without olivine rich rock dust addition takes place) is divided in blocks that are irrigated one after the other. The duration of irrigation for each block is about 12 hours, depending on the plants' need at that time.

Figure 6.37. Drip irrigation system laid out in the pilot area of our field, one tube between every other set of cotton rows (left) and the circular moisture marks around the drip holes after night-time irrigation (right).

During some of these irrigation events, the farmer mixes in agricultural chemicals to optimize the cotton plants' growth. During the **first four drip irrigation** events, he **adds nitrogen fertilizer** to the pumped up groundwater before it irrigates the field – this is known as 'fertigation'. Besides chemicals administered through the irrigation water, there are also some agricultural products sprayed across the field if and when necessary. These include **herbicides** to control the weeds growing between the cotton rows that steal water and nutrients from the plants, and when pests are observed also **insecticides. Plant growth regulators** are used to reduce excessive vertical growth and put more emphasis on the development of cotton bolls. Finally, a **cotton defoliant** is sprayed in late summer to speed up maturing of the plants, leaf removal, regrowth inhibition, and boll opening. As the chemicals sprayed over the crops mostly fall on the foliage, only a very small part ends up on the soil and in the soil water.

Section summary

Late April, cotton is sown in parallel rows (90cm apart) at a density of about 20 seeds per meter. From June through to August, a drip irrigation system is set up on the field for regular irrigation events. This releases water directly onto the soil at specific points 80cm apart from one another.

Throughout the cotton growth season the farmer applies fertilizers, plant growth regulators, insecticides, herbicides and cotton defoliants, both through mixing it with the irrigation water and by spraying over the crop. When entering the soil and soil water, these products can contribute their own chemical signature to the system and might interfere with mineral dissolution and weathering.

Installation of macrorhizons

After cotton sowing, we place back the bamboo sticks and ropes that outline the plots in the experimental area so that we know the right position to install our sampling equipment. Previously, we left the main bamboo markers in place on the bottom and along the right boundary of the field, and carefully stored away the measured ropes with knots indicating specific distances. So it is relatively easy to **reconstruct the experimental area grid** one quarter at a time starting from the right border. First we fix the primary vertical lines, then we put the horizontal divides and lastly the secondary vertical ropes.

Enhanced weathering of the olivine rich rock dusts **produces cations** (Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, ...) and **anions** (HCO_3^-, CO_3^{2-}, ...) which can end up in the soil water and may **change** soil properties such as **pH**, electrical conductivity (**EC**), total alkalinity (**TA**),... It might also release heavy metals such as **Ni** and **Cr**, which are bound into the olivine crystal structure. To track the enhanced weathering process we thus **analyse** the **water in the soil** for the above chemical parameters.

Equipment

- 200 macrorhizons with respective 30mL syringes and wood pieces
- macrorhizon installation kit (purchased with the macrorhizons)
- soil auger (diameter slightly wider than the macrorhizon insertion tool)
- wooden triangle with one 90° and two ca. 30° angles
- plastic buckets with water
- 2-3 people/2-3 days (preparation of macrorhizons 3 people, 1 day)

Figure 6.38. The macrorhizons and syringes to create vacuum.

Method

To collect water from the pore space in the soil, we purchase 'macrorhizons' – essentially **large artificial roots** – from the Dutch company Rhizosphere. These macrorhizons have a 9cm long porous part with an outer diameter of 4.5 mm and a pore size of 0.15 µm. One end of this porous cylinder is sealed off with epoxy whilst the other end is connected through flexible tubing with a syringe. By **applying a vacuum** to this system **with a syringe**, we create a negative pressure that will **suck up water** through the porous end into the tubing and eventually the syringe itself. The tubing is encased in a PVC pipe to protect it and allow easy installation of the porous 9cm cylinder into the soil. A piece of wood keeps the syringe open to maintain the vacuum for a prolonged

amount of time, allowing slow extraction of water from the soil.

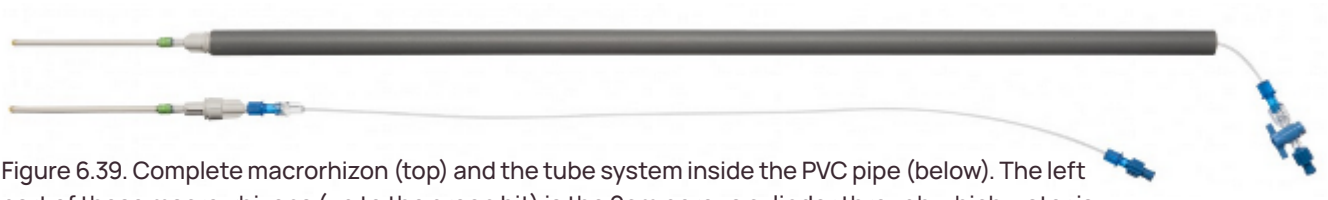


Figure 6.39. Complete macrorhizon (top) and the tube system inside the PVC pipe (below). The left part of these macro-rhizons (up to the green bit) is the 9cm porous cylinder through which water is absorbed when vacuum is applied by opening a syringe that can be attached at the end of the tube on the right side. (image: Rhizosphere)

We **prepare** all the **microrhizons** before we install them in the field. This is done by connecting a syringe filled with clean water to a macrorhizon, removing the protective cap from the porous end and then gradually **pushing** some of the **water through** the macrorhizon to drip out through the porous end. Then we **apply vacuum** by fully opening the syringe and keeping it open by wedging in the piece of wood. The vacuum-pulled macrorhizon is then carefully placed **into a bucket with clean water** and left overnight. Properly functioning macrorhizons should have their 30mL syringes more or less full of water in a couple of hours.

Figure 6.40. Macrorhizons prepared for installation. Notice that most of the syringes are at least half-full of water.

The **macrorhizons** need to be **installed at an angle of 30° to 45°** with the soil to avoid rainwater running down along the PVC tube towards the porous end. We therefore prepared a wooden triangle with this angle so we can place it onto the soil in the same way and easily make a hole at the right angle by guiding the soil auger along the wooden triangle. The depth to which the auger hole needs to be made depends on its angle with the surface and the vertical depth at which we want to sample soil water. At an angle of 30° we need to insert the auger 60cm to reach **a vertical depth of 30cm** from the

surface. Once this hole is made, the macrorhizon guiding tube is inserted and then the exact shape of the **macrorhizon** with its more narrow 9cm end is pre-shaped in the soil with the insertion tool. A prepared and checked macrorhizon is disconnected from its syringe and elongated with the extension tool before being gently **pushed into** the premade hole. The guiding tube is then **carefully** removed from around the macrorhizon without disturbing the latter and the emptied syringe is reconnected to the macrorhizon. A slush mixture of water and the soil from about 25-30cm depth can be poured alongside the macrorhizon to improve contact of the porous end with the surrounding soil. At the surface level, soil is then pushed around the macrorhizon to enclose it more tightly. The syringe is opened and a piece of wood put in place to keep the vacuum.

Figure 6.41. Macrorhizon installation in the experimental plots. To the right, Fotis finishes making a hole with the soil auger that he guided along the wooden triangle in front of him. To the left, Lefteris has installed the guiding tube and is pre-shaping the hole by pushing in the insertion tool. In the middle stands Valadis who prepares and provides macrorhizons for installation. Furthest to the right Prima carefully supervises all the work.

Macrorhizon installation

- 1. Soil auger to make the hole into which one places the
- 2. guiding tube inside which is pushed
- 3. the insertion tool that pre-shapes the hole for
- 4. the macrorhizon, which is first connected to the
- 5. macrorhizon elongation tube for easier installation.
- 6. A slush of water and soil can be poured along the installed macrorhizon before finally
- 7. the syringe is reconnected.
- 8. Installed macrorhizon.

Figure 6.42.

After sowing, each of the experimental plots contains 4 rows of cotton seeds. To minimize influence from the untreated soil around a plot, we **only collect samples** from the area of the **inner 2 cotton rows keeping** about **2m distance from** the bottom and top **borders of the plot**. The macrorhizons are thereby installed right next to the cotton rows to avoid damage from tractor movement as well as to target the soil water within the cotton's root system. Shade from the growing plants turned out to be an extra advantage of placing the macrorhizons so close to the cotton as the plastic syringes quickly became brittle from the intense Greek sunshine. We installed **5 macrorhizons** in **each experimental plot**, and two clusters of each three macrorhizons in the larger pilot areas.

Figure 6.43. Macrorhizon installed in the field with vacuum maintained by inserting the wooden retainer into the syringe.

Figure 6.44. Part of the experimental area after installation of the macrorhizons, five pieces in each plot. Note the diagonal lines in the soil that indicate the rows where cotton was sown. The macrorhizons are installed parallel and right next to these cotton seed lines.

Section summary

Macrorhizons with a porous tip are installed in the soil at a depth of about 30cm. Applying a vacuum at the surface results in extraction of water from the soil through this porous tip.

The macrorhizons need to be installed at an angle of 30°-45° with the surface and care needs to be taken not to damage the porous tip during installation.

Placement next to the cotton seeds will allow soil water sampling from the plants' root zone as well as protective shadow for the syringes earlier on in the growing season.

Each experimental plot received 5 macrorhizons, placed in the centre to avoid interference from the untreated buffer zone. In the pilot area, 6 macrorhizons are used in each treatment for soil water sampling.

Installing lysimeters

The **macrorhizons collect water** from the pores in the soil that is replenished by rainfall and irrigation, and which composition depends on chemical, physical and biological processes in the root zone of the cotton plants. We however **do not know from what volume of soil** a certain volume of water is extracted by the macrorhizons. In order to estimate the amount of CO_2 captured by for example 1 hectare of field, we need to be able to link changes in the soil water chemistry to a specific area and volume of soil where this water was collected from.

Lysimeters are a scientific device for measuring the percolation of water through soils, allowing determination of the soluble constituents in the **water drained from a specific soil volume**. Basically, a lysimeter is a container dug into the ground and filled up with the surrounding soil, collecting the water that drains through this soil at the bottom where it can be sampled for lab analyses.

There are some other important differences between sampling soil water with a macrorhizon or with a lysimeter besides the (un)known soil volume from which water is sampled. A lysimeter collects all the gravity-driven water flow from a specific soil area over a prolonged period of time. A macrorhizon forcefully pulls water from the soil, possibly also water more strongly held into the soil than gravity driven water, for a couple of hours until the vacuum is lost but at which point not all soil water might be collected. For these reasons, the chemical composition of soil water collected with a lysimeter might be different from that of a macrorhizon, even if sampled simultaneously from the same location.

Project Carbdown team member Ralf Steffens took it upon himself to build a series of simple lysimeters following the design of Georg Ardisonne (Hochschule Geisenheim University) for the three parallel EW field trials in 2021.

These **homemade lysimeters** have a **diameter of 20cm** and allow a **soil column of 30cm** on top of a fine mesh. Water percolating through the 9.425 dm^3 soil column is collected in a ca. 3L container below the mesh. From the bottom of the drainage water container, a tube runs along the outside of the lysimeter towards the surface where the water can be sampled with a hand pump. The chemical composition of this drainage water can then be linked to a specific volume of soil and area of the field.

In our field experiment it is **not possible** to **grow cotton within** the **lysimeters nor** to provide them with water from the **drip irrigation** system during the summer as they would overflow. Any water collected with these lysimeters can therefore not be linked to the water collected with macrorhizons. We nevertheless decided to install some of the lysimeters Ralf sent us to try to also collect soil water samples with them.

Equipment

- 14 lysimeters handmade by Ralf Steffens
- large shovels and hand shovel
- 2 people/1 long day

Method

We decide to install **one lysimeter for each** of the different **treatments:** 8 in the experimental area and 6 in the pilot area. Although effects from the untreated bufferzone are not likely an issue in the closed system of the lysimeters, we place them within the central sampling area of the experimental plots to be near the macrorhizons. Due to their size we need to disturb quite some soil and hence install them in the middle between two cotton rows. The lysimeters are about **50cm high** and their **top rim** should be more or less **level with** the **surface of the field**, so we dig a hole of about half a meter depth and slightly narrower width. Whilst digging we are careful to minimize stepping onto the cotton seed rows and pay attention to any differences in the soil as we shovel deeper. The dug out **grey top soil** of horizon A1 is collected in one heap and separated from the **orange tinted soil** of horizon C1 shoveled from **below**.

The bottom of the hole needs to be leveled so that the lysimeter resting on it is horizontal. We then carefully **reconstruct the soil column within the lysimeter** using first the more orange soil and finally the grey soil to fill it up. The **clay rich soil of our field** is **difficult** to dig into and forms blocks that can not be easily broken. This makes reconstruction of the soil column quite challenging. The rest of the soil that we dug out is used to refill the space between the lysimeter and the hole. As the lysimeters had to be installed right between the cotton rows, a bamboo stick with white-red ribbons is placed next to each one to avoid tractor damage.

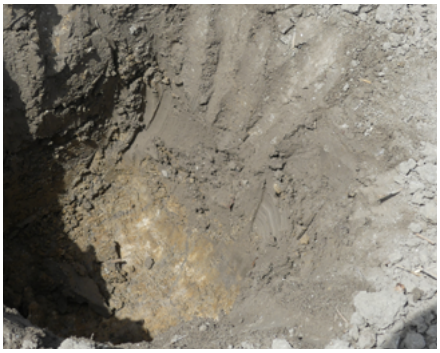


Figure 6.45. Inside of a hole being dug for a lysimeter, clearly showing the two different soil horizons A1 (grey on top) and C1 (orange below).

Figure 6.46. Left: Lysimeter placed inside a hole dug in the pilot area – note the separation of the soil horizons in the two distinct heaps in front of and behind the lysimeter. Right: Lysimeter partially filled up and worked back into the soil in one of the experimental plots. The 5 macrorhizons above it are sampling water from the top area of the picture, the lysimeter placement will not interfere with the soil system where they sample water from.

Figure 6.47. Doris digging out a hole to install the orange lysimeter to the right of him. Due to the size of the lysimeters, they only just fit in between two rows of cotton seeds (note the parallel marks from the cotton sowing that run all across the field) and he needs to be careful to minimise disturbance of the cotton seeds. In the top right corner Lefteris and his colleagues from the Institute are installing macrorhizons in experimental plots.

Section summary

Whereas macrorhizons extract water from an unknown volume within the soil at a short time interval, lysimeters collect soil water that drains through a specific soil volume over a prolonged period of time. The lysimeter thereby collects the entire fraction of gravity-driven soil water, the macrorhizon an unknown percentage of the soil water, also including water more tightly bound to soil particles.

Due to these different circumstances of soil water extraction, the chemical composition of water collected with a lysimeter can be different from that collected with a macrorhizon. The chemistry of soil water collected from lysimeters is however linked to a known surface area and can thus potentially express an amount of enhanced weathering per unit of field surface area.

Although our field experiment would not allow direct comparison between soil water sampled from macrorhizons and lysimeters due to differences in water input and vegetation, we installed one lysimeter in each treatment.

Special care needs to be taken to minimize soil and cotton seed disruption during lysimeter installation, as well as to reconstruct as well as possible the soil column within the lysimeter.

Weather station

The chemical process of mineral weathering requires water to happen and will be enhanced at higher temperatures. More CO_2 removal is therefore expected after intense rain events as well as at higher temperatures, although the latter also represent water loss through evapotranspiration which can counteract this.

If we can clearly identify an enhanced weathering signal in the soil water throughout the cotton season, it might be interesting to evaluate those data against the background of weather events in the same period. This way we might be able to deduce the effects that certain weather events have on the weathering rates. Although there are existing weather stations in Larisa and Volos, the weather in the Thessaly plain is very variable from one place to the next. Grey curtains of rain may be seen pouring down a few kilometers away without a single raindrop falling at the location of the observer.

We therefore decided to install a small weather station right onto our field and purchased a dnt WiFi Weather Station that measures temperature, humidity, rain quantity, wind direction/strength, air pressure and solar radiation. The weather station itself was placed atop a ca 2m metal bar on the edge of the field where there is never shadow. The display it sends the data to was plugged into a power supply inside the small shed close by on the corner of the field.

Figure 6.48. The weather station on the edge of our field during early summer, almost full-grown cotton with first flowers in the background.

Sampling & observation

Sampling & observations

Once the rock dusts and biochar are applied, the cotton is sown, and the macrorhizons and lysimeters are installed, we started the monitoring and sampling that was done throughout the cotton season (from mid-May until late September 2021). Soil water was sampled after major rainfall and irrigation events and analyzed for a series of parameters that may reflect the ongoing enhanced weathering process. Soil samples were taken once during the cotton flowering time and once during the harvest to check for any changes due to the added rock dusts. At the flowering stage, we sampled plant tissue to assess the cotton's nutrient levels. Finally, right before the harvest we sampled cotton balls to investigate any effects our treatments might have had on cotton yield and quality.

Macrorhizon & lysimeter samples

We quickly noticed that the vacuum we apply through the syringes to the **macrorhizons** is lost in about 12 hours. So in order to allow infiltration of water down to 25-30cm, where the macrorhizons' porous tips can take it up, we always **apply vacuum right after** a **rainfall or irrigation** event. Collection of the water samples from the 196 installed macrorhizons can then happen 1 or 2 days later. For each experimental or pilot treatment, we collect all the water sampled from the 5 or 6 macrorhizons in one bottle. The **total volume** of soil water collected **from 5 macrorhizons** in a single experimental plot thereby varies between **0 - 150mL** (Figure 7.1). Mid-June, we estimated that about 15% of the macrorhizons collect a full syringe (30mL), about 60% have 5- 20mL soil water and 20% do not sample any water at all. From then on, vacuum could not be created to about 5% of the installed macrorhizons.

Figure 7.1. A macrorhizon with almost full syringe (left) and the different syringes from one treatment with the soil water they collected and that will be put together in the plastic bottle (right). Notice the steady growth of the cotton plants from 13 May (left) to 11 June (right).

The difficult soil water extraction with the macrorhizons might partially be due to the soil's physical properties related to its mineralogical composition.

Up to 50% of the soil is made up of clay minerals which hold onto water very tightly. The majority of these are swelling clays of the smectite type such as **montmorillonite**. These clays undergo significant volume changes when their water content changes, creating **large cracks** when they **dry out** (Figure 7.2). As we can not see exactly where the porous tip of the macrorhizon is installed, there is the possibility that it finds itself in a void when the montmorillonite dries up – but does suck up water when the soil moisture is replenished. This might explain why **some macrorhizons** that provided us with significant **water** samples **at one time**, are **empty the next** – and vice versa.

Besides this temporal variation in the volume of soil water that we can collect, we also observe a spatial one. From the first water sampling rounds we notice that in some parts of the field there is consistently less water collected in the syringes than in other areas. The **heterogeneous water availability across the field** is in part explained by varying **micro-topography**. The field seems homogenous from satellite imagery and evenly flat during the experimental set up, but once the cotton starts growing subtle changes in its topography become visible as differences in plant growth. Weak depressions which collect more water (Figure 7.2), slightly inclined areas from which water drains faster, variations in soil compaction, clay content, soil composition, … make up a micro-topography that locally affects the soil's water content.

Figure 7.2. Left: Due to the high amount of swelling clays, up to 1.5cm wide cracks develop in the soil when it dries out. Right: Patches with higher soil moisture content – for example close to the irrigation supply pipe or faint depressions – have visibly more weeds growing. Yellow labels are indicating experimental treatments.

Eventually we are able to do **12 rounds of soil water sampling with the macrorhizons** (Table 7.1). The first sampling took place mid-May after an intense rainfall. From June onwards the drip irrigation system is installed and applied whenever the growing cotton plants need water. Due to the hot and dry summer, this is more or less every 5-6 days from late June through to August. As the cotton plants grow, we notice that due to their rise in water consumption we can collect increasingly less water from the macrorhizons. The **irrigation** is a great advantage for the enhanced weathering process throughout the

hot summer months and allows us to **regularly collect soil water** at this time. However, the farmer also uses this irrigation to **add nitrogen fertilizer** to the crop to boost the cotton's growth. The chemical signature of these fertigation events will likely be reflected in the analyses of our water samples and interfere with the EW signature.

Date	Type	Comments
13/05	Rain	First sampling round after intense rainfall
11/06	Rain + drip irrigation	We were not aware that drip irrigation was installed and used once since our last sampling, so when we visited the field to apply vacuum we were surprised to find water in the syringes that had collected in the meantime Fertigation (nitrogen as urea, N-P-K 46-0-0)
28/06	Drip irrigation	Fertigation (nitrogen as urea, N-P-K 46-0-0)
05/07	Drip irrigation	Fertigation (nitrogen as urea, N-P-K 46-0-0)
12/07	Drip irrigation	Fertigation (nitrogen as urea, N-P-K 46-0-0)
14/07	Drip irrigation	
29/07	Drip irrigation	Two weeks since last irrigation due to heavy rainfall 21-22 July
06/08	Drip irrigation	
12/08	Drip irrigation	
19/08	Drip irrigation	
25/08	Drip irrigation	
31/08	Drip irrigation	

Table 7.1. Overview of the 12 sampling sessions in which we collected soil water from the macrorhizons.

Macrorhizon samples give the chemical composition of a continuously changing soil water system at a specific moment in time (right after a rainstorm or irrigation event). Lysimeter samples accumulate soil water over a prolonged period of time from a spatially defined volume of soil. Data from these two types of water samples can thus complement each other to better understand the spatial and temporal changes of the soil water chemistry.

However, in the case of our cotton field experiment we can not directly compare lysimeter and macrorhizon data due to the different environments the soil water was collected from. **No cotton** was sown **within** the **lysimeters** thus eliminating any effects from this plant (uptake of nutrients, release of weak organic acids,…) on the enhanced weathering signature that might be present in the macrorhizon soil water. The lysimeters furthermore **only collected rainwater** as the drip irrigation system could not be implemented within these 20cm diameter systems.

Hence, we were only able to **collect** drained soil **water from** the **lysimeters two times**. We collected lysimeter water for the first time on 22 July after an intense rainfall event – potentially reflecting the cumulative EW signal that was drained from the above soil column since installation of the lysimeters late April. A second and last lysimeter water collection happened 2 months later, on 21 September, right before the cotton harvest. We used a hand held

vacuum pump typically used to bleed the brakes of cars or motorcycles, to collect the water that drained through the soil column and was stored at the bottom of the lysimeters.

Section summary

The amount of soil water we can collect with the macrorhizons varies in space and over time. This is likely due to micro-topographic differences within the soil and the large volume changes the clay undergoes with varying moisture contents.

Thanks to the regular drip irrigation during June, July and August, we could carry out a total of 12 sessions of macrorhizon water sampling. However, during some irrigation events the farmer adds nitrogen fertilizer that may obscure the enhanced weathering signature.

The soil chemistry in the lysimeter is different from that on the field due to the absence of cotton plants, hence lysimeter and macrorhizon water data cannot be directly compared.

The large volume of water discharged during each irrigation event made it impossible for the lysimeters to receive water from the drip irrigation system. They could only collect water from rainfall which resulted in only two sampling rounds of lysimeter water.

Soil & plant tissue sampling

A total of **3 soil sampling** sessions were carried out throughout the cotton season to evaluate any changes potentially related to the olivine rich rock dust application. For each sampling site, we collected 3 to 5 subsamples which were then thoroughly homogenized to a single composite sample. All samples were collected with a soil sampling auger from the **upper 30 cm** of the soil which is the olivine rich rock dust mixing zone (Figure 7.3).

A first soil sampling was performed after the EW experiment's design was marked out onto the field to describe the initial soil conditions before application of the olivine rich rock dusts to the soil. On 3 April 2021 we collected soil samples from each of the 4 control plots in the experimental area and from all six pilot areas. Due to the accidental diagonal plot in the pilot area, the pilot control was split into two triangular areas from which we took a soil sample each.

The following two soil samplings were conducted in the same way (composite soil samples collected with soil sampling auger from the top 30cm) in all 32 experimental and 7 pilot plots. The second soil sampling took place on 27 July 2021, during the flowering period of the cotton growth cycle when the plant had its maximum nutrients' need. A final soil sampling was carried out on 20 September 2021 when the cotton was ready to be harvested.

Figure 7.3. The upper 30 cm of soil are sampled with an auger, collecting multiple small cores across a plot which are combined into a single composite soil sample.

During the second soil sampling session, when the cotton plants are flowering, we also carried out a **plant sampling** to assess potential effects of the olivine rich rock dust application on the cotton plants' nutrient contents. In the central area of each of the 32 experimental plots and from the 7 pilot areas we collect 30-40 cotton leaves of the "medium to upper part" of the plants.

Section summary

We collect soil samples during the flowering stage to check the soil's level of plant nutrients when the cotton needs them the most. Another soil sampling round before the harvest allows us to assess the residual fertility of the soil and to check for any potential contamination caused by the application of soil amendments.

Plant tissue is collected during the flowering stage to assess nutrient levels in the cotton plants and whether this is in any way impacted by the olivine rich rock dust application.

Cotton: growth, collecting & harvest

Figure 7.4. Evolution of cotton from bud, over flower, to growing seed ball and finally mature, open cotton ball.

From sowing in late April to harvest in early October, the growth and fully maturing of the cotton takes about 150-170 days (Figure 7.4 & 7.5) and is closely monitored and duly influenced by the farmer. Right after sowing, soil moisture needs to be quite high to help the seeds sprouting. In the following weeks of initial plant growth, however, a careful balance is kept between drought stressing the plants to produce more flower buds and providing enough water for their growth. Extra fertilizer, nitrogen, is added through fertigation in June and July. A plant growth regulator minimizes the vertical growth of the plants and increases the development of flower buds which later on become the cotton balls. Once the cotton balls are fully grown and start to burst open, a plant defoliant is used to promote further opening of the cotton balls and loss of the leaves in preparation for the harvest.

Figure 7.5. Growth of the cotton plants as observed during macrorhizon water sampling on 13 May (left), 11 June (middle) and 19 August (right). The average final height of the cotton plants is about 1 meter. Notice how in the first ca. 1.5 month the plastic syringes are exposed to full, direct sunlight before getting any shadow from the growing cotton plants.

Prior to the **mechanical harvest** of the cotton, **we manually collect cotton from** each of the experimental plots as well as from three replicates of each pilot treatment and of the farmer's field. To be able to compare the amount of cotton gathered **from** each of these **53 locations**, it is important that we collect cotton from the same size area in each one of them.

In the experimental plots we focused on the inner 2 cotton rows for water and soil sampling to minimize potential effects from the untreated buffer zones. Likewise, we delineate with red-white tape an **area of 3m long and 2 cotton rows wide** within the centre of each experimental plot to manually collect cotton from (Figure 7.6). Within the six pilot treatments and the farmer's neighbouring cotton field we delineate three areas of the same size.

Figure 7.6. Fifty-three areas of each 3m long and 2 cotton rows wide were delineated and marked with red-white flagging tape for cotton handpicking.

On 4 October a team of 11 people handpicked all the cotton from the plants within these 53 marked areas, collecting the cotton from one area in one large bag (Figure 7.7). Afterwards at the Institute we weighed each of these bags to **assess** any differences in **cotton yield** that might be present among our treatments or in comparison to the farmer's field. The results of these cotton yield estimations across our field are presented in **Appendix F**.

We then carefully weighed 500g from each of the 53 cotton bags (Figure 7.8) and sent these to a specialised laboratory, at the Cotton Classification Centre in Karditsa, for analysis of the **quality** parameters **of this cotton**. A detailed overview of the different quality parameters our cotton samples were analysed for can be found in Chapter 8 and the results of the cotton quality analyses can be found in **Appendix G**.

Once we manually collected the cotton for our yield and quality analyses, we **removed all our equipment** to prepare the field **for mechanical cotton harvest**. This meant carefully pulling out the 196 macrorhizons, digging out the 14 lysimeters as well as removing the yellow experimental treatment labels and red-white flagging tape. We took the used macrorhizons back to the Institute where we afterwards inspected and tested them for re-use. Unfortunately, removal of the **lysimeters** revealed that the **clay soil** of our field was **too heavy** for these instruments and weighed down the permeable membrane into the water container below. Only 4 out of 14 lysimeters remained intact.

Timing is crucial for the cotton harvest as the unpredictable weather might **damage or even destroy** the crop. Cotton that has been wet can be moldy which reduces the fiber quality, or strung out by the rain and fallen onto the soil where the cotton picker can not collect it. Halfway through the harvest of our farmer's fields, **heavy rainfall** occurred which delayed harvest of the remaining cotton for almost 2 weeks. The soil needed to dry up first to avoid

the tractor getting stuck in it, and the cotton had to be dry before collection. A lower price was paid for the cotton collected from the fields after this rainfall event than for the one harvested in optimal conditions before.

Figure 7.7. Top: The cotton is being handpicked at 53 different locations from 3m long and 2 cotton rows wide areas. Bottom left: All the cotton manually harvested from one area is collected in a single bag. Bottom right: The cotton handpicking team with the cotton they collected for yield and quality analyses.

Figure 7.8. Left: Cotton samples ready to be sent for quality analysis. Right: Mechanical harvest of the cotton on our field.

Depending on how far most of the cotton balls are open, the **mechanical harvest** is carried out in two sessions. The first time most of the cotton is collected as the harvester machine moves over the plants and extracts the cotton from the open balls of the plants by high-speed rotating spindles (Figure 7.8). If enough immature cotton buds remain on the plants, this mechanical harvesting is repeated when they had a chance to also fully open, about 10 days later.

Section summary

Fertilizers, plant growth regulators and defoliants are used to improve plant health, restrict vertical plant growth and favour cotton bud formation, and speed up opening of the cotton balls and loss of leaves, respectively. Timing of the harvest is crucial as rainfall can damage the cotton crop badly.

Prior to mechanical harvest of the crop, we hand-picked the cotton from fifty-three 3m long and 2 cotton rows wide areas. These samples are analysed to assess any effects our rock dust and biochar treatments might have had on the cotton yield or quality.

Field observations

Although satellite imagery suggests our part of the field is rather homogenous and the field did not seem uneven or sloping whilst setting up the project, **micro-topographical variations** become clear once the cotton starts growing. Local variations in the soil's clay content, porosity, groundwater table and micro-relief result in variable growing conditions for the cotton plants. At some places they are distinctly larger, or smaller, than the general plants across the field. The random location of the 4 replicates of each treatment compensates for this small scale heterogeneity in chemical, biological and physical soil circumstances.

Figure 7.9. Distinct difference in plant growth between the area heavily compacted during our first biochar application attempt (left) and the rest of the cotton field (right and in the distant background).

The area where we unsuccessfully tried to **apply biochar with the wheat-sowing machine** clearly stands out in the early stages of the cotton growth (Figure 7.9). We had driven the tractor over it more than 10 times which strongly compacted the soil and resulted in delayed growth of the cotton plants. A distinct and abrupt difference in plant size marks the boundary between the area where we **compacted the soil** so much and the rest of the field in early June. This difference in plant size becomes less obvious with time, but by the end of September the cotton in this area is **clearly less matured** – the cotton balls not yet open – than the rest of the field (Figure 7.10). We can even see this compaction effect in the farmer's field where we drove the tractor with the trailer for the manual rock dust application. Along the path where we drove the rock dust, the soil got compacted and the cotton balls were less open by harvest time.

Once tilled into the soil and cotton is growing, the rock dusts are no longer visible in the different experimental plots suggesting homogeneous incorporation into the soil. Only the plots where we had to apply the **Norwegian rock dust** whilst it was **partially wet** remain recognizable through their **cm large rock dust aggregates**. Areas treated with biochar are also easily recognised as the larger biochar particles remain visible at the surface despite homogenous incorporation into the soil.

Figure 7.10. The narrow path without vegetation is the boundary between our part of the cotton field (left) and that of the farmer (right). At the end of September, when the cotton is full grown and almost ready for harvest, the areas where we compacted the soil through tractor movement are clearly recognisable. There, the cotton balls are not yet open: the biochar test area in the pilot (bottom left) and the path alongside our part of the field (ca. 3m wide zone to the right of the sand path).

Section summary

Micro-relief differences generate small, local variations in soil conditions. In order to minimize this natural heterogeneity influencing our field experiment it is important to have multiple replicates for each treatment, which are randomly positioned.

Soil compaction from tractor movement during project set up resulted in delayed and diminished crop growth, despite an extra tilling round prior to sowing. This might also affect the enhanced weathering process negatively.

Rock dust needs to be completely dry before field application in order to achieve homogeneous incorporation into the soil.

Unforeseen issues

Figure 7.11. Intense sunlight made the plastic of this syringe so brittle that the connection tip (left) broke off, as well as part of the back to secure the vacuum (right). Such syringes were replaced with new ones.

The outdoor conditions of our field experiments bring their own practical challenges and unforeseen issues. The **sun** is quite **intense** in Greece from early on in the year and there is no shadow across the field. The agricultural area of Thessaly, a large plain surrounded by mountains, experiences strong temperature differences between day and night, summer and winter. After installation of the macrorhizons, it took at least one month for the growing cotton to provide some shade for the subsurface parts. This was enough time for the **plastic of the syringes to degrade** from solar radiation and become **brittle** (Figure 7.11). Although careful handling meant that only up to 10% became inoperative and needed to be replaced, more than half of all syringes had cracks and broken off parts by the end of the season.

Figure 7.12. Syringes were removed from macrorhizons by chewing through the connecting tube (top). A macrorhizon where the connecting tube was pulled out and eventually the syringe removed (bottom)

Another unexpected natural threat for the macrorhizons came from **small mammals** – likely mice or rats, perhaps even a fox. In early August, a number of syringes were found all the way in the farmer's part of the field, the **connection tube** with the **macrorhizon bitten** through. In other cases, the syringe had been dragged and the connection tube was **pulled out** of the macrorhizon (Figure 7.12). Luckily, this behaviour did not last very long. Nevertheless, by mid-August 41 out of the 196 macrorhizons we installed were no longer functioning. Most of them due to natural damage, but some unable to create a vacuum for reasons unclear to us.

We have contemplated measures to protect the macrorhizons and their syringes from weather and animals. The best suggestion was to cover them with flowerpots, however the diameter of these pots would need to be rather large to cover all above ground parts. Placing 196 large flower pots upside down in the field would be practically difficult due to the tightly placed cotton plants and the need for occasional tractor movement. The pots would also locally influence the soil conditions, shading it from sun and any rainfall.

It turned out to be a tough season overall for our water sampling equipment. Although the manufacturer of the **macrorhizons** describes them as **single use**, we **tried to recycle** them upon careful removal and collection. After checking each of them individually and changing the syringe and/or porous tip if needed, only about 50% of them were able to collect water from a bucket after applying vacuum. These macrorhizons were reinstalled in the cotton field for wintertime soil water collecting, but it soon turned out that most of them were not properly functioning after removal from the soil and second installation. As for the **lysimeters** made by Ralf Steffens, **our** up to 50% clay-rich **soil** was **too heavy** for the mesh that separated the soil column from the water reservoir at the bottom. Out of the 14 lysimeters we had installed, 10 were totally destroyed as the mesh had come down.

Another unexpected event was the observation mid-August of a circular pattern in our experimental area of the cotton field where the plants had dried out and cotton buds already opened (Figure 7.13). The most likely explanation for this is that a **lightning bolt struck the field** at this location. The cotton could not recover from this and hence any data from the experimental plots bordering this lightning scar have to be considered as potentially not representative for the rest of the experiment.

Figure 7.13. The circular pattern in our field where the cotton prematurely dried out and opened up, probably as a result from a lightning bolt strike.

Section summary

Moving enhanced weathering experiments from a lab or greenhouse into a farmed cotton field brings its own challenges. As many experimental replicates and spare sampling equipment as practically feasible is a proactive way to reduce the negative impact of unforeseen events.

Soil water sampling is obstructed due to the collapse of most lysimeters and damage to macrorhizons from sun radiation and animals chewing on them. A lightning bolt strike in the field destroyed a circular patch of cotton plants, compromising any data from neighbouring experimental plots.

GPS coordinates of sampling locations

Before removing all our equipment from the field, prior to the harvest, we used a high precision GPS system to identify the spatial coordinates of our sampling locations. We thereby used the Spectra Precision SP60 GNSS Receiver of the Larisa Institute which has a horizontal accuracy of 5–30 cm. The coordinates are expressed in the Geographic Coordinate System GCS_GGRS_1987 (also known as EGSA '87) and presented in **Appendix E**.

For both experimental plots and pilot areas, GPS coordinates were measured in the centre of each macrorhizon group. This results in one location for the 5 macorhizons installed in each experimental plot, and two locations for each pilot area as they contained two groups of three macrorhizons. After harvest and subsequent ploughing and tilling of the field, these GPS coordinates were our guides to find the correct locations to reinstall macrorhizons for winter time soil water sampling (Figure 7.14).

Figure 7.14. Google Earth image of the cotton field overlain with the markers of the sampling locations.

Laboratory analyses & data statistics

Laboratory analyses & data statistics

All soil, water and plant samples collected at the cotton field are transferred to the Institute of Industrial and Forage Crops (IIFC) in Larisa. There they are analysed at the Soil, Water and Plant Analysis accredited Laboratory under guidance of Dr. Miltiadis Tziouvalekas. Once the measurements are carried out, the raw data need to be statistically treated to properly assess the significance of any variability observed throughout the season between different treatments.

Below we briefly summarize the different analytical methods carried out on the various types of samples and give a short introduction to the statistical data treatment.

Cotton yield and quality

Right before mechanical harvest of the cotton took place, we manually collected cotton from equally sized (3m long by 2 cotton rows wide) areas, one in the center of each of the experimental plots and three in each of the pilot areas as well as the farmer's neighboring cotton field. In order to assess potential variability in the **yield** across different treatments or between replicates, we weighed each of them. Results of the cotton yield can be found in **Appendix F**.

Exactly 500g subsamples from each of these 53 cotton samples were then sent to a specialised laboratory of the IIFC at the Cotton Classification Centre in Karditsa to determine cotton fiber quality. Fiber quality parameters were estimated according to the international standard method ISO/IEC 17025:2005 using the high volume fiber test system USTER HVI 1000.

The assessed **cotton fiber quality parameters** are:

- **Lint & seed weight**
  Determination of the % percentage of lint (fibers) or seed to the total weight of a cotton sample.

- **Micronaire**
  Micronaire is a measure of how fine the cotton fibers are and is influenced during the growing period by environmental conditions such as moisture, temperature, sunlight, plant nutrients, and extremes in plant or boll population. Fiber fineness is an important parameter as it affects processing performance and the quality of the end product in several ways. In the opening, cleaning, and carding processes slower processing speeds are required for low-micronaire (or fine-fiber) cottons to prevent damage to the fibers. But yarns made from finer fiber have more fibers per cross-section which results in stronger yarns. A micronaire reading below 3.0 is considered very fine, and 5.0 and above is considered coarse. 3.5 to 4.9 is most desirable for upland cotton varieties.

- **Spinning consistency index (SCI)**
  The spinning consistency index in cotton is a parameter calculated from important fiber quality properties and reflects the quality of the yarn. The formula includes micronaire, strength, length, uniformity and colour values. A high SCI value is a desired feature since higher values mean better yarn quality. SCI values generally vary between 100 and 150 but can go up to 200 in long-fiber cotton varieties.

- **Moisture content**
  Moisture levels are determined by weighing the fiber before and after drying and are reported as a percentage of the weight of the pre-dried specimen. Knowledge of moisture content is important for accurate measurement of other fiber properties.

- **Maturity**
  Maturity of the cotton fibers affects the dye absorbency and retention of the yarn: the greater the maturity, the better the absorbency and retention.

- **Length uniformity (UHML)**
  Length uniformity describes the distribution of the fiber lengths in a cotton sample. Reported fiber lengths represent the average length of the longer half of the fibers. Although fiber length largely depends on the cotton variety, exposure to extreme temperatures, water stress or nutrient deficiencies may result in shorter fibers. Length uniformity affects yarn evenness and strength and the efficiency of the spinning process. Cotton with a low uniformity index is likely to have a high percentage of short fibers. Such cotton may be difficult to process and is likely to produce low-quality yarn.

- **Short fiber index (SFI)**
  A short fiber ratio is a feature associated with immature fiber content and negatively affects the process of spinning.

- **Strength**
  Fiber strength is a measure of the force required to break a sample of fibers and affects the yarn and fabric strength. Increased speeds in modern textile spinning and weaving machinery are placing increased importance on fiber strength as a measure of cotton quality.

- **Elongation**
  Elongation is the extent to which a fiber may be stretched, and is usually tested as part of a strength test expressed in percentage terms. Fiber elongation is related to yarn elongation which helps to withstand the stresses of the weaving process without breakage.

- **Reflectance & Yellowness**
  A cotton fiber's colour grade is determined by the degree of reflectance (%) and yellowness (+b). Reflectance indicates how bright or dull a sample is, and yellowness indicates the degree of pigmentation. The colour of cotton fibers is affected by rainfall, freezes, insects, fungi, and staining through contact with soil, grass, or cotton-plant leaves. Cotton colour can also be influenced by moisture and temperature conditions during storage, both before and after ginning. Colour deterioration because of environmental conditions affects the fibers' ability to absorb and hold dyes and therefore reduces the efficiency of fiber processing.

Appendix G presents the cotton quality data from the 53 samples that were manually collected.

Plant analysis

Cotton plant leaves are dried at 60 ^{0}C and subsequently ground to a fine powder before the following analyses are carried out:

- **N** concentrations are estimated by Kjeldahl wet-oxidation procedure (Bremner & Mulvaney, 1982).
- All other plant nutrients (**K, Ca, Mg, P, Fe, Zn, Cu, Mn, B**) are determined according to the method described by Mills & Jones (1996). The samples are thereby prepared by heating the fine powder in a furnace at 500 °C for 5 hours and subsequent extraction from the ash with 1M HCl.

All data on the nutrients observed in the cotton plants can be found in **Appendix H**.

Soil sample analysis

Upon arrival at the IIFC, all composite soil samples are air-dried, crushed and 2 mm sieved prior to analysis of the following 19 soil properties:

- **Soil texture** (Clay%, Silt%, Sand% content) refers to the proportion of **sand, silt and clay** sized particles that make up the mineral fraction of the soil. This parameter is determined by the hydrometer method (Bouyoukos, 1951).
- **Soil pH** is a measure of the acidity or alkalinity of the soil and **soil electrical conductivity (EC)** measures the amount of salts in the soil. Both parameters are estimated in a suspension of 1:1 water:soil (Doran et al., 1996) with a pH and a conductivity meter, respectively.
- The soil's **carbonate content**, expressed as equivalent amount of the mineral calcite (**$CaCO_3$** %), is determined using the Bernard method by measuring the outgassing CO_2 after addition of HCl (Nelson, 1982).

- **Soil organic matter (SOM)**, the fraction of the soil that consists of plant or animal tissue - such as plant roots and microbes- in various stages of breakdown, is estimated by the Walkley–Black wet oxidation method (Nelson & Sommers, 1982).

- **Soil organic nitrogen (N)**, is determined through Kjeldahl wet-oxidation procedure (Bremner & Mulvaney, 1982).

- **Nitrate-nitrogen (NO_3-N)** measures the amount of available nitrogen in the soil that can be absorbed immediately by plants. It is estimated with a Nitracheck colorimeter (FIAstar 5000 analyzer by Foss, Laurel, Md.) in soil extracts of 2M KCl (Keeney and Nelson 1982).

- **Soil available phosphorus (P)**, the fraction of total P in a soil that is readily available to plant roots, is estimated through the sodium bicarbonate method (Olsen and Sommers, 1982).

- **Exchangeable cations K^+, Na^+, Ca^{2+}, Mg^{2+}** and **Mn^{2+}**, which can be taken up by plant roots, are extracted with 1N ammonium acetate at pH 7, with K and Na concentrations subsequently measured by Corning 410 flame photometer, and Ca, Mg and Mn by Varian AA400 Plus atomic absorption.

- **Cation exchange capacity (CEC)** is a measure of the soil's ability to hold positively charged ions (cations) and hence an important factor in a soil's nutrient absorption capacity and availability for plants. CEC is estimated with the sodium acetate method described by Chapman (1965).

- **Pseudo total heavy metal contents** is the fraction of heavy metals so strongly bound to the soil that it can only be leached from it with specific chemical solutions. This fraction differs from the total heavy metal contents in that it is not part of the soil's silicate matrix. For example, Ni bound inside an olivine grain is part of the soil's total Ni content. But once this olivine grain is dissolved and the released Ni subsequently bound to clay or SOM, it becomes part of the soil's pseudo total Ni content. Pseudo total heavy metal contents are therefore always lower than a soil's total heavy metal contents, analyses of the latter were carried out by Qmineral and can be found in Appendix C. Pseudo total concentrations of **Cd, Cr, Cu, Ni, Pb** and **Zn** are determined according to the procedures described by Page et al. (1982). They are extracted from the soil samples with concentrated HNO_3 (trace metal grade, 65% or 14N) and subsequently measured in the extractant by atomic absorption spectrometry (Varian, SpectrAA-400 Plus, Australia).

Appendix D presents all the data we collected for the above soil parameters during three sampling sessions (before rock dust application, during flowering stage and before harvest).

Soil water analysis

Upon arrival at the IIFC laboratory, the volume of the soil water samples is recorded. As the soil solutions collected with the macrorhizons are clear (the membrane of the macrorhizon has a pore size of 0.15 µm), they are further processed without filtering. The soil solutions sampled from the lysimeters, however, need to be filtered with a Whatman 42 filter (pore size 2.5µm) before analysis because they were not clear. Subsamples taken for Cr and Ni determinations are oxidized with HNO_3 and kept in a refrigerator until analysis. All soil water analyses are carried out in accordance with APHA (1992):

- **CO_3^{2-}** is estimated through titration with 0.1N H_2SO_4 and phenolphthalein as the color indicator.
- **HCO_3^-** is determined through titration of the same samples with 0.1N H_2SO_4 but with helianthine as the color indicator.
- Carbonate Alkalinity (**CA**), expressed in µmol/L, is calculated through the equation CA = $[HCO_3^-] + 2*[CO_3^{2-}]$. Carbonate alkalinity represents the contribution of the carbonate system to Total Alkalinity (TA) which we didn't measure and cannot calculate without concentrations of the other anions contributing to TA. In many cases, however, CA is >90% of TA and we are mainly interested in the change in CA that might result from enhanced weathering.
- **pH** and electrical conductivity (**EC**) are measured with a pH and a conductivity meter, respectively.
- **K** contents are measured by Corning 410 flame photometry.
- **Ca** and **Mg** concentrations are measured directly from the sample solutions with a Varian AA400 Plus atomic absorption spectrometer.
- As **Cr** and **Ni** contents are very low, soil water solution samples are introduced in a graphite furnace prior to analysis by atomic absorption spectrometry.

The soil water data we collected in 12 sampling sessions from the **macrorhizons** can be found in **Appendix I**. **Appendix J** presents the characteristics of the soil water samples collected from the **lysimeters**.

Statistical data reduction

The setup of the **experimental area** consists of a completely randomized block design with 8 treatments (7 materials and the control), each replicated 4 times. This setup allows for statistical evaluation of the data we collected for the various samples. Statistical analysis is performed using the SPSS software package (IBM SPSS statistics version 19).

One-way ANOVA (ANalysis Of Variance) is used to test the variability and evaluate differences in soil properties as a function of rock dust applications. The significance of differences between the treatments was estimated by the Least Significant Difference (LSD) post hoc test for $p \leq 0.05$. Whereas ANOVA indicates if there is a statistically significant difference between treatments, the post hoc LSD test shows exactly which treatments are different from one another. Pearson correlation analysis was performed to investigate the correlation between soil properties. Normality was tested by using the Kolmogorov–Smirnov test. In rare cases, extreme values were replaced by the mean value of remaining 3 replicates.

All above statistical analyses could be performed on the data gathered for the soil, plant, cotton yield and quality parameters as there were 4 replicates for each experimental treatment. Post hoc LSD test could not always be carried out for the macrorhizon soil water data as we could not always collect (enough) soil solution from each of the 32 experimental plots. As the water collected with the lysimeters represents only 1 replicate for each treatment, no statistical analyses could be carried out for these data.

Likewise, the 6 treatments in the **pilot area** were applied as one large replicate plot each. So only for those parameters for which we collected samples from more than 1 point within a specific pilot treatment – for example manual cotton harvest from 3 individual areas within one pilot plot – can we report any statistical significance on the obtained data.

Experimental area - results

Experimental area - results

This section presents the data gathered from the soil, water and cotton crop samples of the experimental area. There are **eight treatments**: seven that each received an olivine rich rock dust at a dose of 40ton/ha (4kg/m^2), and one control where no SRP was added. As there are **four replicates** for each of these eight treatments, we carried out statistical analyses to assess the significance of any variability between treatments in an objective way. So whereas the relevant appendices present the laboratory data of each replicate, the tables in this section summarize those data as **averages per treatment**.

The **statistical significance of any differences** between these averages is indicated with a letter code. Averages that share one or more letters in their code are not significantly different from one another (for example 110 a, 112 a, 120 ab). Only when two averages do not have any same letter in their code (for example 110 ab and 135 cd), they differ significantly and hence represent statistically different results for those two treatments.

When studying the data it is important to keep in mind that (1) The Norwegian (NO) olivine rich rock dust was applied at a higher dose of 4.25kg/m^2 and could not be incorporated into the soil as well as the other SRPs. (2) The treatment combined with biochar received a different fertilizer from the other treatments. (3) From mid-June to early July, nitrogen fertilizer was added together with irrigation water right before soil water sampling sessions.

Cotton yield & quality

The average **cotton yield** obtained for each of the 8 treatments are summarized in Table 9.1 and visualized in Figure 9.1. Our cotton yield ranged from 3688 kg/ha in the treatment IT olivine to 4908 kg/ha in the treatment GR olivine VV + biochar with the yield of the control treatment (4220 kg/ha) falling in between. These values are all within the range of average cotton yields obtained by the other farmers in the area. Both the control and IT olivine treatment, however, have larger standard deviations due to a large spread of yield values for their 4 replicates, probably due to soil heterogeneity across the field. So although Figure 9.1 suggests higher yields for the three treatments with the Greek rock dusts compared to the other three olivine rich rock dust treatments, statistics show **no significant difference between** the eight **treatments**. Addition of rather high doses of olivine rich rock powder therefore does not seem to have any negative or positive effects on cotton yield in the first year of cultivation.

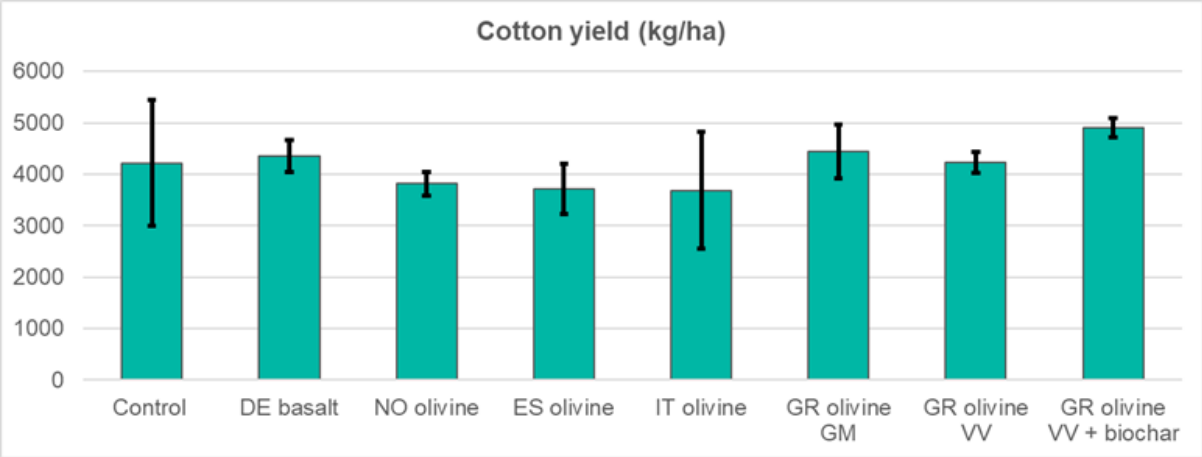


Figure 9.1 Average yields obtained from the 4 replicates of each of the 8 different treatments, error bars represent the respective standard deviations.

Treatments	Replications				Average yield (kg/ha)	SD (kg/ha)	CV (%)
	1	2	3	4			
Control	3163	3184	5084	5449	4220 a	1217.6	28.9
DE basalt	4142	4355	4796	4126	4355 a	312.3	7.2
NO olivine	4089	3521	3815	3833	3815 a	232.4	6.1
ES olivine	3411	4293	3221	3923	3712 a	487.8	13.1
IT olivine	2981	5177	3935	2658	3688 a	1131.4	30.7
GR olivine GM	4047	5153	4504	4061	4441 a	519.4	11.7
GR olivine VV	4381	4172	4411	3961	4231 a	208.8	4.9
GR olivine VV + biochar	4789	4825	5186	4832	4908 a	186.3	14.9

Table 9.1. Average yield values obtained for each of the 8 SRP treatments. The same letter for different yield values shows that there is no significant difference for $p<0.05$ according to the LSD post hoc test. SD = Standard Deviation, CV = Coefficient of Variation.

The **quality of cotton** is determined by its lint weight, moisture, micronaire, maturity, UHML, length uniformity, SFI, strength, elongation, reflectance and yellowness. More information on these physical properties can be found in the previous chapter. Statistical analysis shows that **none** of these **properties** were **significantly affected** by the olivine rich rock dust application and biochar. This result is expected as changes in cotton quality would require significant alteration of the soil, which would probably already have shown in variable crop growth and yield.

Section summary

The Greek olivine rich rock dust with biochar treatment seems to have the highest cotton yield. Statistical analyses however reveal that there is no significant distinction between the crop yield, or the cotton quality, observed for the seven different experimental treatments compared to the control.

Addition of olivine rich rock dusts at a dose of 40ton/ha, with or without biochar, did not have any positive or negative effect on the cotton cultivation within the first year of our experiments.

Cotton quality parameter	Control	DE Basalt	NO olivine	ES olivine	IT olivine	GR olivine GM	GR olivine VV	GR olivine VV + Biochar
Lint weight, %	46 a	46 a	47 a	47 a	47 a	47 a	48 a	48 a
SCI	153,82 a	137,59 a	140,63 a	143,94 a	139,75 a	153,37 a	144,02 a	153,75 a
Moisture, %	7,06 a	6,95 a	7,06 a	7,45 a	7,13 a	6,97 a	7,13 a	7,42 a
Micronaire	4,78 a	4,90 a	4,72 a	4,72 a	4,71 a	4,55 a	4,74 a	4,62 a
Maturity	0,85 a	0,85 a	0,85 a	0,85 a	0,85 a	0,85 a	0,85 a	0,85 a
UHML, mm	30,14 a	29,22 a	29,13 a	28,90 a	29,17 a	29,47 a	29,58 a	30,22 a
Length uniformity	84,18 a	82,88 a	83,20 a	83,92 a	82,85 a	84,65 a	83,24 a	84,29 a
SFI	8,05 a	8,16 a	8,28 a	7,97 a	8,41 a	7,80 a	8,20 a	7,80 a
Strength	35,59 a	33,14 a	33,20 a	34,07 a	33,74 a	34,80 a	34,27 a	34,96 a
Elongation	8,75 a	9,13 a	9,04 a	9,10 a	8,99 a	8,86 a	8,69 a	8,73 a
Reflectance%	76,19 a	76,00 a	75,91 a	72,66 a	74,48 a	74,59 a	75,12 a	75,68 a
Yellowness +b	8,16 a	8,18 a	8,07 a	7,80 a	8,02 a	7,58 a	7,81 a	7,91 a

Table 9.2. Average values of the different cotton quality parameters obtained for the eight treatments. Within one data row of a specific quality parameter, the same letter for different treatments shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test.

Plant nutrient uptake

The nutrient uptake by the cotton plants is expressed as the concentrations of N, P, K, Ca, Mg, Fe, Mn, B, Cu and Zn measured in the plant tissue during the flowering period (Table 9.3). Statistical analysis of these data shows that, apart from phosphorus (P), there is **no significant difference** in the cotton **plants' nutrient** uptake between the various treatments.

Phosphorus contents in the cotton plant tissue are **significantly different** between the **Greek olivine** treatment **with biochar** (overall **highest** value of 0.217%) on one hand, and the control, Italian olivine and Spanish olivine (overall lowest value of 0.162%) on the other hand. As the P content of the Greek olivine rich treatment without biochar does not significantly differ from that of the Spanish one, this difference could reflect the influence of **biochar** on P supply to the plants. Although not statistically significant, there seems to be an overall tendency for the biochar-amended treatment to result in the **highest macro-nutrient** uptake (K, N, P, Ca, Mg). This is in line with the reported improvement of nutrient uptake due to biochar application to the soil (Hossain et al., 2020). Biochar is thereby described as a potential nutrient reservoir for plants and a good amendment to improve soil properties. In our case, it is unclear whether the seemingly higher bio-availability of macronutrients in the biochar treatment is due to the activation of the biochar with a different fertilizer, or solely due to the interaction of the biochar with the soil chemistry.

Plant nutrients (unit)	Control	DE Basalt	NO Olivine	ES Olivine	IT Olivine	GR Olivine GM	GR Olivine VV	GR Olivine VV + Biochar
K (%)	1,03 a	1,08 a	0,85 a	0,86 a	0,96 a	1,05 a	0,86 a	1,12 a
Ca (%)	2,80 a	2,86 a	2,74 a	2,64 a	2,72 a	2,84 a	2,89 a	3,03 a
Mg (%)	0,78 a	0,75 a	0,77 a	0,72 a	0,74 a	0,80 a	0,81 a	0,83 a
N (%)	3,00 a	3,28 a	2,97 a	2,98 a	3,04 a	3,34 a	3,02 a	3,26 a
P (%)	**0,177 bc**	**0,206 ab**	**0,186 abc**	**0,162 c**	**0,175 bc**	**0,194 abc**	**0,187 abc**	**0,217 a**
Fe (mg/kg)	375,75 a	257,75 a	250,00 a	279,00 a	353,50 a	379,75 a	291,75 a	231,25 a
Zn (mg/kg)	76,50 a	107,25 a	33,00 a	76,00 a	66,00 a	32,75 a	35,00 a	62,75 a
Cu (mg/kg)	7,05 a	5,56 a	4,92 a	2,40 a	7,32 a	6,05 a	5,52 a	6,70 a
Mn (mg/kg)	131,25 a	128,25 a	112,75 a	121,25 a	112,00 a	121,25 a	126,50 a	118,75 a
B (mg/kg)	77,25 a	77,25 a	83,50 a	76,75 a	72,50 a	75,75 a	78,75 a	65,75 a

Table 9.3. Average values of the different nutrient concentrations measured in the plant tissue during the flowering period. Within one data row of a specific plant nutrient, the same letter for different treatments shows there is no significant difference between treatments for $p<0.05$ according to the LSD post hoc test. Darker coloured row with white bold text indicates a plant nutrient that varies significantly between certain treatments.

The second highest P content is found in the **DE basalt**, perhaps reflecting its **distinct mineralogical composition** that includes phosphorus rich minerals which are not present in the olivine rich rock dusts. This assumption seems to be supported by the fact that the P content in the DE basalt cotton is also significantly different from that in the ES olivine cotton. The presence of more nutrient-rich minerals in the basalt rock dust might also explain why this treatment resulted in the highest zinc (Zn) content and second highest (after biochar) macro-nutrient contents. Although these tendencies are not significant from a statistical point of view, it is interesting that the treatment with the SRP which theoretically provides the most plant nutrients suggests elevated macronutrient plant uptake.

Comparison of the **nutrient contents** observed in our experiment with the **cotton plant sufficiency ranges** reported by Mills & Jones, 1996 (Table 9.4) shows that all our cotton plants contain insufficient amounts of N, P, K. This suggests that N-P-K fertilization by the farmer is not adequate or these macronutrients are not sufficiently bio-available in this soil with very high clay content, $CaCO_3$ and pH values. Macronutrient contents for Ca and Mg are within the sufficiency range for all treatments. Except for the treatment with ES olivine which shows insufficient amounts, all micro-nutrient concentrations were found to be above the sufficiency levels.

Macronutrients (%)									
N	3,50-4,50	*P*	0,30-0,50	*K*	1,50-3,00	*Ca*	2,00-3,00	*Mg*	0,30-0,90
Micronutrients (mg/kg)									
Fe	50-250	*Mn*	25-350	*B*	20-60	*Cu*	5-25	*Zn*	20-200

Table 9.4 Sufficiency ranges of nutrient concentrations in cotton leave tissues (Mills & Jones, 1996).

Section summary

Overall, there is no statistically significant difference between the nutrient uptake of cotton plants growing in the eight different treatments. The only statistical difference is between the P content of cotton leaves in the Spanish olivine (lowest), Italian olivine and control on one hand, and the Greek olivine with biochar (highest) on the other hand.

Although not statistically significant, the treatment with biochar generally shows the highest macronutrient uptake. It is unclear whether this reflects the interaction of the biochar with the soil, or the different fertilizer with which the biochar was activated.

The treatment with German basalt has the highest zinc and second highest macro nutrient contents. Even though this nutrient uptake is not statistically different from the olivine rich rock dusts, it could reflect the higher fertilization potential of basalt due to its different mineralogy.

Soil properties

About 20 different soil properties were analysed in samples collected prior to rock dust application (3 April), during the flowering period (27 July) and before the cotton harvest (20 September). As satellite imagery and preliminary soil samples indicated that the soil across this field is rather homogenous, only a limited number of samples were collected prior to rock dust application: the four replicates of the control spread across the experimental area. In the following two sampling sessions soil was taken from all replicates of all treatments.

The soil data are statistically analysed to assess (1) any variability between treatments within the same sampling session and (2) any changes throughout the cotton growing season within the same treatment.

Soil heavy metal concentrations discussed in this chapter refer to pseudo total contents – all heavy metals in different soil pools except for those within a silicate crystal matrix.

Soil properties	Control	DE basalt	NO olivine	ES olivine	IT olivine	GR olivine GM	GR olivine VV	GR olivine VV + biochar
pH	8,10 a	8,17 a	8,07 a	8,20 a	8,12 a	8,07 a	8,15 a	8,10 a
EC (µS/cm)	784,25 a	704,50 a	785,75 a	658,75 a	698,50 a	849,00 a	618,75 a	693,75 a
$CaCO_3$ (%)	24,25 a	26,00 a	25,00 a	25,75 a	24,75 a	24,25 a	24,50 a	24,25 a
SOM (%)	0,89 a	0,61 a	0,76 a	1,05 a	0,83 a	0,73 a	0,87 a	0,97 a
N_tot (%)	**0,084 ab**	**0,081 ab**	**0,080 ab**	**0,086 ab**	**0,074 b**	**0,087 ab**	**0,088 ab**	**0,088 a**
NO_3_N (mg/kg)	11,49 a	12,06 a	12,76 a	18,34 a	3,19 a	8,06 a	8,01 a	18,71 a
P_olsen (mg/kg)	**10,12 ab**	**4,85 b**	**10,42 ab**	**15,85 a**	**3,30 bc**	**8,40 b**	**13,52 ab**	**10,70 ab**
K_exch (cmol+/kg)	0,53 a	0,51 a	0,53 a	0,62 a	0,51 a	0,54 a	0,51 a	0,52 a
Na_exch (cmol+/kg)	1,04 a	0,91 a	1,08 a	0,97 a	0,87 a	0,90 a	0,91 a	1,03 a
Ca_exch (cmol+/kg)	**34,25 c**	**32,25 c**	**34,25 c**	**35,00 c**	**35,25 c**	**35,75 bc**	**39,50 ab**	**40,00 a**
Mg_exch (cmol+/kg)	8,92 a	8,52 a	9,05 a	9,12 a	9,57 a	9,20 a	9,12 a	9,27 a
CEC (cmol+/kg)	**42,25 cd**	**44,00 d**	**43,00 bcd**	**44,25 abcd**	**45,00 abc**	**44,00 abcd**	**45,50 ab**	**48,00 a**
Cd (mg/kg)	0,15 a	0,14 a	0,22 a	0,17 a	0,16 a	0,11 a	0,13 a	0,20 a
Cr (mg/kg)	122,61 a	133,62 a	95,68 a	123,77 a	117,81 a	101,61 a	120,03 a	86,59 a
Cu (mg/kg)	27,14 a	28,50 a	24,96 a	27,04 a	26,24 a	28,52 a	27,80 a	25,70 a
Ni (mg/kg)	210,66 a	227,46 a	230,02 a	225,63 a	233,99 a	222,57 a	239,35 a	215,89 a
Pb (mg/kg)	9,75 a	9,90 a	10,44 a	9,22 a	9,68 a	9,69 a	9,47 a	10,69 a
Zn (mg/kg)	45,47 a	48,36 a	43,64 a	44,49 a	42,87 a	47,43 a	45,15 a	43,82 a

Table 9.5. Average values of the different soil parameters measured in soil samples collected during the flowering period. Within one data row of a specific soil parameter, the same letter for different treatments shows there is no significant difference between the treatments for $p<0.05$ according to the LSD post hoc test. Darker coloured rows with white bold text indicate soil parameters that vary significantly between treatments.

Variability across treatments during flowering stage

Table 9.5 presents the soil parameters obtained during the flowering stage, about 4 months into the experiment. Except for available P, total N, exchangeable Ca and CEC, no soil properties show significant differences between distinct treatments.

A soil is considered to have a medium supply of **available phosphorus** when its concentration ranges from 7 to 20 mg/kg, and high amounts when it ex-

ceeds 20 mg/kg (Olsen & Sommers, 1982). In order to increase the soil's low initial contents of available P (2-3mg/kg) we applied fertilizer to obtain an acceptable soil P availability of about 10mg/kg. Despite the uniform application of this phosphorus fertilizer, the soil's available P **varies significantly** during the flowering period.

Control, NO olivine and GR olivine + biochar treatments still contain about 10mg/kg. Whereas available P seems reduced in the treatments with GR olivine GM, DE basalt and ES olivine (lowest at 3.30mg/kg), the soil of treatments GR olivine VV and IT olivine (highest at 15.85 mg/kg) show an increase. The reason for these significant differences in the soil's available P contents is unclear and needs further investigation.

The previous section discusses that P is the only nutrient taken up by the plants with statistical differences between the treatments. Interestingly, comparison of the available P found in the soil and the amount of P measured in the plants shows **no correlation between** those two phosphorus pools (Figure 9.2). Biochar application to the soil is known to improve available P (Li et al., 2022), but significantly high P contents in the plants are combined with only average available P in the soil. Likewise, the elevated P uptake by cotton growing in the DE basalt is paired with very little available P in the soil of this treatment. It seems that different processes regulate **P availability in the soil and P uptake by plants**.

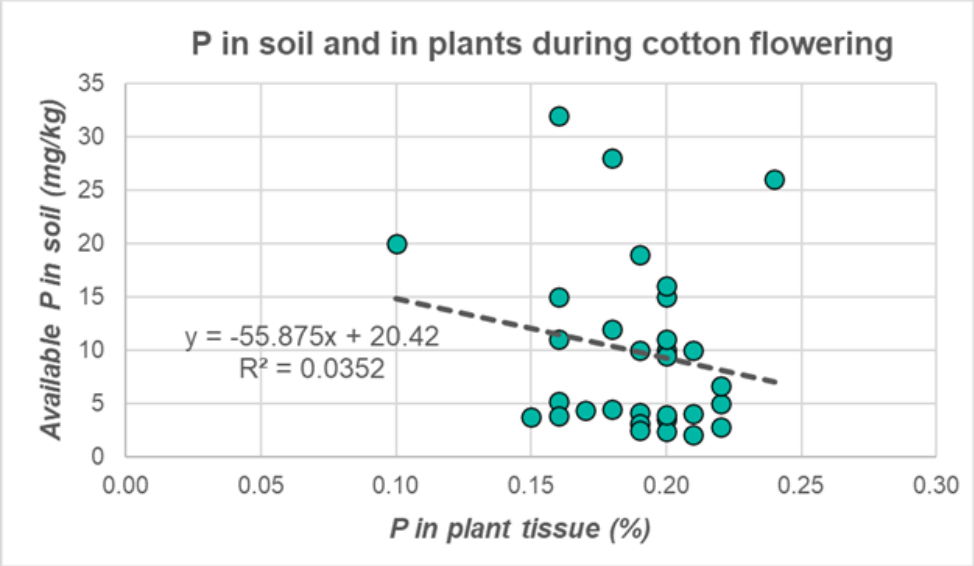


Figure 9.2. Comparison of P taken up by plants and soil available P during flowering.

Although there is a statistical difference in the **total nitrogen** found in the soil of the IT olivine treatment (lowest) and that of the GR olivine + biochar application (highest), there are no significant differences between the nitrate concentrations. **Soil exchangeable calcium** contents are found to be highest for the GR olivine rich rock dusts, particularly the Ca^{2+} in the soils of the Vitruvit (VV) treatments is significantly different from that of the non-Greek

olivine rich rock dusts. Consequently, the **cation exchange capacity** of the soils also shows some **significant differences**. It seems that the Control treatment has the overall lowest CEC which is statistically distinct from the highest CEC in the biochar amended soil.

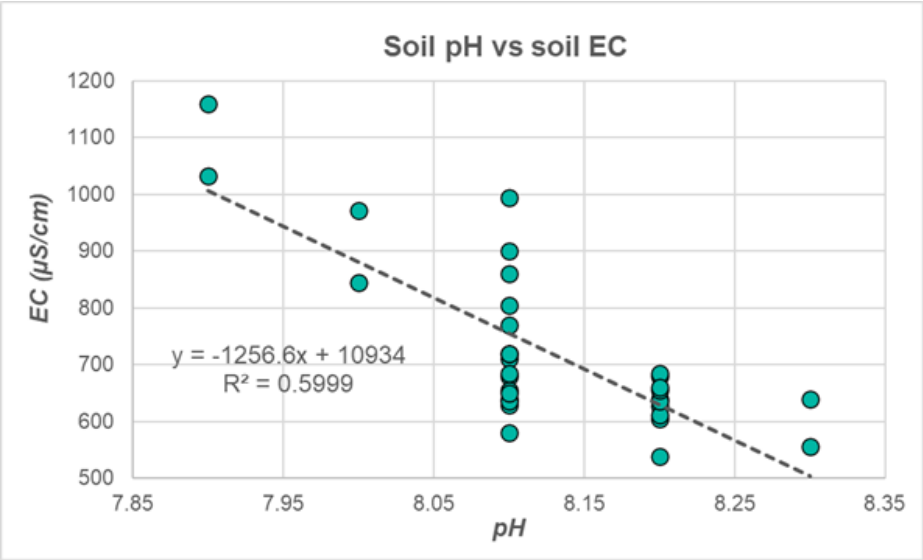


Figure 9.3. Negative correlation between the soil pH and soil EC measured in the flowering period.

Although the soil samples taken during flowering do not show any significant differences between treatments for either **pH** or electrical conductivity (**EC**), these two soil parameters are **negatively correlated** with one another (Figure 9.3). Low soil pH reflects high concentrations of positively charged hydrogen ions, which may in turn increase the EC of the soil. (Mohd-Aizat et al, 2014).

Given the high **$CaCO_3$** content of the soil prior to rock dust application it is not surprising that there were no significant differences observed in $CaCO_3$ contents of the different treatments four months into the experiment. Soil organic matter (**SOM**) does not show any statistically relevant differences between the treatments, also not for the one with the 0.3kg/m² biochar addition. Soil concentrations of **heavy metals** are statistically the same across the eight different treatments. Elevated pseudo total nickel contents across the entire experimental area reflect high background levels due to the soil's geological parent material.

Section summary

During the cotton flowering stage, most soil parameters don't show any significant differences between the treatments. Soil pseudo total heavy metal concentrations do not differ significantly between treatments, with elevated Ni contents reflecting natural background levels. Uniformly high initial $CaCO_3$ contents remain the same for all plots four months into the experiment.

Despite addition of biochar to one treatment, SOM is not significantly different for any of the treatments. Although there is a negative correlation between soil pH and soil EC, neither of these soil parameters displays significant variation between treatments.

Total N contents show some statistical differences, but these are not reflected in nitrate concentrations. As is the case for P uptake by cotton plants, available soil P shows significant differences between treatments. There is however no correlation between these two phosphorus pools, suggesting they are affected by different soil processes.

Significantly higher exchangeable Ca in the soil treated with the GR olivine rich rock dusts coincides with a similar trend for soil CEC. Overall, the Greek rock dust with biochar treatment has both the highest CEC and the most exchangeable Ca.

Variability across treatments at harvest time

About two months after the flowering period sampling and about 6 months into the experiment, we took a last set of soil samples from all 32 experimental plots prior to the manual cotton harvest. Table 9.6 presents the averages obtained for the different soil parameters along with the results of their statistical analysis.

Once again, most soil parameters show no statistical differences between treatments. The ones that do have significant variability before harvest, however, are not entirely the same as those that stood out during the flowering stage. Whereas significant variability was observed **in total N and available P** at the end of July, these soil parameters do **not statistically differ** across the treatments by late September. The only trend that might be discernible is the higher available P in the biochar amended soil in comparison to all other treatments. Soil pH and EC again display a negative linear relationship ($R^2 = 0.48$).

Besides **exchangeable Ca** and **CEC**, **exchangeable Mg** now also shows **significant differences** across treatments. But whereas during flowering the highest values in the biochar amendment are statistically different from the lowest ones in the control, these particular two treatments are no longer significantly different from one another prior to harvest. This time, both of them are significantly different from the lowest CEC and exchangeable Ca and Mg values observed in the IT olivine treatment.

The most **interesting change** from the soil property variations during flowering is seen in the **soil heavy metal contents** at harvest time. Where no statistical variation is present across the treatments at the end of July, there are some **significant differences** for **pseudo total Cr and Ni** contents by late September. For both Cr and Ni, the average concentrations measured in the Control and DE basalt treatments are among the lowest ones. The highest average Cr and Ni contents are observed in the soil of the ES olivine and IT olivine treatments, respectively.

Soil properties	Control	DE basalt	NO olivine	ES olivine	IT olivine	GR olivine GM	GR olivine VV	GR olivine VV + biochar
pH	8,25 a	8,25 a	8,37 a	8,35 a	8,40 a	8,30 a	8,35 a	8,32 a
EC (µS/cm)	626 a	510,75 a	525,00 a	455,75 a	455,00 a	566,75 a	459,00 a	484,00 a
$CaCO_3$ (%)	18,00 a	20,00 a	22,00 a	21,25 a	21,75 a	18,75 a	21,25 a	21,00 a
SOM (%)	1,09 a	1,15 a	0,93 a	1,01 a	1,08 a	1,05 a	0,95 a	0,87 a
N_tot (%)	0,087 a	0,092 a	0,90 a	0,083 a	0,097 a	0,085 a	0,082 a	0,083 a
NO_3_N (mg/kg)	10,82 a	5,82 a	2,25 a	2,40 a	2,67 a	2,32 a	2,75 a	10,80 a
P_olsen (mg/kg)	6,75 a	6,12 a	2,82 a	2,15 a	6,40 a	3,35 a	5,10 a	9,25 a
K_exch (cmol+/kg)	0,41 a	0,43 a	0,38 a	0,38 a	0,50 a	0,39 a	0,41 a	0,44 a
Ca_exch (cmol+/kg)	**42,75 ab**	**43,50 ab**	**44,25 a**	**41,75 abc**	**38,00 c**	**42,50 ab**	**41,52 abc**	**40,25 bc**
Mg_exch (cmol+/kg)	**9,22 ab**	**9,70 a**	**9,80 a**	**9,35 ab**	**8,07 b**	**9,90 a**	**10,22 a**	**9,70 a**
CEC (cmol+/kg)	**49,00 a**	**50,50 a**	**50,50 a**	**47,25 a**	**38,00 c**	**42,50 b**	**48,75 a**	**47,00 a**
Mn (mg/kg)	1,72 a	1,95 a	1,85 a	2,02 a	2,05 a	2,07 a	2,02 a	2,10 a
Cd (mg/kg)	0,09 a	0,03 a	0,09 a	0,05 a	0,04 a	0,04 a	0,02 a	0,03 a
Cr (mg/kg)	**134,03 b**	**134,69 b**	**139,97 ab**	**160,42 a**	**142,44 ab**	**138,17 ab**	**141,25 ab**	**139,77 ab**
Cu (mg/kg)	28,64 a	29,72 a	27,64 a	29,04 a	29,39 a	28,71 a	28,90 a	29,10 a
Ni (mg/kg)	**124,56 b**	**129,00 ab**	**144,42 ab**	**151,61 ab**	**156,01 a**	**143,06 ab**	**150,68 ab**	**153,92 a**
Pb (mg/kg)	9,07 a	6,96 a	10,10 a	8,71 a	7,40 a	8,14 a	6,96 a	6,87 a
Zn (mg/kg)	40,57 a	42,72 a	42,74 a	42,11 a	41,84 a	44,62 a	42,44 a	42,28 a

Table 9.6. Average values of the different soil parameters measured in soil samples collected right before harvest. Within one data row of a specific soil parameter, the same letter for different treatments shows there is no significant difference between the treatments for $p<0.05$ according to the LSD post hoc test. Darker coloured rows with white bold text indicate soil parameters that vary significantly between treatments.

Nickel and chromium are those heavy metals that olivine dissolution is expected to release to the soil. Could the significant differences in pseudo total Ni and Cr soil contents, which seem to have developed about 6 months after rock dust application, be **linked to enhanced weathering** of olivine? Figure 9.4 shows a very weak positive correlation ($R^2 = 0.20$) between soil contents of nickel and chromium at harvest time. This suggests that the pseudo total concentrations of both these heavy metals increase simultaneously, as would be the case when they are simultaneously released from dissolving olivine. It will be interesting to see whether this soil's already high background levels for Ni and Cr will show both higher concentrations and a better correlation with time as weathering of the added SRPs progresses.

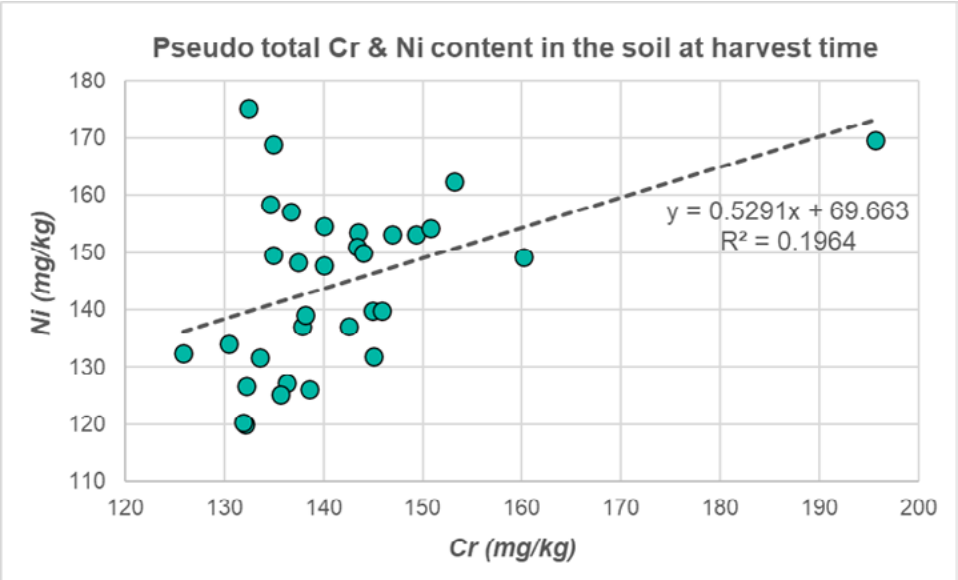


Figure 9.4. Very weak positive correlation between pseudo total Cr and Ni contents observed in the soil at harvest time.

Section summary

As seen before during flowering, most soil parameters do not display statistical differences between treatments at harvest time. Those soil properties that do show significant variations at harvest (Ca, Mg, CEC, Ni & Cr) are thereby not entirely the same as those with statistical differences at the flowering stage (P, N, Ca & CEC).

A potentially important change compared to 2 months earlier are the statistical differences in pseudo total Ni and Cr soil contents. These are now significantly lower in the control and DE basalt than in any of the olivine rich SRP treatments. This might reflect dissolution of olivine 6 months into the experiment.

Seasonal variability throughout cotton growing

Besides assessing potential variation between different treatments at a specific moment in time, the soil data also present the opportunity to assess any significant variation over time within a specific treatment. The variation of the soil properties throughout the growing season is presented for each of the 8 treatments in Table 9.7. As our field did not show particular soil variability in either bare soil reflectance satellite imagery or preliminary soil analyses, we only sampled the 4 control plots prior to rock dust application. Since these plots are randomly spread throughout the experimental area, we assume that these initial soil properties are representative for the initial soil conditions of the other 7 treatments.

Soil parameters show a **lot more significant variation throughout the** cotton growing **season** (seasonal variation) **than** they do **between different treatments** at any given time. Seasonal variation of a certain soil parameter is thereby often the same in all treatments, including the control, suggesting the specific soil parameter to be governed by physical, chemical or biological processes other than enhanced weathering. The nutrient demands of plants, for example, change significantly throughout the growing season with the greatest demands during flowering.

A **significant variation** of **soil pH** values is recorded in **all eight treatments**. In comparison to its initial value in spring, soil pH is thereby **reduced by up to 0.25 units during** the **flowering** period in summer before increasing again towards its initial value in autumn (Figure 9.5). This common seasonal trend is ascribed to high biological activity in summer time when lower moisture levels and better aeration change the soil CO_2 pressure (Van Lierop, 1990). Another, or additional, cause for the decrease in soil pH in late July might be the nitrogen fertilization that was carried out from mid-June through to mid-July.

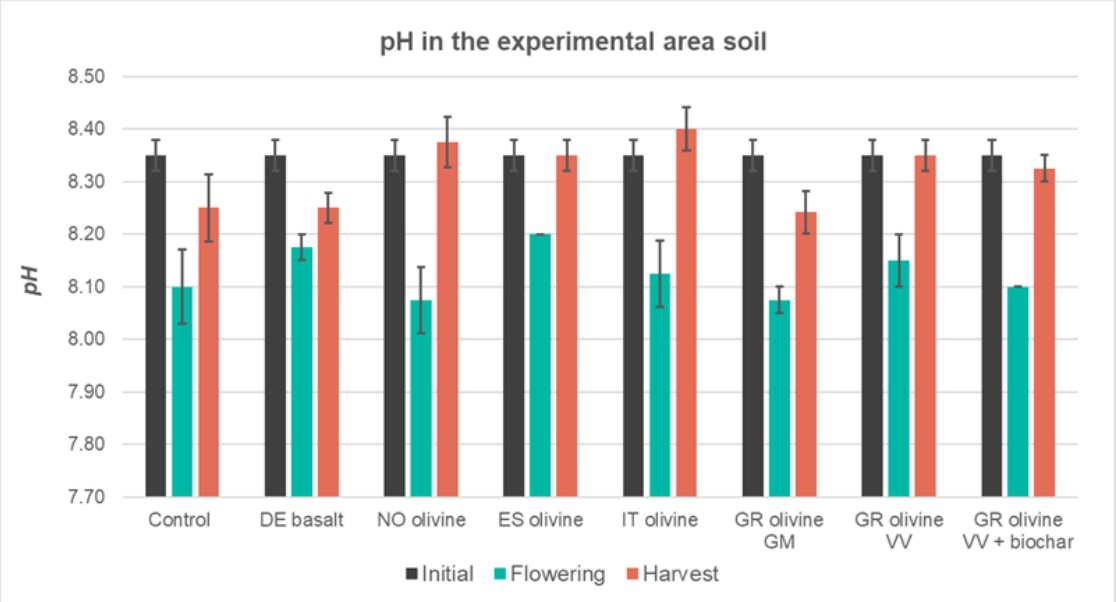


Figure 9.5. Average soil pH values of the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

Soil properties	Control			DE basalt			NO olivine			ES olivine		
	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest
pH	8,35 a	8,11 b	8,25 ab	8,35 a	8,17 b	8,25 ab	8,35 a	8,07 b	8,37 a	8,35 a	8,20 b	8,35 a
EC	499,25 a	784,25 a	626,00 a	499,25 a	704,50 a	510,75 a	499,25 b	785,75 a	525,25 ab	499,25 b	658,75 a	455,75 b
CaCO3	23,75 a	24,25 a	18,00 a	23,75 b	26,00 a	20,00 c	23,75 a	25,00 a	22,00 a	23,75 b	25,75 a	21,25 c
SOM	0,73 b	0,89 ab	1,09 a	0,73 b	0,61 b	1,15 a	0,73 a	0,76 a	0,93 a	0,73 b	1,05 a	1,01 a
N_tot	0,072 a	0,084 a	0,087 a	0,072 a	0,08 a	0,09 a	0,072 a	0,080 a	0,090 a	0,07 a	0,08 a	0,08 a
NO3_N	4,80 a	10,82 a	11,49 a	4,80 a	4,55 a	5,82 a	4,80 ab	12,66 a	2,25 b	4,80 a	18,34 a	2,40 a
P_olsen	2,725 b	10,12 a	6,75 ab	2,72 a	4,85 a	6,12 a	2,72 b	10,42 a	2,82 b	2,72 b	15,85 a	2,15 b
K_exch	0,38 b	0,53 a	0,42 b	0,38 b	0,51 a	0,43 ab	0,38 b	0,53 a	0,38 b	0,38 b	0,62 a	0,38 b
Ca_exch	28,75 c	34,25 b	42,75 a	28,75 c	32,25 b	43,50 a	28,75 c	34,25 b	44,25 a	28,75 c	35,00 b	41,75 a
Mg_exch	8,35 a	8,92 a	9,22 a	8,35 b	8,52 b	9,70 a	8,35 c	9,05 b	9,80 a	8,35 a	9,12 a	9,35 a
CEC	35,75 c	42,25 b	49,00 a	35,75 b	40,00 b	50,50 a	35,75 c	43,00 b	50,50 a	35,75 c	43,75 b	49,00 a
Cd		0,15 a	0,09 a		0,14 a	0,03 b		0,22 a	0,09 b		0,17 a	0,05 b
Cr	136,01 a	122,60 a	134,03 a	136,01 a	133,62 a	134,69 a	136,01 a	95,68 b	139,97 a	136,01 a	123,77 a	160,42 a
Cu	26,40 b	27,14 ab	28,64 a	26,40 b	28,50 ab	29,72 a	26,40 a	24,95 a	27,64 a	26,40 b	27,03 ab	29,04 a
Ni	148,16 b	210,66 a	124,56 b	148,16 b	227,46 a	129,00 b	148,16 b	230,02 a	144,42 b	148,16 b	225,63 a	151,61 b
Pb	5,32 b	9,75 a	9,07 a	5,32 c	9,90 a	6,96 b	5,32 b	10,44 a	10,10 a	5,32 b	9,22 a	8,71 a
Zn	39,67 a	45,47 a	40,57 a	39,67 b	48,36 a	42,72 ab	39,67 a	43,64 a	42,74 a	39,67 a	44,49 a	42,11 a

Soil Properties	IT olivine			GR olivine GM			GR olivine VV			GR olivine VV + biochar		
	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest
pH	8,35 a	8,12 b	8,40 a	8,35 a	8,07 b	8,30 a	8,35 a	8,15 b	8,35 a	8,35 a	8,15 b	8,32 a
EC	499,25 b	698,50 a	455,00 b	499,25 b	849,00 a	566,75 b	499,25 b	618,75 a	459,00 b	499,25 b	693,75 a	484,00 b
CaCO3	23,75 a	24,75 a	21,75 b	23,75 a	24,25 a	18,75 a	23,75 a	24,50 a	21,25 b	23,75 a	24,25 a	21,00 b
SOM	0,73 a	0,83 a	1,08 a	0,73 b	0,73 b	1,05 a	0,73 a	0,87 a	0,95 a	0,73 b	0,98 a	0,87 ab
N_tot	0,07 a	0,08 a	0,09 a	0,07 a	0,08 a	0,08 a	0,07 a	0,08 a	0,08 a	0,07 a	0,087 a	0,08 a
NO3_N	4,80 a	3,19 a	2,67 a	4,80 a	8,06 a	2,32 a	4,80 a	8,01 a	2,75 a	4,80 a	18,71 a	10,80 a
P_olsen	2,72 a	3,30 a	6,40 a	2,72 a	8,40 a	3,35 a	2,72 a	13,52 a	5,10 a	2,72 a	10,70 a	9,25 a
K_exch	0,38 a	0,51 a	0,50 a	0,38 b	0,54 a	0,39 b	0,38 b	0,51 a	0,41 ab	0,38 b	0,52 a	0,44 ab
Ca_exch	28,75 b	35,25 a	38,00 a	28,75 c	35,75 b	42,50 a	28,75 c	39,50 b	41,25 a	28,75 b	40,00 a	40,25 a
Mg_exch	8,35 a	9,57 a	8,07 a	8,35 b	9,20 b	9,90 a	8,35 b	9,12 b	10,22 a	8,35 b	9,27 ab	9,70 a
CEC	35,75 b	45,00 a	38,00 b	35,75 b	44,00 a	42,50 a	35,75 b	47,50 a	48,75 a	35,75 b	48,00 a	47,00 a
Cd		0,16 a	0,05 a		0,11 a	0,04 a		0,13 a	0,03 b		0,20 a	0,03 b
Cr	136,01 a	117,81 a	142,44 a	136,01 a	101,61 b	138,17 a	136,01 a	120,03 a	141,25 a	136,01 a	86,59 b	139,77 a
Cu	26,40 a	26,24 a	29,39 a	26,40 a	28,52 a	28,71 a	26,40 a	27,80 a	28,90 a	26,40 b	25,70 b	29,10 a
Ni	148,16 b	233,99 a	156,01 b	148,16 b	222,56 a	143,06 b	148,16 b	239,35 a	150,68 b	148,16 b	215,90 a	153,92 b
Pb	5,32 b	9,68 a	7,40 ab	5,32 b	9,69 a	8,14 ab	5,32 b	9,46 a	6,96 b	5,32 c	10,69 a	6,87 b
Zn	39,67 a	42,87 a	41,84 a	39,67 a	47,43 a	44,62 a	39,67 a	45,15 a	42,44 a	39,67 a	43,82 a	42,28 a

Table 9.7. Average values of the soil parameters measured for different treatments before rock dust application, during flowering and at harvest time. Statistical analysis carried out on these data assesses the significance of seasonal variation within a certain treatment. Within horizontal rows, the same letter for different sampling times of the same treatment indicates that the specific soil parameter does not show significant seasonal variation for $p<0.05$ according to the LSD post hoc test. Darker coloured rows with white bold text indicate soil parameters that show seasonal variability for all 8 treatments. Light orange coloured data highlight significant seasonal variation of a specific soil parameter for some of the treatments. Units of soil parameters as in Table 9.6.

The **negative correlation** between soil **pH and EC**, already observed in the soil data of the flowering and harvest time separately, is even stronger throughout the growing season (R^2 = 0.72). Similar observations are reported by Collins et al. (1970). The seasonal trend of **higher EC** during the **flowering** period before returning to initial values is thereby significant for all olivine rich rock dusts but not statistically confirmed for the control and DE basalt treatment.

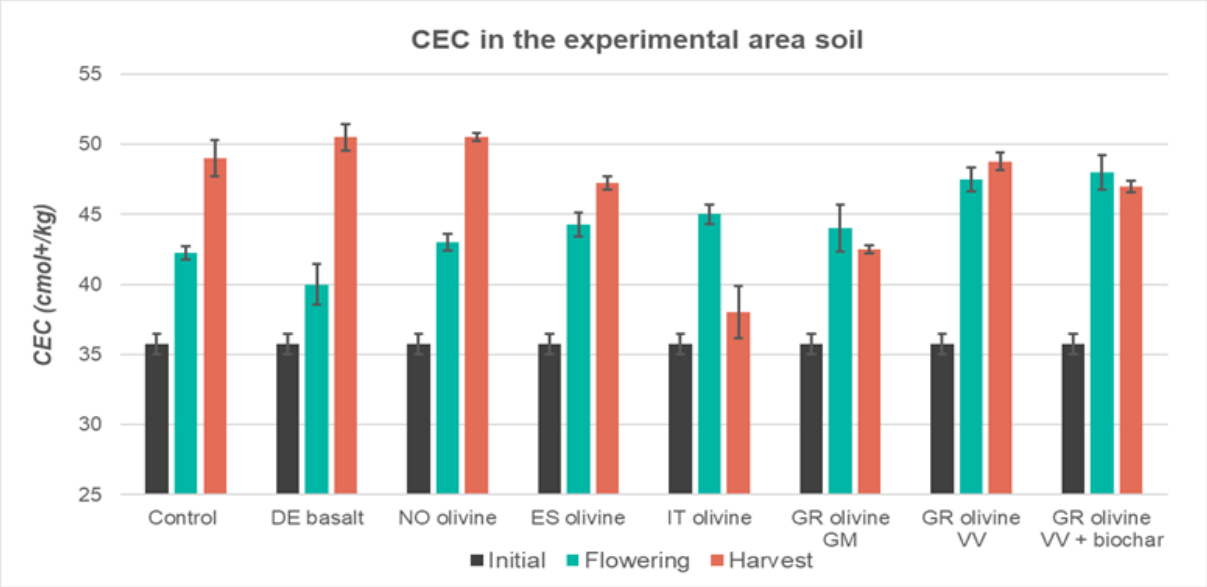


Figure 9.6. Average soil CEC values of the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

Another soil parameter that follows the same **significant seasonal variation** for all eight treatments is the cation exchange capacity (Figure 9.6). All treatments show a **steady increase** in **CEC** from early April through to late September and some of the adsorbed basic cations show a similar trend. The steady **increase** in **exchangeable Ca** (figure 9.7) is significant for all eight treatments but the continuous **increase** of **exchangeable Mg** is not statistically confirmed for the control or IT and ES olivine treatments. The reason for this continuous increase in soil Ca and Mg is unclear, but the fact that it's also observed in the control suggests that it is not dissolution of added Ca-Mg silicates. **Exchangeable K**, on the other hand, shows a significant **decrease from flowering** stage to harvest (figure 9.8). This trend might be attributed to uptake by the cotton plants in later growth stages, or perhaps by increased availability of K at corresponding lower soil pH values.

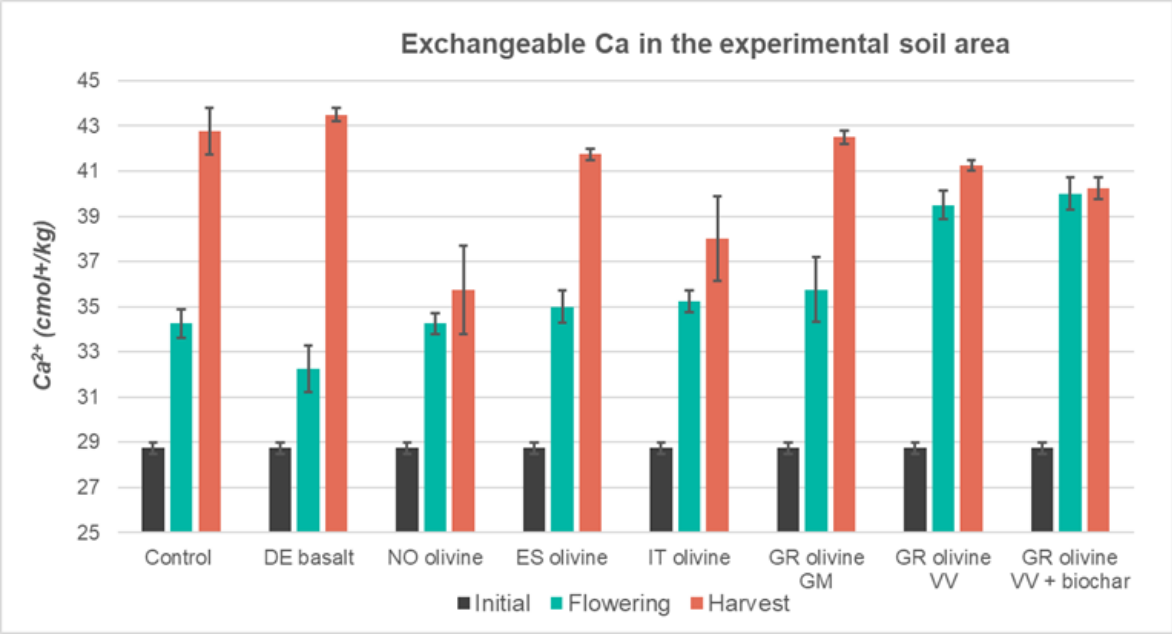


Figure 9.7. Average soil exchangeable Ca values of the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

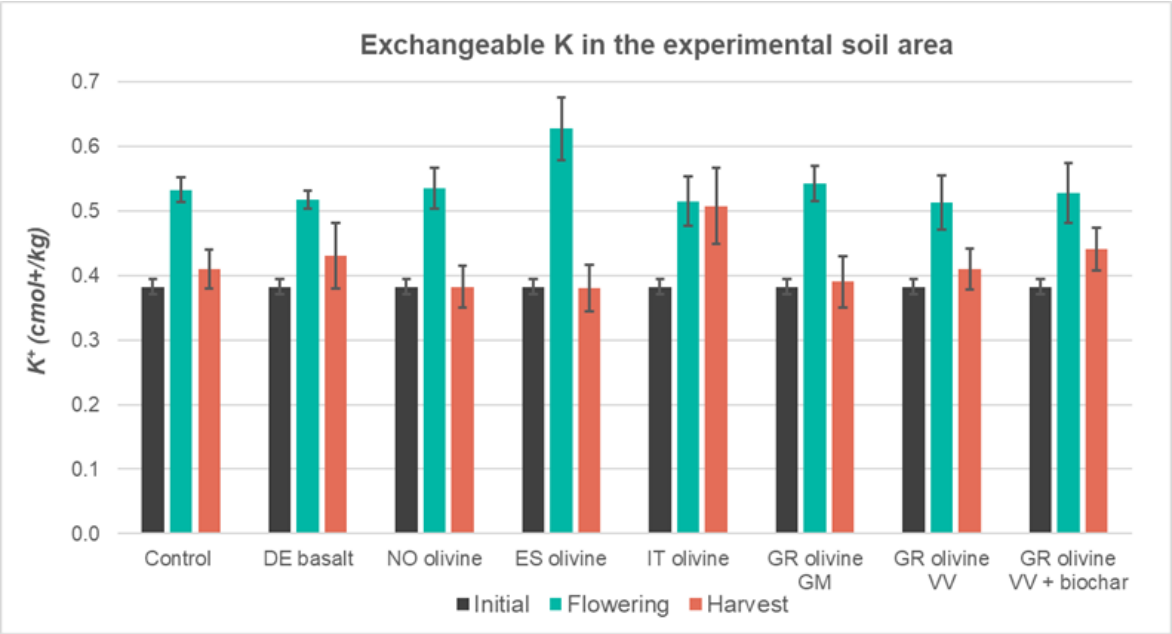


Figure 9.8. Average soil exchangeable K contents for the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

With the exception of the GR olivine VV treatment, **$CaCO_3$** soil contents are about **2-3% lower at harvest** time than earlier on in the season. Soil Cd contents also **decrease** in the period between flowering stage and harvest, whilst soil contents of **Cu** tend to **slightly increase**.

Soil concentrations of pseudo total **Ni** (Figure 9.9), **Pb and Zn** show a "concave" seasonal trend where an **increase** from **spring to summer** is **followed by** a **decrease** from summer to autumn. There is a slight negative correlation between soil pH on one hand and pseudo total Ni (R^2 = 0.49) and Zn (R^2 =

0.28) contents. This might suggest that these soil heavy metal contents are either influenced directly by pH, or by the same processes which govern the seasonal pH variation. The reason for these trends is unclear and should be further investigated. They could for example reflect lower soil pH in summertime, micronutrient plant uptake or other bio-chemical processes. Soil contents of pseudo total **Cr**, on the other hand, display a "convex" seasonal trend (Figure 9.10), often statistically significant, with an **initial decrease** in Cr contents **followed by** a **steady increase** from flowering to harvest. No correlation was observed between pH and pseudo total Cr contents of the soil.

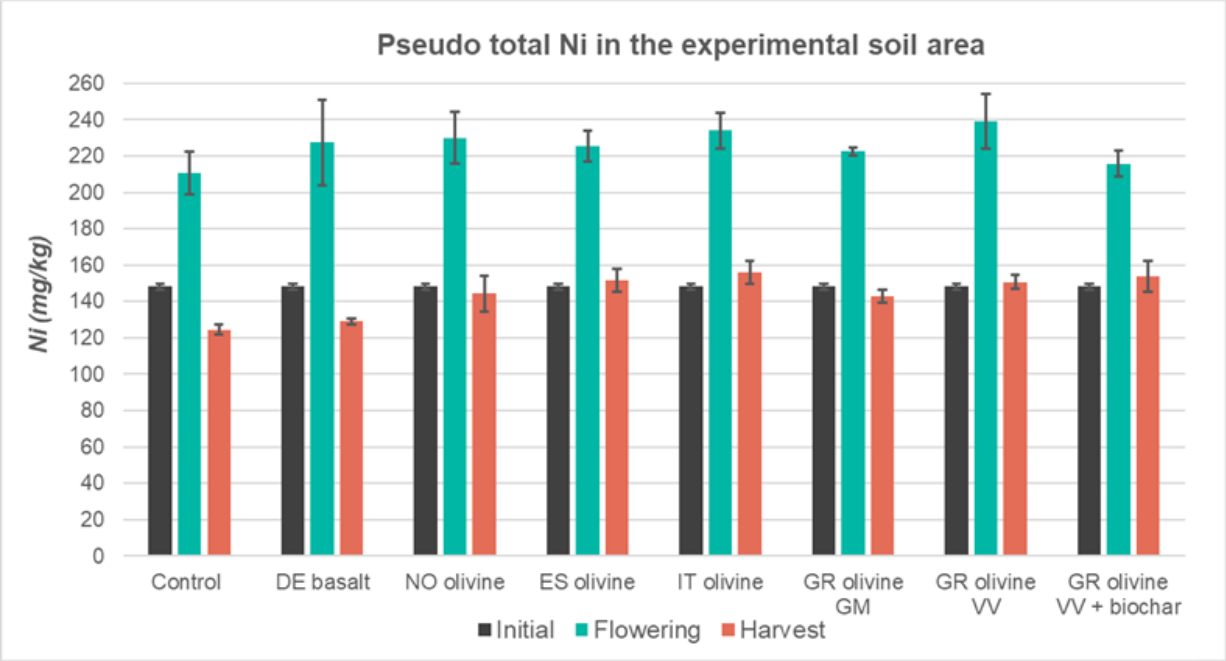


Figure 9.9. Average pseudo total nickel contents of the soil for the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

The overall trend of **continuously increasing** soil organic matter (**SOM**) is significant for most treatments, including the control. The reason for this soil parameter's increase throughout the season is the constant development and growth of the cotton's root zone.

Whereas **total nitrogen** seems to slightly increase towards the end of the season, **nitrate** soil contents suggest a concave seasonal trend with higher values during flowering as a result of the successive nitrogen fertilizations. However, these two soil parameters are the only ones whose seasonal variations are **not statistically significant** for **any** of the eight **treatments**.

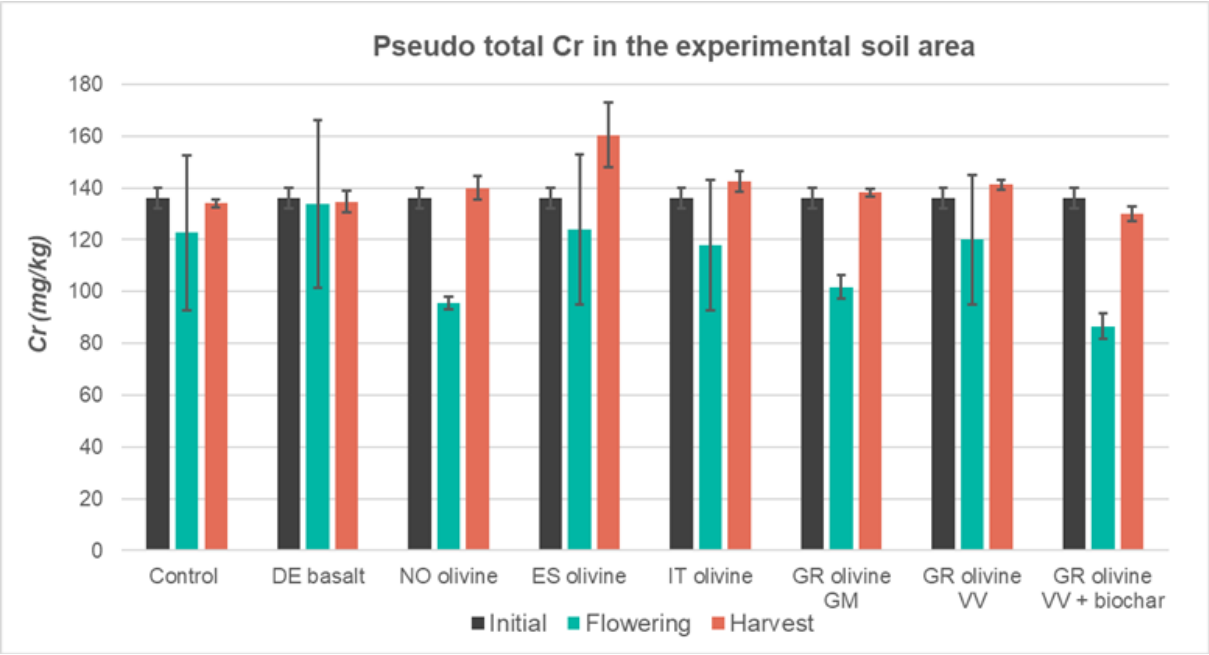


Figure 9.10. Average pseudo total chromium contents of the soil for the eight experimental treatments before rock dust application, during the flowering stage and before the harvest. Error bars represent the Standard Error over 4 replicates.

Most treatments show a significant seasonal variation for **extractable soil P** contents with an initial increase to **highest values at** the **flowering** stage followed by lower values at harvest.

Section summary

In contrast to the limited statistical variation of soil properties between different treatments, most of them do show significant differences throughout the growing season. These seasonal trends are often the same for all eight treatments, suggesting that they are not reflecting enhanced weathering of the added olivine rich rock dusts.

The clearest seasonal variability that is significant for all treatments is the lower pH during summer time. This might be due to nitrogen fertigation during the first part of the summer. A negative correlation between soil pH and pseudo total Ni and Zn might indicate that their seasonal variability is controlled by the same processes.

Macrorhizon soil water

We could carry out soil water samplings with the macrorhizons twelve times between 13 May and 31 August 2021. During this time, a number of macrorhizons broke, got destroyed by mammals or could (temporarily) not sustain any vacuum. Hence, we could not always collect (enough) soil solution from each one of the 32 experimental plots. As a result, a full statistical analysis is not possible for some parameters during particular sampling dates.

Table 9.8 presents the macrorhizon soil solution data after statistical treatment for each of the 12 sampling sessions. Average values are calculated for the replicates of each treatment to allow comparison of a specific water parameter between the treatments at a given time. The Anova test does not indicate any significant variability between the treatments for most of the parameters throughout the season. For those data in which a statistical difference was identified, we carried out a post hoc LSD test and represent the results in the table with a light blue background and **bold font**. The letter code is thereby as follows: treatments with the same letter for a certain soil water property are not significantly different for $p<0.05$. In a few cases, Anova suggested significant variability between treatments for a particular parameter but there were not enough data to carry out a post hoc LSD test. These data are indicated in orange-red.

Despite seemingly large differences in soil water parameter values, statistical analyses suggest that addition of the olivine rich rock dusts is generally not reflected in significant variability between treatments. The only parameter that does show statistical differences between treatments on more than two sampling occasions is the soil water's nickel concentration. Below we discuss the soil water data we obtained, describing both the few significant variabilities between treatments indicated in Table 9.8 as well as the variation of these parameters throughout the season.

Water volume: The total volume of soil water sampled from the 5 macrorhizons in each plot was recorded throughout the season, except for the first sampling on 13 May 2021, and is shown in Figure 9.11. The collected volume generally **varies between 10 and 80 mL**, with no water sampled at all for the DE basalt in the second sampling and as much as 135 mL collected for the ES olivine in the last sampling round. The changing success in soil water collected from the macrorhizons varies: (1) **From location to location** within the experimental area of the field due to soil heterogeneities and microtopography. (2) From one sampling date to the next due to **varying performance** of the **macrorhizons** – see zigzag patterns for individual treatments and (3) throughout the season – overall smallest volumes **late July to early August** when the summer heat and plant growth are highest, causing maximum **evapotranspiration**. The statistical difference between water volumes for two sampling dates (Table 9.8) is likely not of scientific significance but merely reflecting heterogeneous soil water sampling conditions in time and space.

Nevertheless, it is interesting that from DE basalt and NO olivine – the two rock powders with the finest grains - the lowest water volumes are collected throughout the season. The lower sample volumes obtained late July to early August made it impossible to measure the Ca^{2+}, Mg^{2+} and K^{+} concentrations at that time.

	Volume L	CO_3^{2-} µmol/L	HCO_3^{-} µmol/L	CA µmol/L	pH	EC µS/cm	Ca^{2+} µmol/L	K^{+} µmol/L	Mg^{2+} µmol/L	Ni µg/L	Cr µg/L
13-May-21											
Control		0.00	7331	7331	8.42	**982 ab**	1702	22.2	1742	2.49	1.44
DE basalt		0.00	4999	4999	8.51	**756 b**				5.34	1.62
NO olivine		0.00	7831	7831	8.52	**1099 ab**	1639	21.1	1987	7.38	2.48
ES olivine		0.00	6332	6332	8.47	**854 ab**	2056	31.7	1717	6.79	2.94
IT olivine		0.00	5249	5249	8.47	**828 ab**	1684	21.0	1424	1.63	1.82
GR olivine GM		0.00	7498	7498	8.48	**1130 a**	2247	40.4	2186	8.89	0.98
GR olivine VV		0.00	6248	6248	8.42	**877 ab**	2175	50.0	1607	1.91	2.11
GR-VV + biochar		0.00	6832	6832	8.37	**1001 ab**	2814	61.9	2092	13.42	0.67
11-Jun-21											
Control	43.75	0.00	6873	6873	8.28	1140	**1942 b**	**25.8 ab**	**2008 b**	**8.69 c**	4.87
DE basalt											
NO olivine	20.00	0.00	7165	7165	8.45	1123	**1536 b**	**22.8 ab**	**2028 b**	**6.86 c**	2.13
ES olivine	53.33	0.00	6998	6998	8.36	1070	**1977 b**	**21.5 ab**	**2053 b**	**4.24 c**	3.70
IT olivine	40.50	0.00	7373	7373	8.34	991	**1964 b**	**19.2 b**	**1834 b**	**11.74 b**	4.20
GR olivine GM	15.00	0.00	7248	7248	8.32	1009	**1796 b**	**24.6 ab**	**2016 b**	**10.84 b**	4.51
GR olivine VV	29.75	0.00	6373	6373	8.46	1038	**2093 b**	**35.0 ab**	**2147 b**	**38.02 ab**	10.27
GR-VV + biochar	20.00	0.00	7123	7123	8.32	1247	**2886 a**	**37.1 a**	**3308 a**	**44.04 a**	12.41
28-Jun-21											
Control	**48.75 ab**	0.00	4874	4874	8.15	**2129 a**	5278	56.9	2944	**7.46 ab**	3.76
DE basalt	**20 b**	0.00	4499	4499	7.92	**13678 b**	5094	46.8	2552	**11.70 ab**	6.45
NO olivine	**23.75 ab**	0.00	5499	5499	8.14	**1417 ab**	5287	97.7	3163	**4.24 b**	5.28
ES olivine	**80 a**	0.00	5374	5374	8.00	**1613 ab**	4769	46.2	3010	**2.63 b**	3.16
IT olivine	**50 ab**	0.00	5165	5165	8.06	**1502 ab**	4805	47.7	2314	**11.50**	7.25
GR olivine GM	**60 ab**	0.00	4999	4999	7.92	**1871 ab**	5843	63.1	3599	**3.45 b**	4.46
GR olivine VV	**46.25 ab**	0.00	5124	5124	8.09	**1630 ab**	5294	44.8	2368	**4.52 b**	5.47
GR-VV + biochar	**29.33 ab**	0.00	4749	4749	8.15	**1363 b**	3934	34.8	1876	**31.72 a**	5.71
05-Jul-21											
Control	59.25	250	3624	4124	8.20	1256	5457	25.5	**2048 ab**	25.59	3.01
DE basalt	18.33	917	2666	4499	8.13	1221	5621	43.1	**2348 a**	1.16	2.50
NO olivine	29.25	250	3624	4124	8.20	1280	4791	26.9	**2315 a**	1.11	3.18
ES olivine	76.25	500	3832	4832	8.25	1249	4710	21.9	**2033 ab**	5.55	2.61
IT olivine	58.33	0	3832	3832	8.20	1282	4348	33.4	**2307 a**	4.02	3.20
GR olivine GM	40.00	0	4249	4249	8.25	1291	4591	33.0	**2076 ab**	2.13	3.21
GR olivine VV	47.50	0	3749	3749	8.20	1272	4473	26.8	**1626 bc**	22.48	4.51
GR-VV + biochar	28.75	0	3749	3749	8.13	1617	3824	35.2	**1401 c**	7.50	2.94

Table 9.8. Average values of the different soil solution properties measured in the macrorhizon water samples for each of the 12 sampling sessions. The same letter for different treatments in a vertical light blue column shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test

	Volume L	CO_3^{2-} µmol/L	HCO_3^- µmol/L	CA µmol/L	pH	EC µS/cm	Ca^{2+} µmol/L	K^+ µmol/L	Mg^{2+} µmol/L	Ni µg/L	Cr µg/L
12-Jul-21											
Control	**80 a**	0	5265	5265	8.14	1184	2417	30.8	2066	13.51	**4.44 ab**
DE basalt	**26.25 ab**	250	4524	5024	8.12	1018	2268	55.8	4909	9.01	**2.72 b**
NO olivine	**22 ab**	333	4166	4832	8.16	998	1948	31.5	1776	8.64	**4.02 ab**
ES olivine	**76.25 ab**	250	6123	6623	8.24	1131	2282	23.4	2115	10.15	**4.03 ab**
IT olivine	**41.25 ab**	250	5074	5574	8.29	1078	2150	36.7	1997	7.84	**5.16 ab**
GR olivine GM	**42.5 ab**	250	4899	5399	8.30	1120	2157	33.6	1812	9.60	**5.16 ab**
GR olivine VV	**40 ab**	0	4665	4665	8.23	1028	2455	28.1	2098	21.35	**15.94 a**
GR-VV + biochar	**13.25 b**	667	4999	6332	8.25	1188	2181	33.8	1810	19.55	**3.06 b**
14-Jul-21											
Control	75.00	0	5798	5798	8.09	1223	2226	26.0	1949	**5.30 ab**	3.33
DE basalt	27.50	1000	4499	6499	8.18	1231	1950	27.1	1669	**3.05 b**	2.84
NO olivine	16.67	1666	5665	8998		1251	1723	18.2	1803	**3.64 b**	4.00
ES olivine	58.25	250	6798	7298	8.11	1281	1892	24.0	1814	**1.72 b**	3.10
IT olivine	43.75	333	5932	6598	8.05	1214	2225	22.6	2041	**2.55 b**	3.82
GR olivine GM	47.50	250	5898	6398	8.22	1276	2224	34.8	1978	**9.10 ab**	3.70
GR olivine VV	55.00	333	5399	6065	8.18	1169	2200	32.2	1925	**1.92 b**	2.95
GR-VV + biochar	19.50	1000	6498	8498		1287	2362	33.8	2080	**12.06 a**	2.70
29-Jul-21											
Control	57.50	0	7448	7448	8.00	1302	1937	21.0	2532	3.53	2.04
DE basalt	25.00	0	4999	4999	8.08	1429	1958	27.0	2357	9.29	2.18
NO olivine	20.00	0	5998	5998		1841	2445	22.0	3904	64.19	2.42
ES olivine	36.25	500	5599	6598	8.20	1424	2136	18.4	2865	6.09	2.58
IT olivine	23.50	0	6498	6498	8.18	1240	1878	17.9	2246	6.65	2.29
GR olivine GM	27.50	0	4499	4499	8.16	1358	2234	24.9	2488	15.52	3.45
GR olivine VV	25.00	0	5499	5499	8.12	1230	1680	32.0	1848	11.70	2.60
GR-VV + biochar	35.00	0	5998	5998	8.14	1187	1644	33.0	1767	22.69	2.00
06-Aug-21											
Control	51.00	0	4932	4932	7.86	1535				51.85	11.22
DE basalt	11.33	0	3999	3999	8.22	1407				12.91	3.71
NO olivine	16.67	0	3332	3332	8.19	1420				26.50	6.34
ES olivine	21.25	500	4499	5499	8.21	1417				11.35	4.09
IT olivine	30.00	667	5332	6665	8.13	1380				11.97	5.91
GR olivine GM	25.00	0	5665	5665	8.12	1548				19.66	5.25
GR olivine VV	55.00	0	6198	6198	8.06	1439				10.07	5.32
GR-VV + biochar	30.00	0	4999	4999	8.17	1574				28.54	4.61

Table 9.8. Continued. Average values of the different soil solution properties measured in the macrorhizon water samples for each of the 12 sampling sessions. The same letter for different treatments in a vertical light blue column shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test.

	Volume L	CO_3^{2-} µmol/L	HCO_3^- µmol/L	CA µmol/L	pH	EC µS/cm	Ca^{2+} µmol/L	K^+ µmol/L	Mg^{2+} µmol/L	Ni µg/L	Cr µg/L
12-Aug-21											
Control	80.00	0.00	5399	5399	7.91	1398	2271	21.0	2375	5.13	2.38
DE basalt	30.00	0.00	5499	5499	7.89	1632	2426	12.0	3042	15.08	2.81
NO olivine	23.33	0.00	4999	4999	8.12	1620	2146	21.0	2117	8.40	3.40
ES olivine	31.25	0.00	5748	5748	8.16	1405	2200	11.9	2539	6.31	3.76
IT olivine	12.50				8.17	1532				5.17	3.67
GR olivine GM	16.25	0.00	5998	5998	8.31	1369	2173	24.3	2287	19.84	4.77
GR olivine VV	50.00	0.00	6998	6998	8.17	1491	2289	14.1	2699	8.48	3.93
GR-VV + biochar	50.00	0.00	5499	5499	8.20	1308	1802	16.4	2100	17.44	2.25
19-Aug-21											
Control	26.67	0	2999	2999	8.11	1476	2478		2653	**8.75 b**	3.11
DE basalt	20.00	0	4999	4999	8.11	1660	2363		2886	**7.18 b**	2.64
NO olivine	12.50	1500	3499	6499	8.29	1422				**12.26 ab**	3.90
ES olivine	53.75	0	4499	4499	8.07	1448	2263		2443	**8.82 b**	3.55
IT olivine	40.00	1000	4665	6665	8.21	1339	2119		2154	**5.88 b**	3.43
GR olivine GM	15.00	1500	2499	5499	8.31	1204	1772		1590	**15.41 ab**	2.91
GR olivine VV	45.00	0	5465	5465	8.17	1361	2089		2216	**5.47 b**	3.04
GR-VV + biochar	25.00	1500	4999	7998	8.23	1483	2060		2325	**30.12 a**	3.09
25-Aug-21											
Control	27.50	1000	3499	5499	8.35	1410	2783	13.3	2785	**5.87 b**	3.95
DE basalt	15.00	1333	2999	5666	8.29	1246	2313	2.3	2898	**6.67 b**	4.15
NO olivine	10.75	2000	3749	7748	8.26	1480	2035	0.0	2810	**11.16 ab**	4.24
ES olivine	37.50	500	3949	4949	8.34	1350	2252	8.4	2311	**5.80 b**	3.85
IT olivine	41.25	1900	4249	8048	8.37	1433	2357	8.4	2278	**5.14 b**	4.28
GR olivine GM	25.00	667	3666	4999	8.23	1326	2094	14.3	1897	**12.64 ab**	2.90
GR olivine VV	31.67	1000	4665	6665	8.29	1308	2013	8.4	2046	**4.55 b**	3.25
GR-VV + biochar	31.67	667	4399	5732	8.30	1245	2114	18.2	2078	**20.17 a**	3.18
31-Aug-21											
Control	37.75	0	6058	6058	8.13	1349	2071	19.7	2138	17.48	6.38
DE basalt	26.67	0	6748	6748	8.15	1368	1857	12.3	2418	10.53	8.46
NO olivine	28.33	500	6748	7748	8.43	1575	2169	14.5	2693	6.90	2.90
ES olivine	135.00	375	6198	6948	8.22	1407	2056	15.5	2324	6.29	2.84
IT olivine	63.75	1000	6123	8123	8.35	1412	2289	15.5	2377	4.66	3.13
GR olivine GM	24.50	1000	5998	7998	8.32	1354	2040	43.5	1956	8.74	2.15
GR olivine VV	35.25	833	6298	7965	8.30	1306	2103	19.4	2281	6.82	2.79
GR-VV + biochar	37.50	750	7098	8598	8.28	1412	1944	20.6	2044	20.14	58.65

Table 9.8. Continued. Average values of the different soil solution properties measured in the macrorhizon water samples for each of the 12 sampling sessions. The same letter for different treatments in a vertical light blue column shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test.

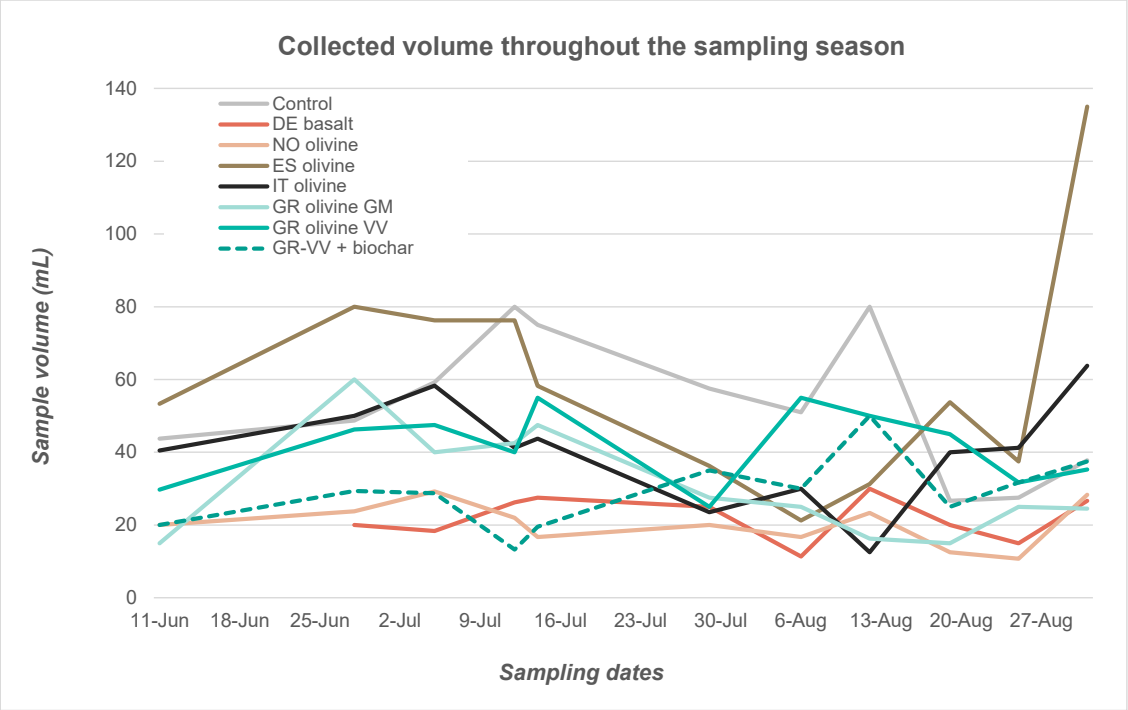


Figure 9.11. Average volume of soil water collected for each of the 8 experimental treatments throughout the eleven last sampling sessions.

Carbonates (CO_3^{2-}): The concentration of carbonate ions did **not** show **significant variability between** the different **treatments** in any of the sampling sessions (Table 9.8). In the first few samplings, no carbonate ions were detected in any of the soil solutions. **From early July, some** of the treatments' soil water chemistry includes **carbonate anions** (figure 9.12). Carbonate concentrations generally went down again in the first part of August but then peaked again in the second part of the same month. As the control water composition is showing the same pattern, this carbonate concentration trend is not likely to reflect dissolution of the added rock dusts.

Bicarbonates (HCO_3^-): Bicarbonate ion concentrations also do **not** show any **statistical differences between** the **treatments** (Table 9.8). They show roughly the same seasonal trend for all eight treatments which is complementary to the observed carbonate pattern (Figure 9.13). Higher **bicarbonate concentrations** observed in all treatments from the start **drop** from **early July** and partially recover again in a peak towards the end of July and in late August.

Carbonate Alkalinity (CA): As carbonate alkalinity was calculated from the measured carbonate and bicarbonate concentrations, this parameter showed the same general trend as the previous two: no significant difference between treatments at any sampling session (Table 9.8) and somewhat lower values in the first part of July and of August.

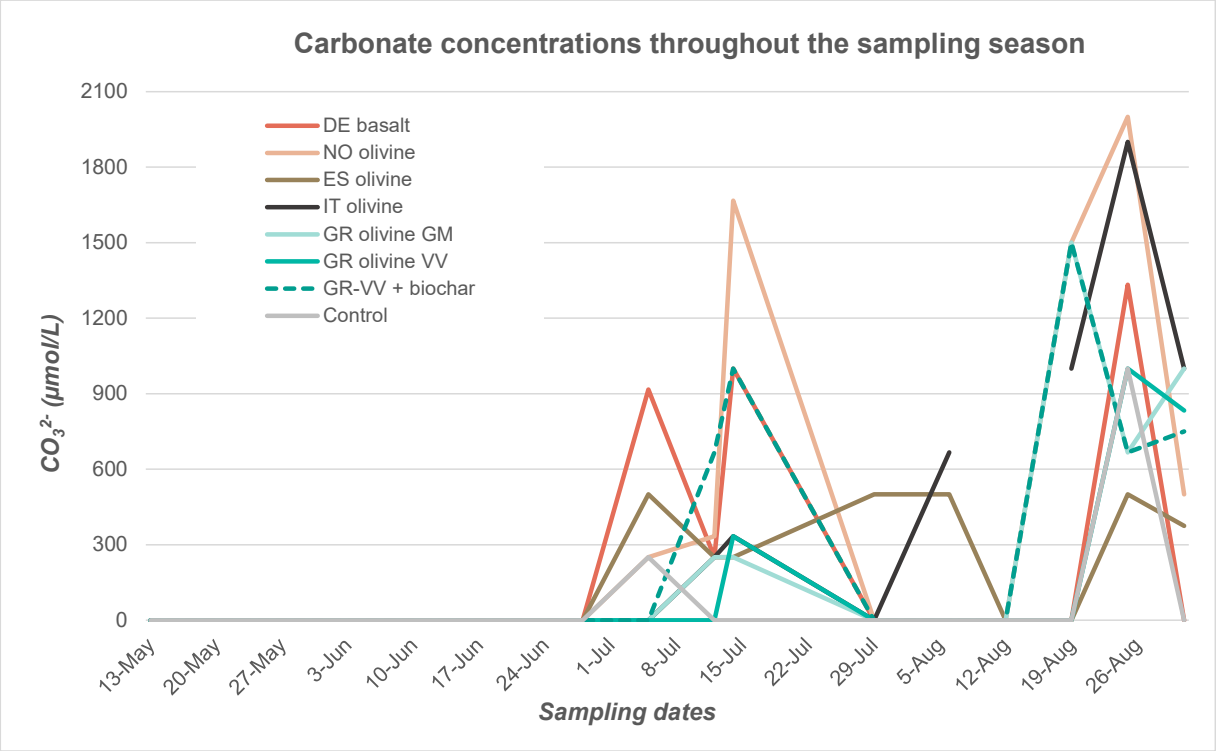


Figure 9.12. Average carbonate concentrations of soil water collected for each of the 8 experimental treatments throughout the sampling season.

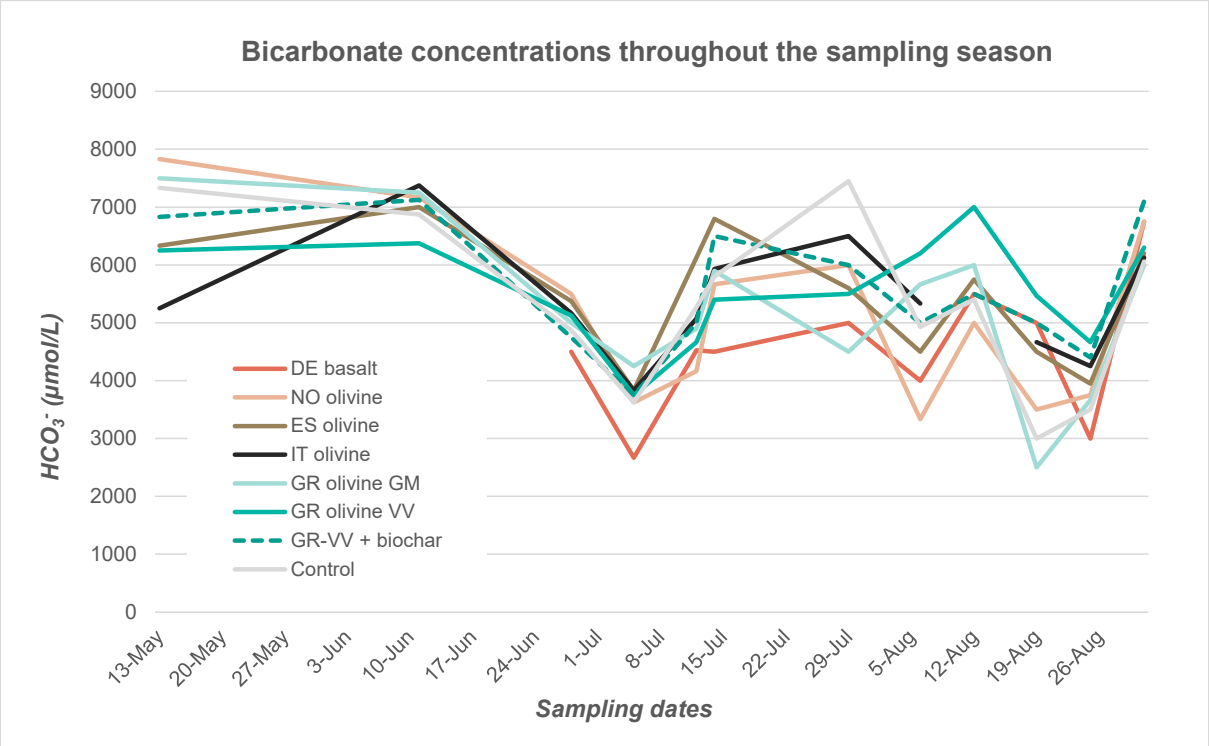


Figure 9.13. Average bicarbonate concentrations of soil water collected for each of the 8 experimental treatments throughout the sampling season.

pH: The pH of the soil solution was **alkaline** in all treatments and throughout the sampling season, ranging from **7.86 to 8.52**. Despite the variability of this parameter, there is **no statistically significant difference between** the eight **treatments** (Table 9.8). Overall, the **seasonal trend** of the pH seems quite similar to that of the bicarbonate anions (Figure 9.15 and 9.13, respectively) and hence somewhat inverse to the carbonate concentration pattern. This is no surprise as the speciation of CO_2 dissolved in an aqueous solution depends on the latter's pH.

Figure 9.14 shows an example of the relationship between pH and the speciation of CO_2 as dissolved gas, bicarbonates and carbonates calculated at a temperature of 20°C and electrical conductivity of 250 µS/cm. It shows that with changing pH a decline in bicarbonates goes hand in hand with an increase in carbonates, as can be observed in our data. The variation of soil water pH throughout the sampling season itself is unlikely linked to enhanced weathering as it is the same for all treatments including the control. The seasonal variability possibly reflects changes in **evapotranspiration** and **addition of nitrogen fertilizer** from **mid June to mid July**. It is worth noting that these high pH values also affect the solubility and availability of nutrients such as phosphate ions in a similar way. At pH values below 6.5 phosphate ions are bound by Al compounds whereas at higher pH phosphate ions are bound by Ca compounds (Pierzinsky et al., 2005). At pH values greater than 8.0, the concentration of $H_2PO_4^-$ ions decreases up to zero and the concentration of HPO_4^{2-} ions increases. The solubility, and therefore availability, of phosphate ions is higher at pH values around 6.5. The high pH values measured in our soil solutions hence indicate significantly reduced availability of phosphorus.

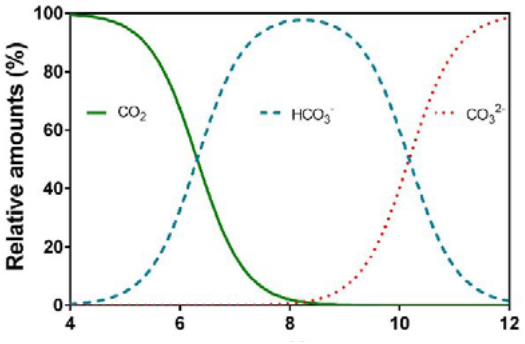


Figure 9.14. Relative speciation (%) of carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) in water as a function of pH. The example given is at 20°C and electrical conductivity of 250µS/cm. Pedersen et al., 2013.

Ca^{2+}, Mg^{2+} and K^+: The soil water concentrations of the basic cations of calcium, magnesium and potassium generally do **not** show **statistically significant variability** between the **different treatments**. The one **exception** is observed in the 2nd sampling on **11 June** where the concentration of all three cations is by far **highest** in the **Greek olivine treatment with biochar** (Table 9.8). Curiously, in the following weeks the Ca^{2+}, Mg^{2+} and K^+ concentrations of the other 7 treatments increase more quickly than those of the treatment including biochar (Figures 9.16, 9.17 and 9.18). Hence, by **5 July** the roles have reversed and the **biochar** treatment now has the **lowest** concentrations of these cations, even significantly so for magnesium.

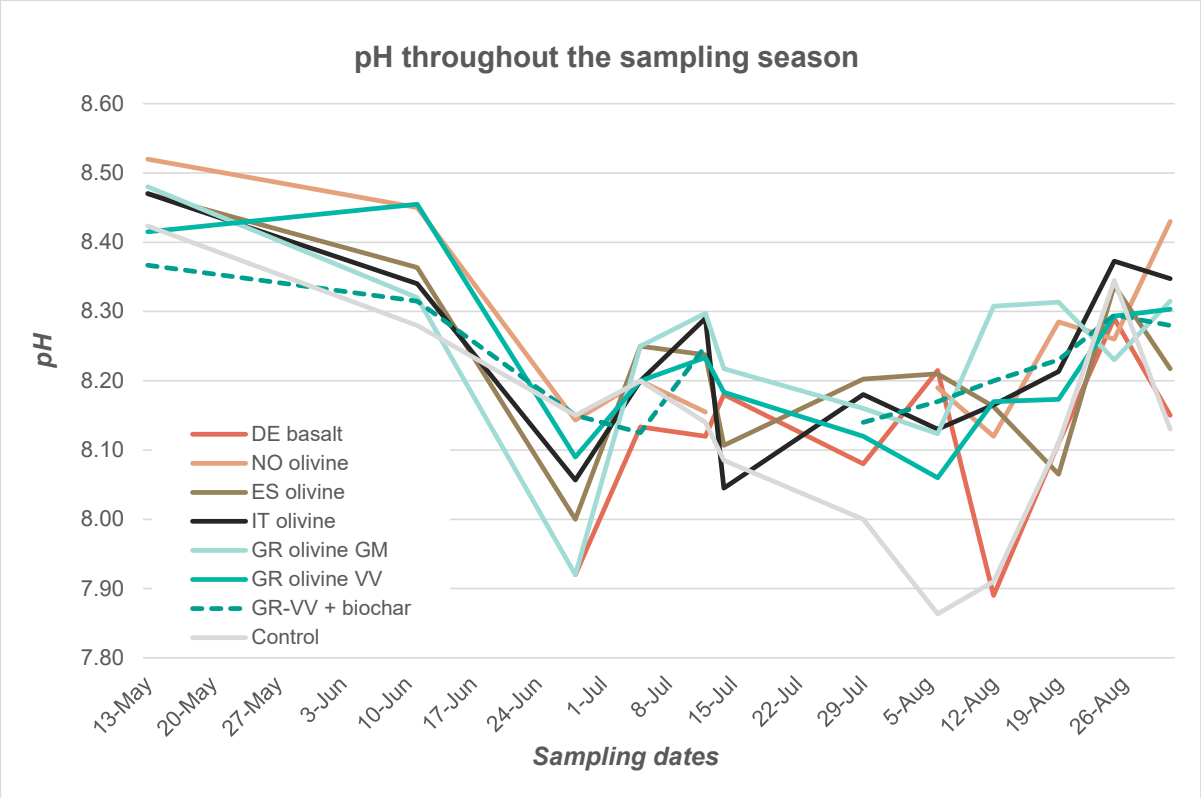


Figure 9.15. Average pH values of the soil water collected for each of the 8 experimental treatments throughout the sampling season.

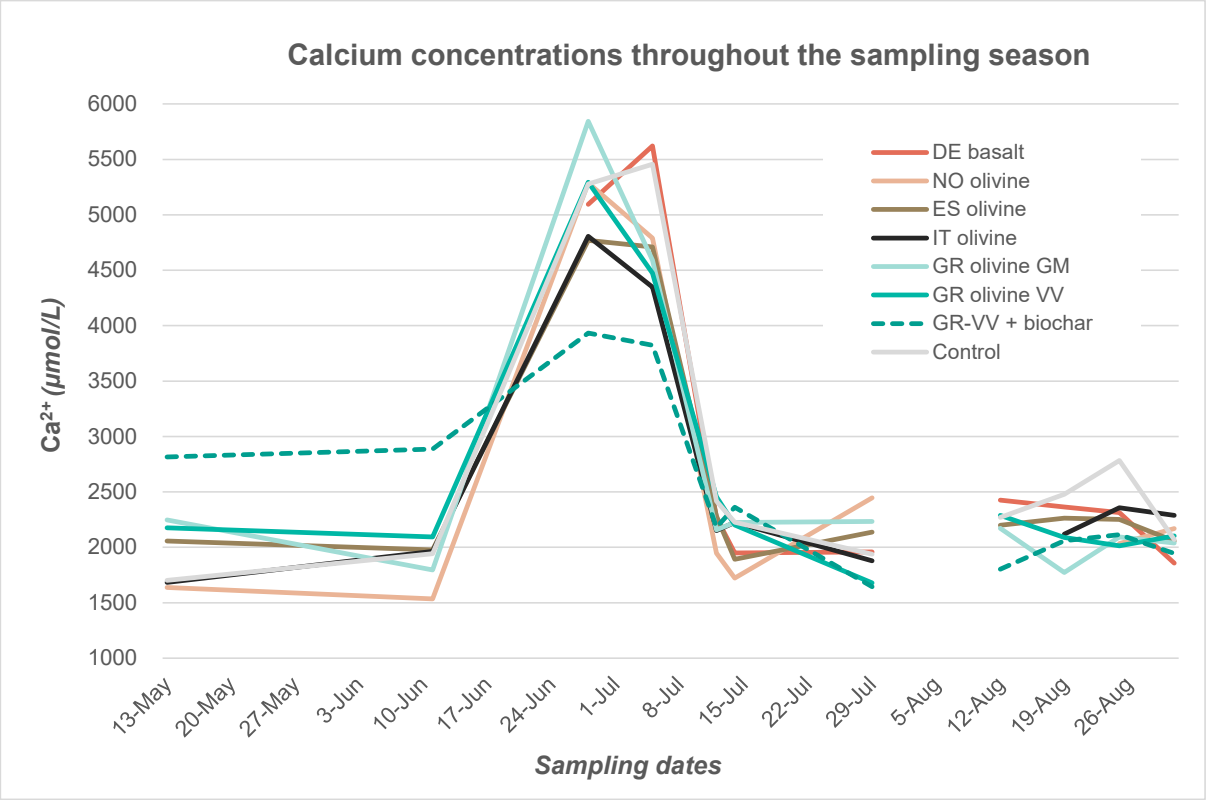


Figure 9.16. Average calcium cation concentrations in the soil water collected for each of the 8 experimental treatments throughout the sampling season.

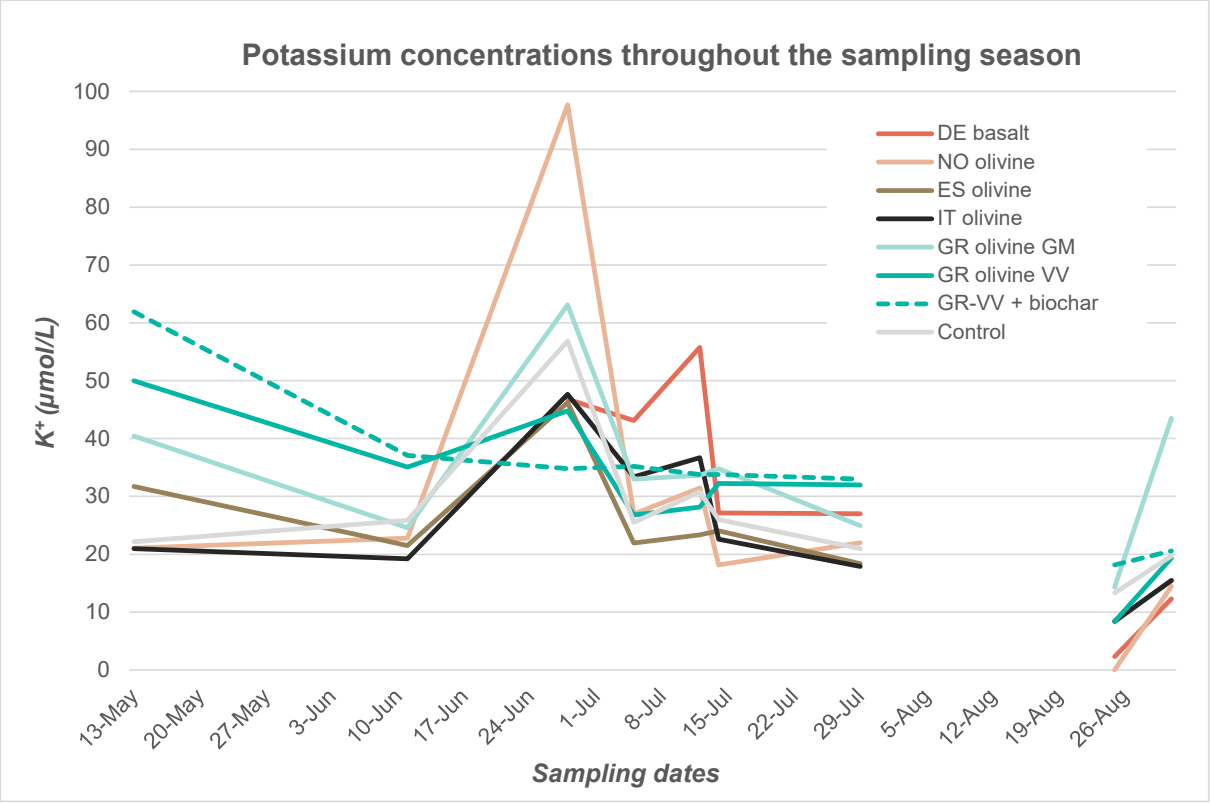


Figure 9.17. Average potassium cation concentrations in the soil water collected for each of the 8 experimental treatments throughout the sampling season.

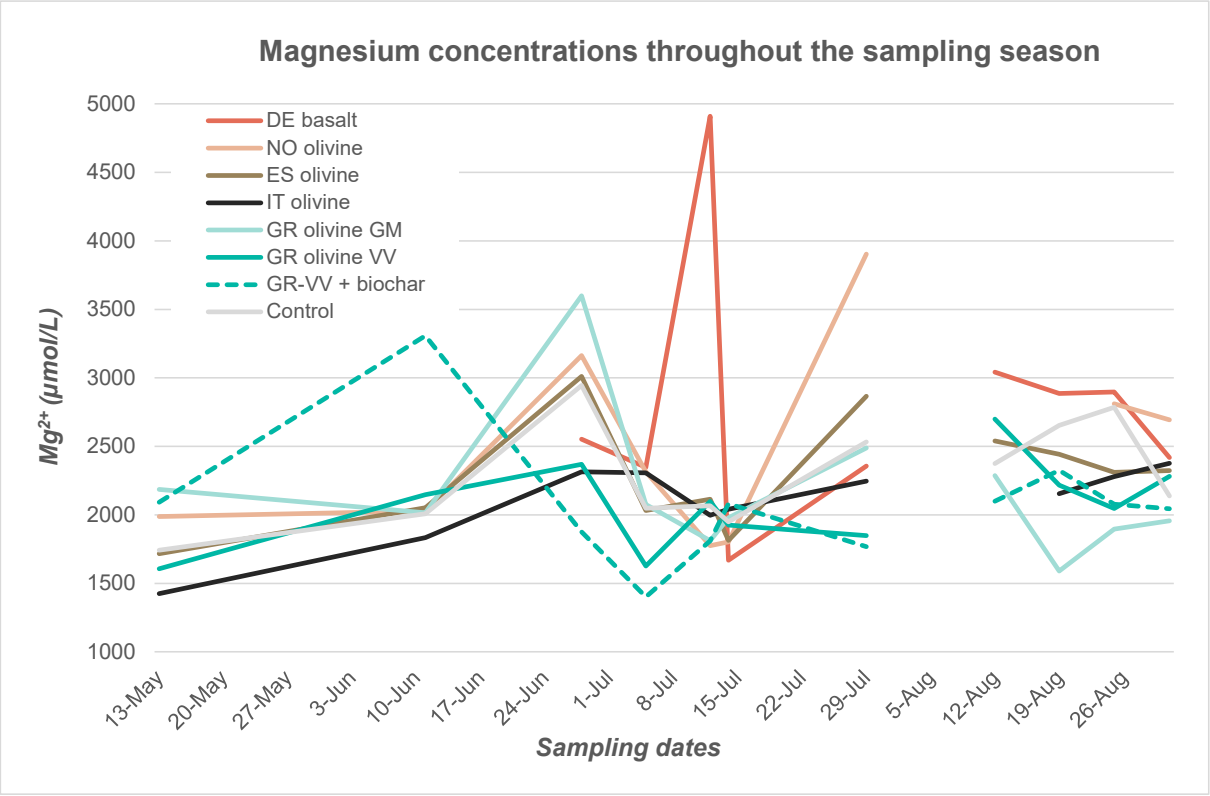


Figure 9.18. Average magnesium cation concentrations in the soil water collected for each of the 8 experimental treatments throughout the sampling season.

This general cation trend is most obvious for Ca^{2+} and coincides in time with the nitrogen fertiliser addition to the irrigation water. The fertigation thus seems to temporarily decrease the pH, leading to dissolution of the $CaCO_3$ and subsequent increase in Ca^{2+} ions. Another possible way through which fertigation with urea could influence the calcium contents of the soil water is that the added NH^{4+} exchanged with adsorbed Ca^{2+}, releasing the Ca^{2+} in solution. The distinctly different trend for the biochar treatment during this period of time suggest that whilst equilibrating to this new chemical environment, the biochar holds on more strongly to these three plant nutrients.

Electrical conductivity (EC): Only **early** on **in the season** is there some statistical difference between treatments (Table 9.8). Mid May the highest EC for the Greek olivine rich rock dust GM treatment is significantly different for the **lowest EC** observed in the **DE basalt** treatment. At the end of July, the still lowest EC of the DE basalt is statistically different from the highest value which is now observed in the control.

Overall, the electrical conductivity of the soil solution shows an increase from the start of the season (700-1100 µS/cm) to harvest time (1200-1550 µS/cm). The control treatment thereby falls within the EC values of the olivine rich rock dust additions, suggesting that there is no significant variability between different treatments (Figure 9. 19). The **generally increasing trend** of EC **throughout** the cotton **season** is somewhat disturbed from mid-June to early July. Knowing that electrical conductivity reflects the amount of cations and anions in the soil solution, this might be linked to the increase of basic cations during the fertigation period.

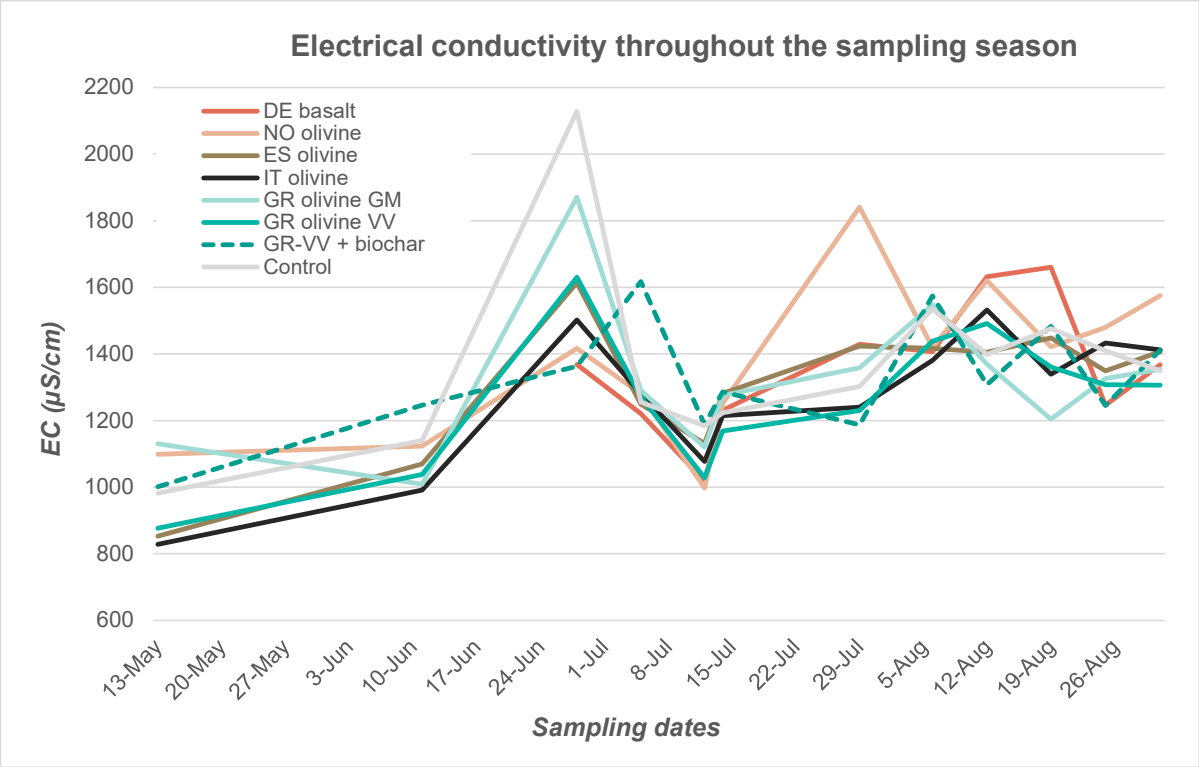


Figure 9.19. Average electrical conductivity of the soil water collected for each of the 8 experimental treatments throughout the sampling season.

Heavy metals **Ni and Cr**: The soil water parameter showing statistically **significant differences** between treatments in most sampling sessions is **Ni** concentration (Table 9.20). This heavy metal is present in distinctly **higher concentrations** in the Greek olivine with **biochar treatment**, from mid-May to late June and again from mid-August onward (Figure 9.20). Ni concentrations for the biochar treatment range from 12.1 to 44.0 µg/L. Interestingly, whereas the Ni concentration in the Control is usually rather low, it shows two peak values of 25.6 and 51.9 µg/L which are distinctly higher than the biochar treatment concentrations at those two respective times. Similarly, the overall rather low Ni contents observed in the NO olivine treatments have one peak value that represents the overall highest observed Ni concentration (64.2 µg/L).

The biochar treatment also has higher **Cr concentrations** at the start and end of the season, but the **variability between treatments** is generally **not statistically significant** for this soil water property (Figure 9.21). The only significant difference was observed in the 5th sampling where the highest concentration was found in the treatment Greek olivine rock dust from Vitruvit (15.9 µg/L) and the lowest Cr amounts where in the treatments DE basalt (2.72 µg/L) and Greek olivine with biochar (3.06 µg Cr/L) (Table 9.8). The by far **highest Cr** concentrations recorded in soil water during this season, however, was during the last sampling in the **biochar treatment** (58.6 µg/L) (Figure 9.21). Amann et al. (2018) published similar increases of Ni and Cr concentrations in the aqueous solutions from EW pot experiments with olivine.

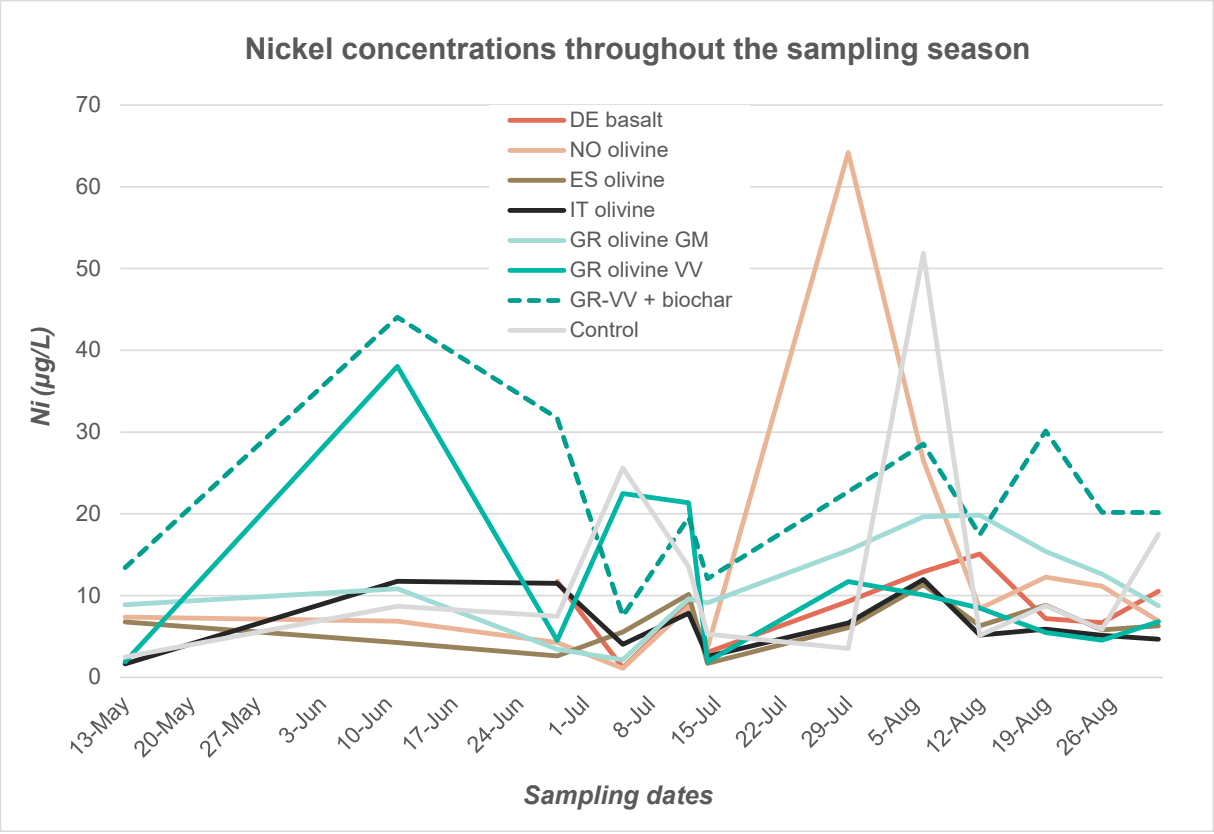


Figure 9.20. Average nickel concentrations measured in the soil water collected for each of the 8 experimental treatments throughout the sampling season.

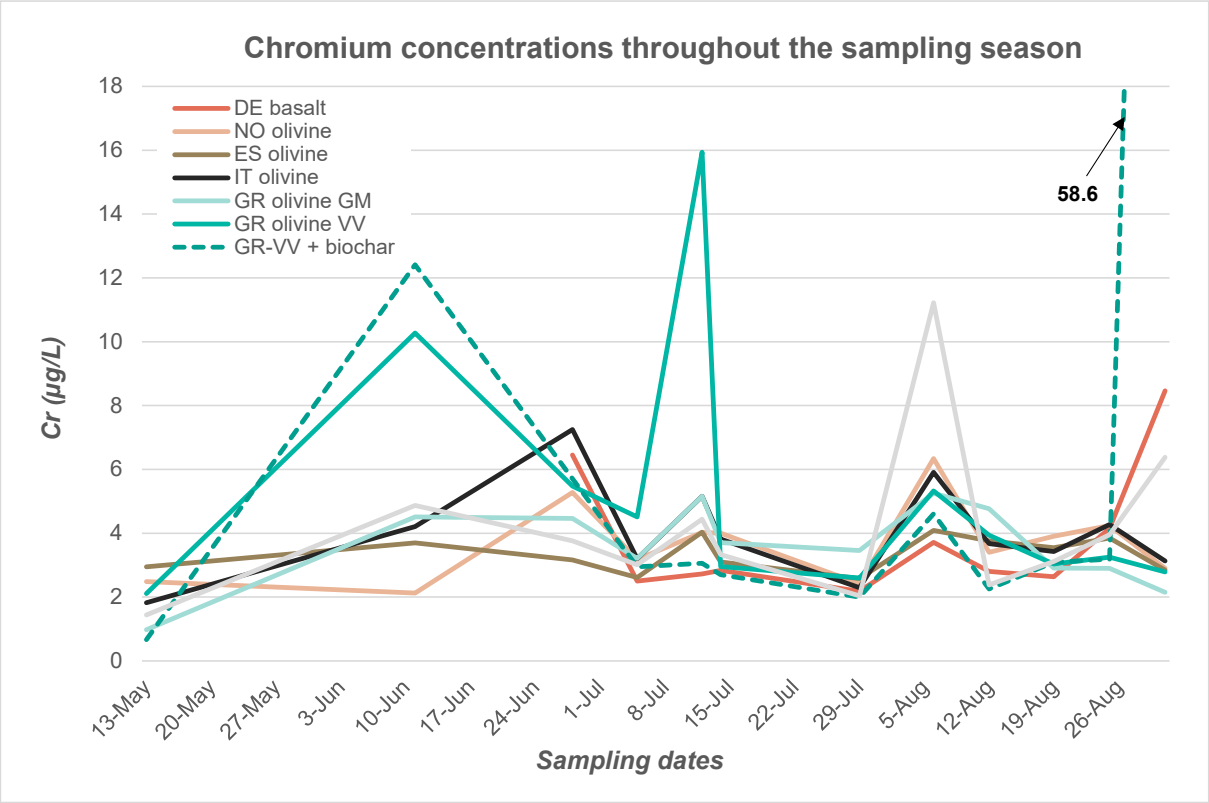


Figure 9.21. Average chromium concentrations measured in the soil water collected for each of the 8 experimental treatments throughout the sampling season.

The seemingly higher Ni and Cr contents in soil water collected from the treatment with Greek olivine rich rock dust and biochar are rather surprising. One of the reasons to test the biochar was its potential role as a heavy metal sink, adsorbing Ni and Cr cations that are released upon olivine dissolution.

Section summary

The soil water properties generally show little to no statistically significant variability between the eight different treatments within a single sampling session.

Mid-June the treatment of Greek olivine with biochar had distinct Ca^{2+}, Mg^{2+} and K^{+} concentrations that were significantly higher than the other seven treatments. A few weeks later, however, this trend had reversed and the biochar treatment had the lowest cation contents, reflected in a significantly different EC.

The same treatment of Greek olivine with biochar shows significantly different Ni concentrations, with the overall highest values, on a number of occasions. The by far highest Cr level is also recorded in the biochar treatment at the end of the season. This is contrary to what we expected the effect of the biochar addition would be on the soil water heavy metal contents.

Seasonal variability observed for pH, CO_3^{2-}, HCO_3^{-}, EC, Ca^{2+}, Mg^{2+} and K^{+} across all eight treatments is likely reflecting changes in soil chemistry due to addition of fertilizer and variation in evapotranspiration.

Lysimeter soil water

As we only had one lysimeter for each of the eight treatments, **no statistical analysis** can be carried out on these soil water data. Interpretation of the soil solution chemistry collected from the lysimeters is further complicated by the **few samples** we could collect throughout the season. The drip irrigation system could not be incorporated within the lysimeters (it would flood them) so their only water input was from the rainfall that occurred at the start and end of the season.

After installation on 28 April, we collected water from the lysimeters on 22 July for six of the eight treatments. We could not sample any water accumulated throughout the first 3 months of the experiment for the ES olivine and GR olivine VV treatments. Two months later, we did a second and last lysimeter water collection but due to the hot and dry weather there was only water from three treatments. Control and GR olivine GM are thereby the only treatments for which we could collect lysimeter soil water at both sampling sessions. Table 9.9 presents the results of the analyses of the lysimeter water samples.

	Vol. (mL)	CO_3^{2-} (µmol/L)	HCO_3^- (µmol/L)	CA (µmol/L)	pH	EC (µS/cm)	Ca^{2+} (µmol/L)	K^+ (µmol/L)	Mg^{2+} (µmol/L)	Ni (µg/L)	Cr (µg/L)
22-Jul-21											
Control	40	1000	2999	4999	8.19	291	436	38	134	8.23	2.01
DE Basalt	20						219	79	165	9.99	3.52
IT olivine	40	1000	1000	2999	8.10	288	493	26	123	7.54	0.93
GR olivine GM	500	100	4299	4499	7.88	1161	1517	44	189	11.86	2.12
GR-VV + biochar	150	200	1800	2199	7.92	1768	2639	22	3613	280.74	1.99
21-Sep-21											
Control	150	400	1800	2599	7.98	1873				14.67	1.99
ES olivine	150	400	1900	2699	8.13	1670				8.60	1.27
GR olivine GM	350	400	3299	4099	8.2	1252				8.01	1.85

Table 9.9. Soil solution data for the water samples collected from the lysimeters. No statistical analysis could be carried out due to the limited number of samples.

When trying to interpret these lysimeter water data it is important to keep in mind the **different environment** they are collected from **compared to** the **macrorhizon water** data: (1) No irrigation water from early June to late August also means no nitrogen fertilizer was added. (2) The absence of cotton plants within the lysimeters means that no enhancement of rock dust weathering through plant roots and associated micro-organisms could take place.

Table 9.9 suggests there is no correlation between the collected **water volume** and the different soil water properties. Comparison of the **bicarbonate** (Figure 9.22) and TA data of the lysimeter water with the values observed in the macrorhizon water around the same time shows a similar variability between treatments but distinctly lower concentrations in the lysimeter water.

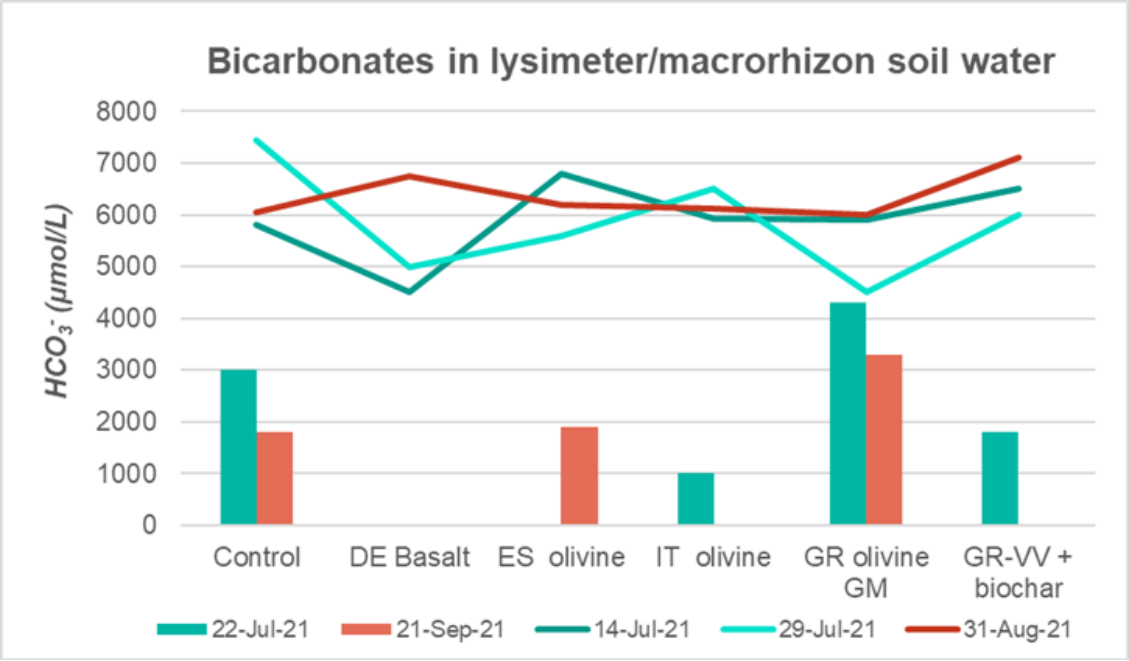


Figure 9.22. Bicarbonate concentration in the soil water collected from lysimeters (bars) and macrorhizons (lines) observed around similar times

The **pH** (Figure 9.23) and carbonate concentrations observed in the lysimeter water seem to be within the same range as those in the macrorhizon soil solutions. It has to be pointed out, however, that pH is a logarithmic property meaning that a pH decrease of 0.1 reflects a 30% increase in H^+ concentration.

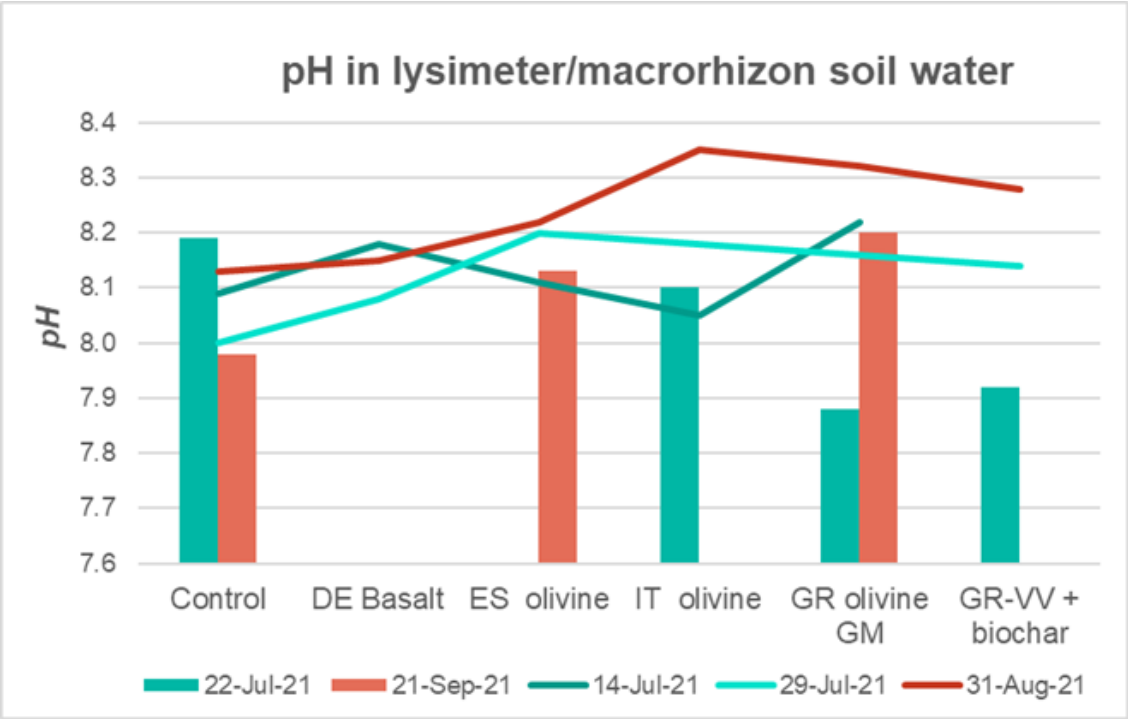


Figure 9.23. pH values in the soil water collected from lysimeters (bars) and macrorhizons (lines) observed around similar times.

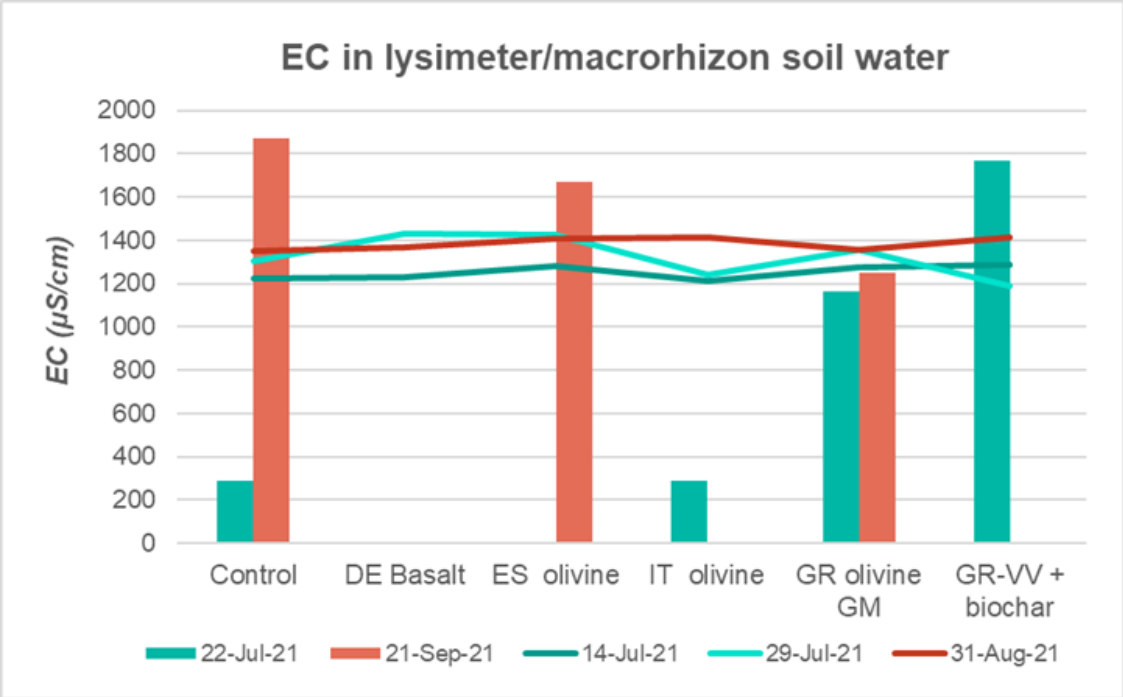


Figure 9.24. EC values in the soil water collected from lysimeters (bars) and macrorhizons (lines) observed around similar times.

Compared to the values observed in the macrorhizon water, the **electrical conductivity** of the lysimeter water shows **much** more **variability** (Figure 9.24). Whereas the EC of macrorhizon water ranges from 1200 to 1400 µS/cm **across treatments and time**, values in the lysimeter water have ranges of 300-1850 µS/cm and 1250-1850 µS/cm for the first and second samplings, respectively. Within one treatment, the control thereby shows the maximum variability between the two samplings whereas the GR olivine GM values are close to the macrorhizon range on both occasions.

Electrical conductivity is a measure of the amount of **cations** and anions present in the soil water. The Mg^{2+}, Ca^{2+} and K^{+} data for the first lysimeter sampling on 22 July seem to suggest that the EC values of the lysimeter water are largely representing its Ca^{2+} concentrations (Figure 9.25). Potassium cation contents are rather low for all treatments and **significant amounts of Mg^{2+}** were only recorded in the GR olivine VV + **biochar treatment**. K^{+} contents in the lysimeter water samples is similar to those in the macrorhizon water sampled at the same time. The only exception is the **DE basalt** which has **higher K^{+}** which might reflect dissolution of this particular rock dust's K-containing minerals. Apart from the high values observed in the biochar treatment, **Mg^{2+} contents** are much **lower** in the **lysimeter** soil solution **than** in the **macrorhizon** water. Ca^{2+} concentrations from the lysimeter samples show a large variability (10-105 mg/L) compared to the values observed in macrorhizon water at the same time (80-90 mg/L).

Overall, **heavy metal** contents observed in the **lysimeter samples** are **similar** to slightly lower than the ones in the **macrorhizon** water (Ni: 7-15 µg/L, Cr:1-3.5

µg/L, Figures 9.20 and 9.21 respectively). This is well below the drinking water limits for Ni which the Environmental Protection Agency (EPA) in the US sets to 100µg/L and the World Health Organization (WHO) to 70µg/L. The only exception is the **extremely high nickel** concentration of 281 µg/L observed after three months in the Greek olivine treatment that also includes **biochar** (Figure 9.26).

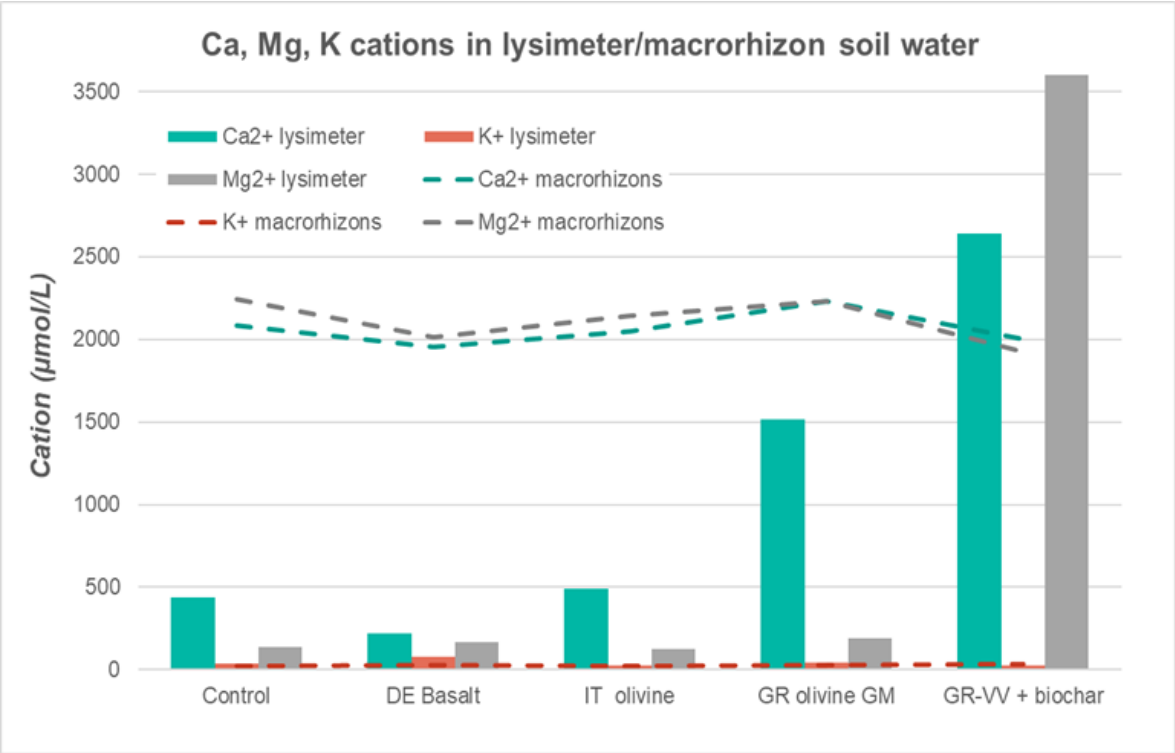


Figure 9.25. Calcium, magnesium and potassium cation concentrations observed in the lysimeter water collected on 22 July 2021 (bars) and compared to the macrorhizon Mg^{2+}, Ca^{2+} and K^{+} contents in the macrorhizon water at the same time.

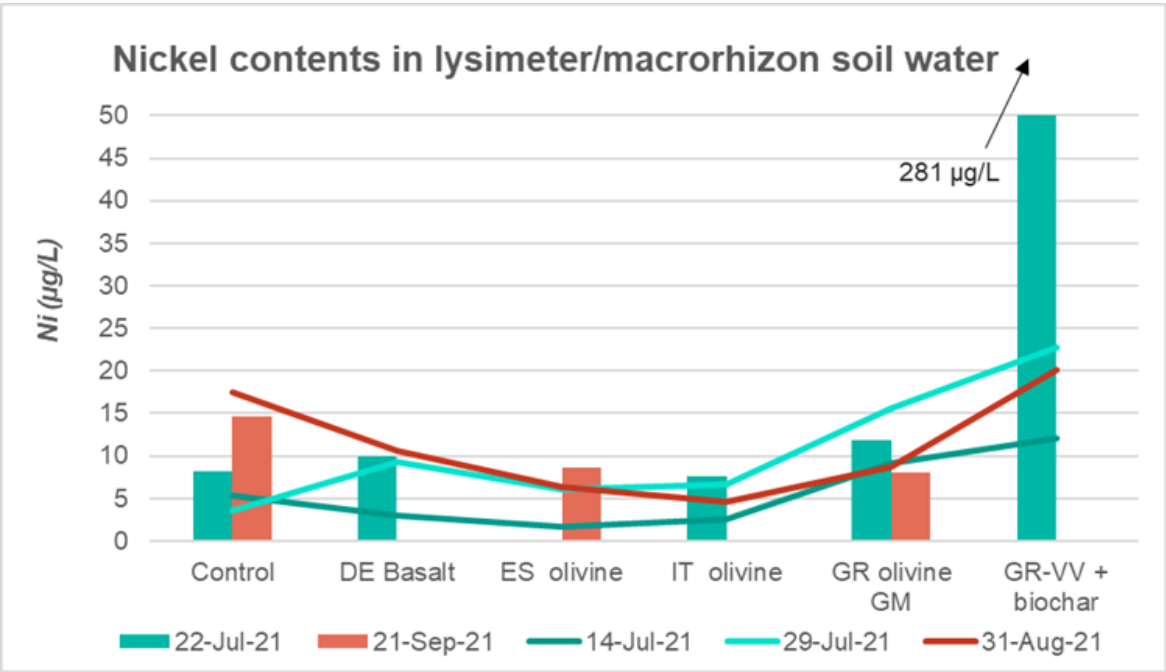


Figure 9.26. Nickel concentrations in the soil water collected from lysimeters (bars) and macrorhizons (lines) observed around similar times.

Although this elevated heavy metal concentration is not observed for chromium in the lysimeter water data, the by far highest Cr concentration (59µg/L) in any of the macrorhizon water samples is found in the same biochar treatment in the last sampling at the end of August (Figure 9.27). International drinking water limits for Cr vary range from 50µg/L (WHO) to 100µg/L (EPA).

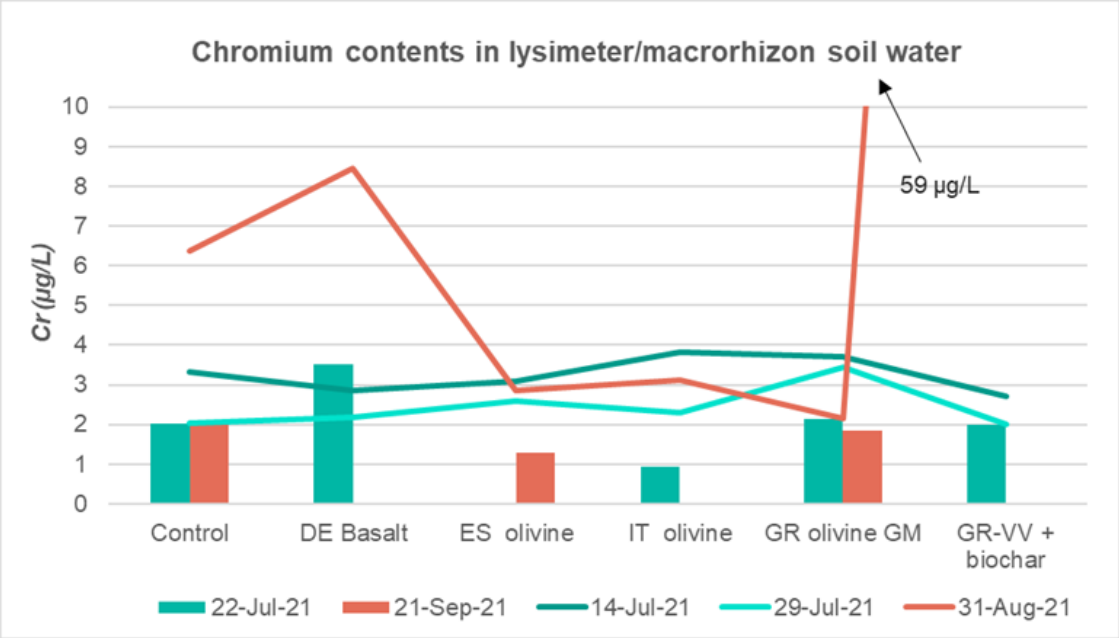


Figure 9.27. Chromium concentrations in the soil water collected from lysimeters (bars) and macrorhizons (lines) observed around similar times.

Due to the limited number of samples, it was not possible to statistically test the data of the lysimeter water chemistry for significant differences. Any of the above observations, such as differences between lysimeter and macrorhizon water samples, or interpretations, such as DE basalt releasing more K^+, are therefore just hypotheses that need more investigation in further experiments. Especially the higher heavy metal content observed for the treatment that includes biochar warrants further research.

Section summary

As the data obtained for the geochemistry of the lysimeter water samples are very limited, they cannot represent any statistically significant trends or allow meaningful interpretation. The different environment they represent compared to the macrorhizon samples nevertheless makes it interesting to compare the two types of soil water.

For most soil water properties the lysimeter values are within the same range as the macrorhizon data but might show larger variability. Only the HCO_3^-, TA, Ca^{2+} and Mg^{2+} contents seem to be lower in the lysimeter solutions.

The olivine rich rock dust treatment with the biochar represents an exception as it has the by far highest Mg^{2+} and Ni concentrations.

Pilot area results

Pilot area - results

This chapter presents all data of the soil, water and cotton crop samples of the pilot area. The pilot part of the 2021 experiment is mainly to **test** the **practical aspects** of enhanced weathering within an agricultural setting. Only the two **Greek olivine rich rock dusts** are applied but at rates 33 times lower than in the experimental area **(1.2 ton/ha)**. This application rate is in accordance with current Greek legislation regarding the amount of nickel one is permitted to annually add to 1 hectare of land (maximum 3kg). The application and potential effects of **biochar** are also tested, both with and without the Greek rock dusts.

The field set-up for the pilot area consists of **6 treatments** which each have **one** large replicate area. In case of water, soil and plant data we took samples from two distinct locations within each pilot area. Cotton yield and quality were assessed for three different samples within each pilot area. Whereas the laboratory data for each of these samples is reported in the relevant appendices, here we present the **average values of** the **2 or 3 replicates**. In comparison to the experimental area, data gathered from the pilot area have less scientific weight as their **statistics** are **not as strong** as when one has 4 replicates.

Whenever possible, we calculate the statistical significance of any differences between the average values and indicate them with a letter code. Averages that share one or more letters in their code are not significantly different from one another (for example 110 a, 112 a, 120 ab). Only when two averages do not have any same letter in their code in (for example 110 ab and 135 cd), they differ significantly and hence represent statistically different results for those two treatments.

When studying these data it is important to keep in mind that (1) the soil in the pilot area with only biochar was heavily compacted due to a first failed attempt to apply the biochar with the wheat-sowing machine. (2) From mid-June to early July, nitrogen fertilizer was added simultaneously with irrigation water right before soil water sampling sessions.

Cotton yield & quality

Cotton was harvested from three distinct areas within each pilot treatment, defined randomly, to obtain a number of replicates that is sufficient for statistical comparison.

The average **cotton yields** obtained for the six pilot treatments range from 3840 kg/ha to 4664 kg/ha. From the graph in Figure 10.1 it seems that whereas all treatments with Greek olivine rich rock dusts have somewhat higher yields than the control, the yield of the treatment with only biochar is lower than the control. This lowest yield observed in the biochar treatment probably reflects

the fact that the soil in this plot was highly compacted by the agricultural machinery during biochar application. Soil compaction deteriorates physical soil properties such as soil porosity, soil bulk density and water infiltration rate which in turn seriously affect plant development. Moreover, as a result of soil compaction, many "closed" cotton balls were observed at harvest time, indicating a delay in ball development and cotton maturing.

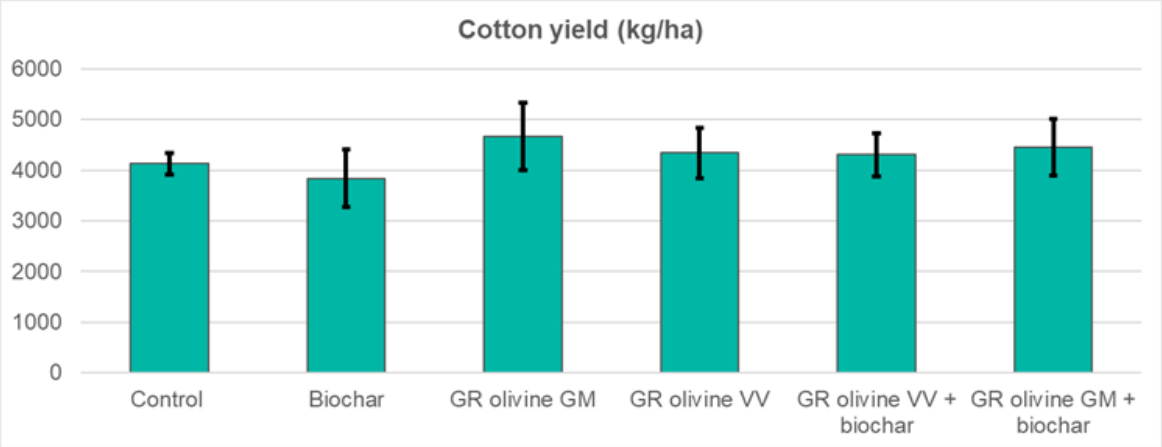


Figure 10.1 Average yields obtained from the 3 replicates of each of the 6 different treatments, error bars represent the respective standard deviations.

Statistical analyses of the variability of the cotton yield between the 6 treatments however shows that none of them is significantly different from another (Table 10.1). This is in line with the results of the experimental area where the Greek olivine rich rock dusts also seem to have higher cotton yields but statistical analysis shows that they are not significantly different from the other treatments.

Treatments	**Replications**			**Average yield (kg/ha)**	**SD (kg/ha)**	**CV (%)**
	1	**2**	**3**			
Control	3898	4325	4154	4126 a	215	5.2
Biochar	4440	3298	3781	3840 a	573	14.9
GR olivine GM	4281	4284	5428	4664 a	661	14.2
GR olivine VV	3784	4498	4733	4339 a	494	11.4
GR olivine VV + biochar	3891	4744	4293	4309 a	427	9.9
GR olivine GM + biochar	4328	3963	5068	4453 a	563	11.7

Table 10.1. Average yield values obtained for each of the 6 SRP treatments. The same letter for different yield values shows that there is no significant difference for $p<0.05$ according to the LSD post hoc test.

Respective percentages of lint and seed weight, moisture, micronaire, maturity, UHML, length uniformity, SFI, strength,elongation, reflectance and yellowness are the physical properties that determine the **quality of cotton**. Chapter 8 offers more information on each of the individual cotton quality parameters. Statistical analysis shows that across the pilot area **none** of these **properties** are **significantly affected** by the olivine rich rock dust application

or biochar. There were also no statistically significant differences in cotton quality across the experimental treatments which represent much higher rock dust application rates.

Cotton quality parameters	Control	Biochar	GR olivine GM	GR olivine VV	GR-VV + biochar	GR-GM + biochar
Lint weight %	0,47 a	0,46 a	0,46 a	0,46 a	0,47 a	0,46 a
Seed weight %	0,53 a	0,54 a	0,54 a	0,54 a	0,53 a	0,54 a
SCI	149,1 a	152,6 a	145,8 a	141,4 a	149,7 a	142,4 a
Moisture%	7,0 a	7,2a	7,3 a	7,2 a	7,4 a	7,3 a
Micronaire	4,5 a	4,7 a	4,9 a	4,9 a	4,6 a	4,7 a
Maturity	0,84 a	0,86 a	0,86 a	0,86 a	0,85 a	0,85 a
UHML mm	29,6 a	30,5 a	29,0 a	29,4 a	29,9 a	29,3 a
Length uniformity	84,2 a	83,6 a	83,9 a	82,9 a	84,1 a	83,4 a
SFI	7,9 a	7,8 a	7,9 a	8,5 a	7,7 a	7,9 a
Strength	33,6 a	35,6 a	34,5 a	34,3 a	33,8 a	33,3 a
Elongation	9,2 a	8,2 a	8,9 a	8,7 a	8,3 a	8,6 a
Reflectance %	75,9 a	75,8 a	76,2 a	75,9 a	76,7 a	76,4 a
Yellowness +b	8,3 a	8,2 a	8,4 a	8,1 a	8,4 a	8,1 a

Table 10.2. Average values of the different cotton quality parameters obtained for the six pilot treatments. Within one data row of a specific quality parameter, the same letter for different treatments shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test.

Section summary

Although the Greek olivine rich rock dust treatments seem to have somewhat higher cotton yields, statistical analysis could not distinguish them from the control and biochar only treatments. There is also no statistically significant distinction between the cotton qualities observed for the six different pilot treatments.

These treatments represent much lower olivine rich rock dust addition (1.2 ton/ha) than in the experimental area (40 ton/ha). As there were also no positive or negative effects observed on the cotton cultivation in the experimental plots, these results are not surprising.

Plant nutrient uptake

The concentrations of N, P, K, Ca, Mg, Fe, Mn, B, Cu and Zn observed in the cotton plant tissues during the flowering stage represent the nutritional status of the crop, and is shown in table 10.3.

Whereas in the experimental area phosphorus is the only plant nutrient with **significant variability** between treatments (Table 9.3), there does **not** seem to be any statistical distinction between the treatments in the pilot area. But the pilot area does reflect the same **phosphorus** trend as the experimental area: GR olivine VV + biochar has the highest P content and the control the lowest P (Table 10.3). Comparing the equivalent pilot treatments with and without biochar, it seems that P content is always somewhat **higher when biochar** was **applied** (Figure 1.4).

Plant nutrients	Control	Biochar	GR olivine GM	GR olivine VV	GR-VV + biochar	GR-GM + biochar
N (%)	3,14 a	3,12 a	3,10 a	3,10 a	3,31 a	2,90 a
P (%)	0,17 a	0,18 a	0,19 a	0,18 a	0,22 a	0,20 a
K (%)	1,09 a	0,98 a	1,12 a	1,10 a	1,07 a	1,09 a
Ca (%)	2,66 a	2,42 a	2,52 a	3,06 a	2,95 a	3,18 a
Mg (%)	0,77 a	0,64 a	0,71 a	0,89 a	0,81 a	0,89 a
Fe (mg/kg)	395 a	353 a	275 a	339 a	255 a	311 a
Zn (mg/kg)	37,0 a	111,5 a	51,5 a	72,0 a	84,5 a	53,0 a
Cu (mg/kg)	7,3 a	5,9 a	7,3 a	8,4 a	7,8 a	4,9 a
Mn (mg/kg)	125 a	104 a	108 a	132 a	125 a	107 a
B (mg/kg)	71,5 a	64,5 a	67,5 a	77,5 a	58,0 a	69,0 a

Table 10.3. Average values of the different nutrient concentrations measured in the plant tissue of the pilot treatments during the flowering period. Within one data row of a specific plant nutrient, the same letter for different treatments shows there is no significant difference between these treatments for $p<0.05$ according to the LSD post hoc test.

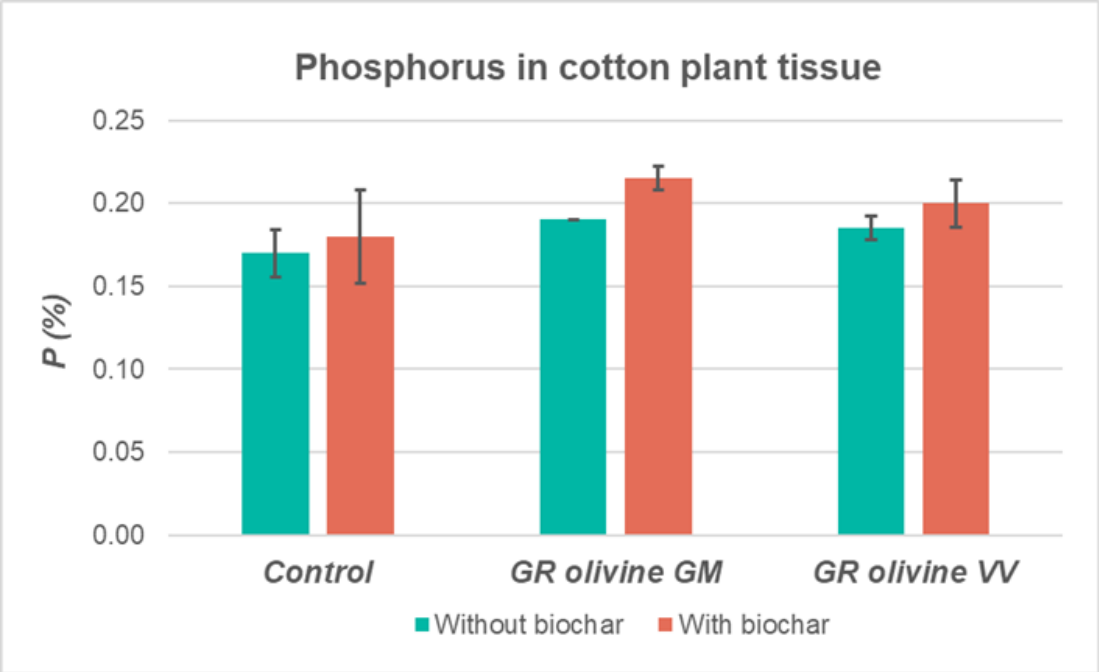


Figure 10.2. Average phosphorus contents in the cotton leaves of the pilot treatments during the flowering stage. Error bars represent 1 standard deviation over 2 replicates.

The overall tendency for the single biochar-amended treatment of the experimental area to have the highest plant macronutrient contents is, however, not reflected in the pilot area. Plant tissue contents of K, N, Ca and Mg do not show any **consistent difference** between the same soil treatments **with and without biochar** (Figure 10.3). This seems to confirm that the higher macronutrient content in the cotton of the experimental biochar treatment is due to the different fertilization management. Except for the experimental treatment with biochar which received a liquid fertilizer, the same granular fertilizer was used all across our field.

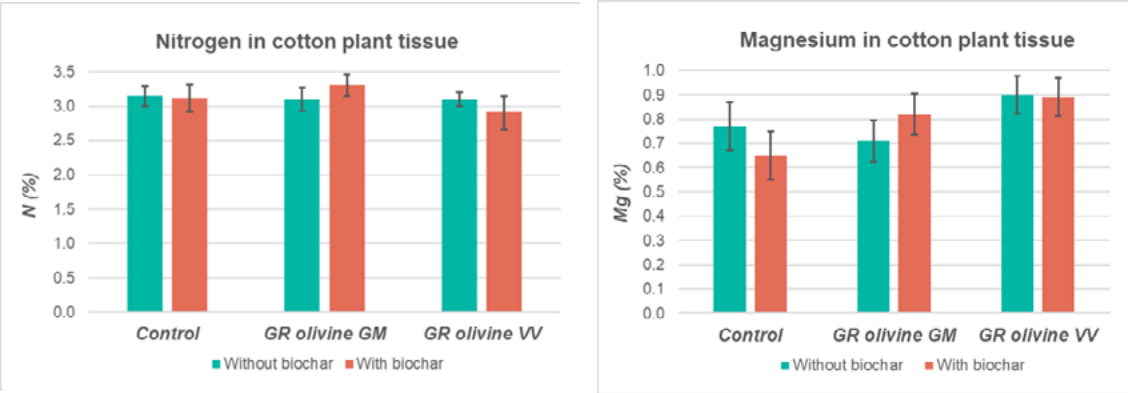


Figure 10.3. Average nitrogen (left) and average magnesium (right) contents in the cotton leaves of the pilot treatments during the flowering stage. Error bars represent standard deviation over 2 replicates.

Table 10.4 shows the nutrient sufficiency values of cotton leaves as defined by Mills & Jones (1996). Comparison with the nutrient values observed in the pilot area shows that the main nutrients **N, P and K** are **below** the **sufficiency level** values in all 6 treatments. All other elements, such as secondary nutrients Ca and Mg and trace elements Fe, Mn, Zn, Cu and B, fall within the range of sufficiency for cotton. This indicates that the basic N-P-K fertilization of this cotton field is not optimal and could be corrected in order to get better yields.

Macronutrients (%)									
N	3,50-4,50	*P*	0,30-0,50	*K*	1,50-3,00	*Ca*	2,00-3,00	*Mg*	0,30-0,90
Micronutrients (mg/kg)									
Fe	50-250	*Mn*	25-350	*B*	20-60	*Cu*	5-25	*Zn*	20-200

Table 10.4 Sufficiency ranges of nutrient concentrations in cotton leave tissues (Mills & Jones, 1996).

Section summary

Plant nutrient values in the pilot do not show any significant variability between different treatments, but the statistical analysis is not so reliable as it is carried out with only 2 replicates.

The higher P content observed in the experimental area for the biochar treatment is also reflected in the pilot area where treatments with biochar have somewhat higher P contents than those without.

There is however no other consistent difference in nutrient uptake between cotton grown in soil with and without biochar. This suggests that the higher nutrient values observed in the experimental treatment with biochar are due to the different fertilizer it was treated with.

All pilot cotton plants have N, P, K contents below the sufficiency levels for this crop.

Soil properties

About 20 different soil properties were analysed in samples collected prior to rock dust application (3 April), during the flowering period (27 July) and before the cotton harvest (20 September). Analysis of the soil properties during the flowering stage is particularly important because this time represents the highest uptake of nutrients from the soil by the cotton plants. Soil composition at harvest time is important to assess the residual fertility of the soil and to check for any potential contamination caused by the application of soil amendments.

The resulting soil data are interpreted to assess (1) any variability between treatments within the same sampling session and (2) any changes throughout the cotton growing season within the same treatment. As the statistical data presented below only represent average values for two sample replicates, they are not as statistically significant as observations made for the same soil properties of the experimental area where there are four replicates.

Flowering stage (27 July 2021)						
Soil propertles	**Control**	**Biochar**	**GR olivine GM**	**GR olivine VV**	**GR-VV + biochar**	**GR-GM + biochar**
pH	8,15 a	8,20 a	8,10 a	8,10 a	8,05 a	8,20 a
EC (µS/cm)	824,5 a	655,0 a	831,0 a	850 ,0 a	881,5 a	815,5 a
$CaCO_3$ (%)	25,0 a	25,0 a	24,0 a	22,5 a	30,0 a	26,0 a
SOM (%)	0,875 a	1,100 a	0,905 a	1,150 a	1,150 a	1,300 a
N_tot (%)	0,091 a	0,095 a	0,087 a	0,089 a	0,080 a	0,085 a
NO_3_N (mg/kg)	4,73 a	14,21 a	11,58 a	15,81 a	9,21 a	15,54 a
P_olsen (mg/kg)	2,85 a	10,95 a	3,80 a	10,50 a	14,55 a	9,30 a
K_exch (cmol+/kg)	0,485 a	0,465 a	0,470 a	0,505 a	0,525 a	0,490 a
Na_exch (cmol+/kg)	0,99 a	0,97 a	1,14 a	0,87 a	0,88 a	1,08 a
Ca_exch (cmol+/kg)	39,0 a	39,5 a	41,0 a	38,5 a	40,0 a	40,0 a
Mg_exch (cmol+/kg)	8,55 a	8,80 a	9,55 a	8,55 a	8,95 a	9,40 a
CEC (cmol+/kg)	45,5 a	47,0 a	49,0 a	45,5 a	47,5 a	49,0 a
Cd (mg/kg)	0,245 a	0,215 a	0,235 a	0,215 a	0,170 a	0,180 a
Cr (mg/kg)	89,73 a	86,45 a	89,18 a	82,04 a	84,55 a	85,14 a
Cu (mg/kg)	**26,43 a**	**26,48 a**	**25,70 b**	**25,08 bc**	**24,48 bc**	**22,06 c**
Ni (mg/kg)	220,06a	207,41 a	213,03 a	211,90 a	210,21 a	225,13 a
Pb (mg/kg)	***10,00 b***	***10,51 ab***	***10,82 ab***	***11,07 ab***	***11,38 a***	***10,91 ab***
Zn (mg/kg)	***45,01 a***	***45,29 a***	***43,76 ab***	***43,41 ab***	***40,50 ab***	***39,00 b***

Table 10.5. Average values of the different soil parameters measured for two replicate soil samples collected during the flowering period. Within one data row of a specific soil parameter, the same letter for different treatments shows there is no significant difference between the treatments for $p<0.05$ according to the LSD post hoc test. Darker blue-green rows with white bold text indicate soil parameters that might vary significantly between treatments.

Variability across treatments during flowering stage

The different soil properties observed during the flowering stage are presented in Table 10.5. Based on statistical analyses of limited samples, there is **only some difference** between the treatments with regards to the soil pseudo total concentrations of copper (**Cu**), lead (**Pb**) and zinc (**Zn**). Lead contents thereby seem to be highest in the Greek rock dust from Vitruvit combined with biochar and lowest in the control. This pattern is however inverted for copper and zinc which seem to be significantly higher in the control and biochar-only treatments compared to the Vitruvit rock dust with biochar.

There is no obvious explanation why these pseudo total heavy metal contents would vary due to rock dust application: dissolution of both Greek rock dusts is expected to release Ni and Cr for which no differences are observed. For the experimental treatments whose rock dust application rates are 33 times higher, there were no significant differences in pseudo total heavy metal contents during the flowering stage. It is therefore likely that these statistical differences **represent soil heterogeneity** of Cu, Pb and Zn contents which is inherent to the field itself, or to the "experimental error" involved.

The significant variability in N, P, exchangeable Ca and CEC observed during flowering across the overall smaller area of the experimental treatments is not reflected in the pilot treatments. Apart from the differences in Cu, Pb and Zn, **all other soil parameters** seem **statistically** the **same** in the pilot area during the flowering stage.

Variability across treatments at harvest time

The soil sampled across the pilot area prior to the harvest also shows **some differences** for the soil **pseudo total heavy metal** contents. Copper shows a similar pattern as during the flowering stage with the Vitruvit rock dust + biochar treatment having the lowest concentrations. Lead contents seem to have somewhat increased since flowering in all olivine rich rock dust treatments, the highest values are present in combination with biochar. Although zinc values have a slightly larger range, no statistical variability was detected.

At harvest, there seem to be some significant differences for nickel being highest in the control and lowest in the olivine rich rock dust + biochar treatments. The likelihood that this might reflect the biochar's ability to adsorb heavy metals is rather small given the fact that the pilot treatment with only biochar has significantly higher Ni contents. Given the large variability of pseudo total Ni soil contents throughout the season (Figure 10.4), very similar to the pattern observed in the experimental area, it seems more plausible that these data reflect **soil heterogeneity**.

The **variability** of remaining plant nutrients phosphorus and calcium in the pilot area indicates lower contents for the Greek rock dusts combined with

biochar. Since the treatment with biochar only has (the) high(est) **P and Ca** contents, this does not seem to reflect strong retention of these nutrients by the biochar. Initial **soil heterogeneity** is likely the reason for these apparent differences.

Harvest time (20 September 2021)						
Soil properties	**Control**	**Biochar**	**GR olivine GM**	**GR olivine VV**	**GR-VV + biochar**	**GR-GM + biochar**
pH	8,35 a	8,25 a	8,20 a	8,30 a	8,30 a	8,30 a
EC (µS/cm)	558,5 a	670,0 a	574,5 a	535,0 a	557,0 a	551,5 a
$CaCO_3$ (%)	22,0 a	21,5 a	21,5 a	19,5 a	22,0 a	21,5 a
SOM (%)	1,010 a	0,950 a	0,835 a	0,900 a	0,945 a	0,720 a
N_tot (%)	0,0865 a	0,0835 a	0,0835 a	0,0735 a	0,0870 a	0,0830 a
NO_3_N (mg/kg)	4,35 a	17,50 a	2,85 a	0.08	7,15 a	4,75 a
P_olsen (mg/kg)	**7,20 a**	**8,00 a**	**5,80 a**	**8,20 a**	**2,10 b**	**3,80 a**
K_exch (cmol+/kg)	0,47 a	0,48 a	0,40 a	0,41 a	0,40 a	0,42 a
Ca_exch (cmol+/kg)	**42,0 a**	**41,0 ab**	**41,0 ab**	**40,5 ab**	**40,5 ab**	**39,5 b**
Mg_exch (cmol+/kg)	9,30 a	8,90 a	9,75 a	9,45 a	10,00 a	9,70 a
Cd (mg/kg)	0,14 a	0,17 a	0,19 a	0,20 a	0,20 a	0,22 a
Cr (mg/kg)	129,36 a	124,10 a	126,26 a	135,17 a	129,25 a	128,36 a
Cu (mg/kg)	**27,44 ab**	**27,54 ab**	**27,52 ab**	**28,44 a**	**26,95 ab**	**25,69 b**
Ni (mg/kg)	**123,77 a**	**120,59 a**	**121,99 b**	**116,57 ab**	**112,28 b**	**113,08 b**
Pb (mg/kg)	**11,38 c**	**11,80 c**	**11,64 c**	**12,55 bc**	**14,28 a**	**14,10 ab**
Zn (mg/kg)	39,79 a	46,99 a	39,55 a	39,21 a	39,07 a	42,90 a

Table 10.6. Average values of the different soil parameters measured for two replicate soil samples collected at harvest time. Within one data row of a specific soil parameter, the same letter for different treatments shows there is no significant difference between the treatments for $p<0.05$ according to the LSD post hoc test. Darker blue-green rows with white bold text indicate soil parameters that might vary significantly between treatments.

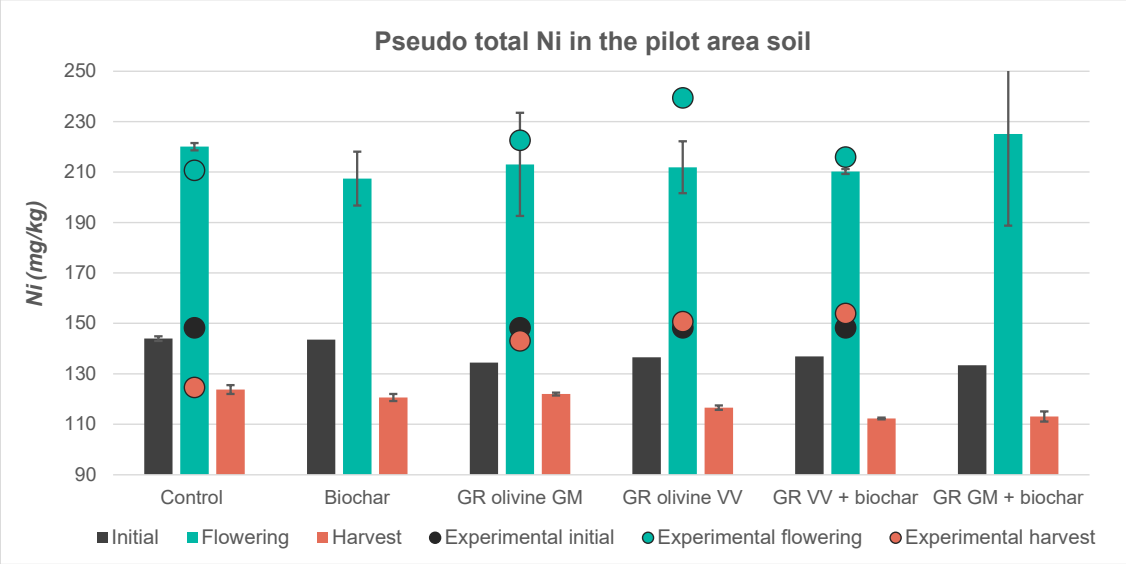


Figure 10.4 Average pseudo total nickel contents observed in the soil of the pilot treatments columns before rock dust application, during the flowering stage and before the harvest. Error bars represent standard error over 2 replicates. Round data points represent the average pseudo total Ni concentrations observed in the experimental area in the 4 treatments in common with the pilot area.

Seasonal variability throughout cotton growing

Above discussion on the soil properties observed during the flowering stage and before harvest indicates that the limited data collected in the pilot area (two replicates) limits the significance of statistical analysis carried out on them. Studying the seasonal variation of the pilot area's soil properties (Table 10.7), this **limited statistical reliability** is also apparent when comparing the pH data with those of the experimental area (Table 9.7). With 4 replicates for each sample, the more statistically sound soil property data of the experimental area showed a **significant seasonal variability of pH** for all the treatments. The common pH trend observed in all the **experimental treatments** is thereby a decrease at the flowering stage before more or less returning to the initial values before harvest (see Chapter 9). The exact **same pattern** is observed for the pH values of the **pilot** area soil (Figure 10.5) **but** the **statistical** analysis does **not** identify any significant **differences** in 5 of the 6 treatments (Table 10.7).

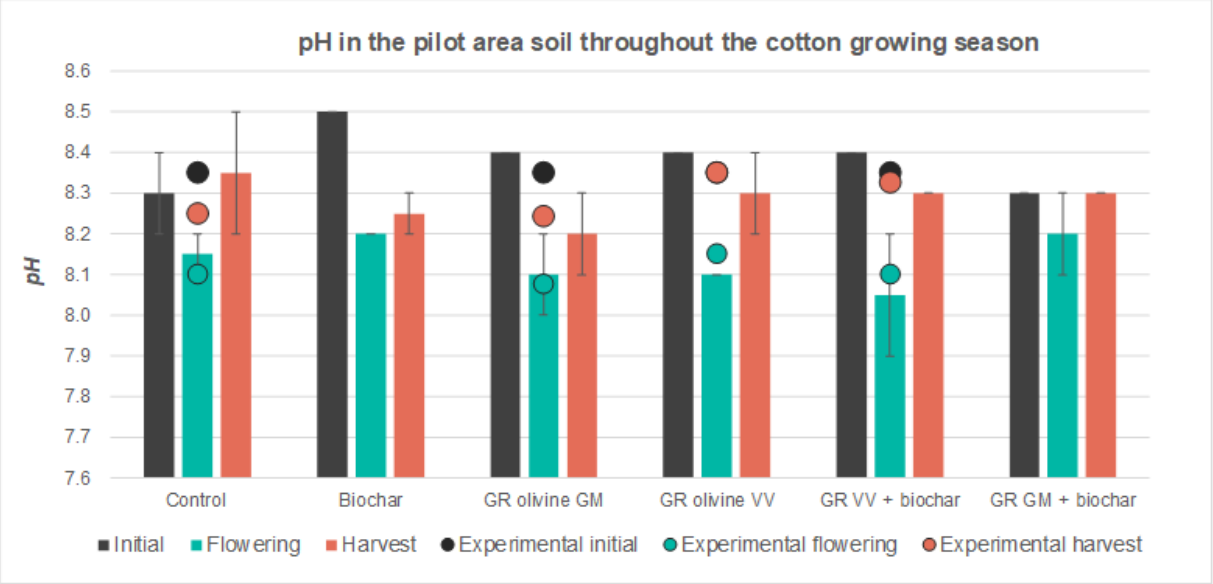


Figure 10.5 Average pH soil values of the pilot (columns) before rock dust application, during the flowering stage and before the harvest. Error bars represent the standard errors over 2 replicates. Round data points represent the average pH values observed in the experimental area in the 4 treatments in common with the pilot area.

On the contrary, the same **seasonal Cr** variability that seems statistically significant across all pilot treatments is observed to be statistically relevant for only 3 out of 8 experimental treatments. The common pseudo total Cr pattern is thereby the same as the pH trend with distinctly **lower** values at the **flowering** stage (Figure 10.6). It is not clear, however, whether variation of chromium speciation with changing soil pH might play a role at this pH range.

The seasonal Ca, and pseudo total Ni and Pb trends identified in the experimental area are also observed in the pilot area. **Calcium and lead** (Figure 10.7) contents **increase significantly throughout** the season. Pseudo total **nickel** contents show the same trend as pseudo total chromium with significantly **higher** values at **flowering** stage compared to initially and at harvest time.

	Control			Biochar			GR Olivine GM		
	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest
pH	8,30 a	8,15 a	8,35 a	8,50 a	8,20 b	8,25 b	8,40 a	8,10 a	8,20 a
EC	562,0 a	824,5 a	558,5a	433,0 b	655,0 a	670,0 a	419,0 a	831,0 a	574,5 a
CaCO3	24,0 a	25,0 a	22,0 a	23,0 b	25,0 a	21,5 b	22,0 a	24,0 a	21,5 a
SOM	0,78 a	0,88 a	1,01 a	1.00 a	1,01 a	0,95 a	1,10 a	0,91 a	0,84 a
N_tot	0,079 a	0,091 a	0,087 a	0,071 b	0,095 a	0,084 a	0,080 a	0,087 a	0,084 a
NO3_N	4,97 a	4,73 a	4,35 a	4,61 b	14,21 a	17,50 a	1,42 b	11,58 a	2,85 b
P_olsen	6,00 a	2,85 a	7,20 a	2,30 a	10,95 a	8,00 a	2,20 a	3,80 a	5,80 a
K_exch	0,37 a	0,49 a	0,47 a	0,36 a	0,47 a	0,48 a	0,31 b	0,47 a	0,40 b
Ca_exch	**29,0 b**	**39,0 a**	**42,0 a**	**29,0 b**	**40,0 a**	**41,0 a**	**29,0 b**		**41,0 a**
Mg_exch	8,70 a	8,55 a	9,30 a	8,30 a	8,80 a	8,90 a	8,30 b	9,55 a	9,75 a
Cd		0,245 a	0,141 a		0,215 a	0,173 a		0,235 a	0,199 a
Cr	**133,86 a**	**89,73 b**	**129,37 a**	**132,48 a**	**86,45 c**	**124,10 b**	**122,84 a**	**89,18 b**	**126,27 a**
Cu	26,58 a	26,43 a	27,45 a	26,52 a	26,48 a	27,54 a	26,05 ab	25,07 b	27,53 a
Ni	**143,98 b**	**220,07 a**	**123,78 c**	**143,54 b**	**207,20 a**	**120,60 b**	**134,48 b**	**213,03 a**	**122,00 b**
Pb	**4,795 b**	**10,00 a**	**11,38 a**	**4,73 c**	**10,52 b**	**11,80 a**	**4,67 c**	**10,82 b**	**11,64 a**
Zn	34,60 b	45,01 a	39,80 ab	34,58 a	45,29 a	47,00 a	32,20 b	43,76 a	39,55 a

	GR Olivine VV			GR Olivine VV + Biochar			GR Olivine GM + Biochar		
	Initial	Flowering	Harvest	Initial	Flowering	Harvest	Initial	Flowering	Harvest
pH	8,4 a	8,1 a	8,3 a	8,4 a	8,1 a	8,3 a	8,3 a	8,2 a	8,3 a
EC	429,0 b	850,0 a	535,0 b	425,0 a	881,5 a	557,0 a	644,0 a	815,5 a	551,5 a
CaCO3	24,0 a	22,5 a	19,5 a	23,0 b	30,0 a	22,0 b	23,0 ab	26,0 a	21,5 b
SOM	0,71 a	1,15 a	0,90 a	1,20 a	1,15 ab	0,95 b	2,20 a	1,30 ab	0,72 b
N_tot	0,075 a	0,089 a	0,074 a	0,084 a	0,080 a	0,087 a	0,078 a	0,085 a	0,083 a
NO3_N	**0,95 b**	**15,81 a**	**2,00 b**	**0,51 b**	**9,21 a**	**7,15 a**	**3,40 b**	**15,54 a**	**4,75 b**
P_olsen	2,2 a	10,5 a	8,2 a	2,5 b	14,6 a	2,1 b	2,8 a	9,3 a	3,8 a
K_exch	0,31 a	0,51 a	0,41 a	0,38 a	0,53 a	0,40 a	0,36 a	0,49 a	0,42 a
Ca_exch	**29,0 b**	**38,5 a**	**40,5 a**	**30,0 b**	**40,0 a**	**40,5 a**	**30,0 b**	**40,0 a**	**39,5 a**
Mg_exch	8,10 a	8,55 a	9,45 a	8,50 b	8,95 b	10,00 a	8,10 b	9,40 a	9,70 a
Cd		0,22 a	0,21 a		0,17 a	0,21 a		0,18 a	0,22 a
Cr	**125,26 a**	**82,04 b**	**135,17 a**	**128,24 a**	**84,55 b**	**129,25 a**	**117,87 a**	**85,14 b**	**128,36 a**
Cu	**26,10 ab**	**25,08 b**	**28,44 a**	**26,02 ab**	**24,48 b**	**26,95 a**	**25,75 a**	**22,06 b**	**25,69 a**
Ni	136,57 b	211,90 a	116,57 b	136,88 a	210,21 a	112,28 b	133,37 a	225,13 a	113,08 a
Pb	**4,42 b**	**11,07 a**	**12,55 a**	**4,40 b**	**11,38 a**	**14,29 a**	**4,00 a**	**10,91 b**	**14,10 b**
Zn	32,63 b	43,41 a	39,21 ab	33,28 b	40,50 a	39,07 a	32,28 a	3,01 a	42,90 a

Table 10.7. Average values of the soil parameters measured for different pilot treatments before rock dust application, during flowering and at harvest time. Statistical analysis carried out on these data assesses the significance of seasonal variation within a certain treatment. Within horizontal rows, the same letter for different sampling times of the same treatment indicates that the specific soil parameter does not show significant seasonal variation for $p<0.05$ according to the LSD post hoc test. Dark green rows with bold white text indicate soil parameters that show seasonal variability for most treatments. Light green coloured data highlight seasonal variation of a specific soil parameter for some of the treatments. Units of soil parameters as in Table 10.6.

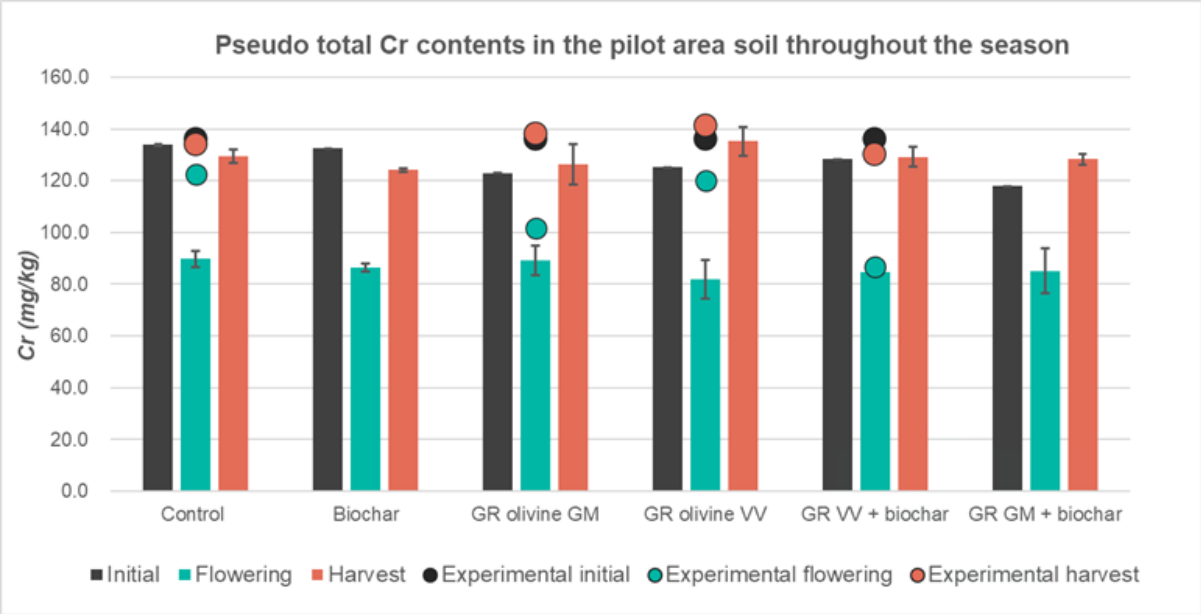


Figure 10.6. Average pseudo total Cr concentrations in the soil of the pilot (columns) before rock dust application, during the flowering stage and before the harvest. Error bars represent the standard errors over 2 replicates. Round data points represent the average pseudo total Cr contents observed in the experimental area in the 4 treatments in common with the pilot area.

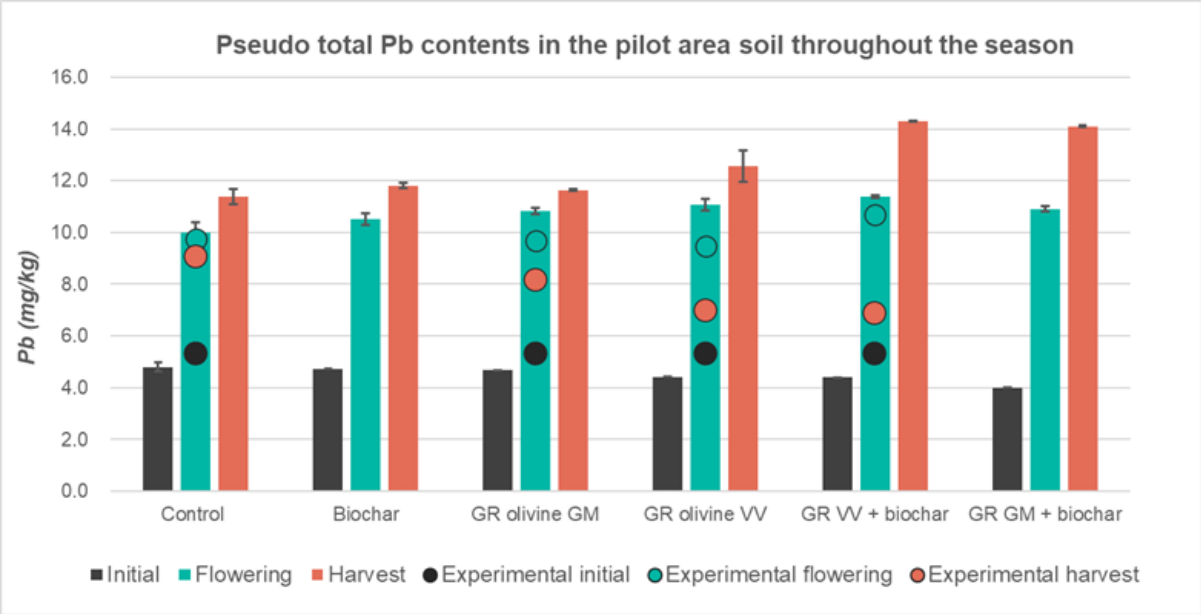


Figure 10.7 Average pseudo total Pb concentrations in the soil of the pilot (columns) before rock dust application, during the flowering stage and before the harvest. Error bars represent the standard errors over 2 replicates. Round data points represent the average pseudo total Pb contents observed in the experimental area in the 4 treatments in common with the pilot area

In general, the soil properties of the **pilot area** show the **same** tendencies **as** observed in Chapter 9 for the **experimental plots**. Soil pH ranges from 8.15 to 8.5 and decreases during the flowering stage, whilst electrical conductivity increases at this time. An overall tendency of slightly increasing Mg soil contents throughout the season is also seen in the pilot area. Nitrate values seem to have some significant seasonal variation but without a clear pattern across the treatments. Calcium carbonate, total N and exchangeable K and

Mg do not show significant seasonal variability – they also did not in the experimental area.

Pseudo total zinc concentrations increase strongly from initial to flowering stage composition and then slightly decrease again by harvest. Available P (Figure 10.8) shows a similar peak at flowering stage except for the control and GR olivine GM. This could have something to do with more intense activity of the root system during the flowering stage which increases the release of P associated with organic matter and iron complexes. However, it is unclear why this is then only observed in 4 out of the 6 treatments. Copper reflects an increase in soil concentrations throughout the season. Similar seasonal trends are observed in the experimental data where they are also not statistically significant for any treatment.

Figures 10.4 through to 10.8 also compare the soil data of pilot area to the experimental area for those four treatments they had in common, albeit at lower application rates (control, olivine rich rock dust Grecian Magnesite (GM), olivine rich rock dust Vitruvit (VV) and VV with biochar). This comparison shows that the concentrations observed in pilot and experimental plots largely fall within the same range and have similar variations throughout the season. This suggests that these soil parameters are mainly controlled by chemical, biological and physical parameters other than enhanced weathering of added materials.

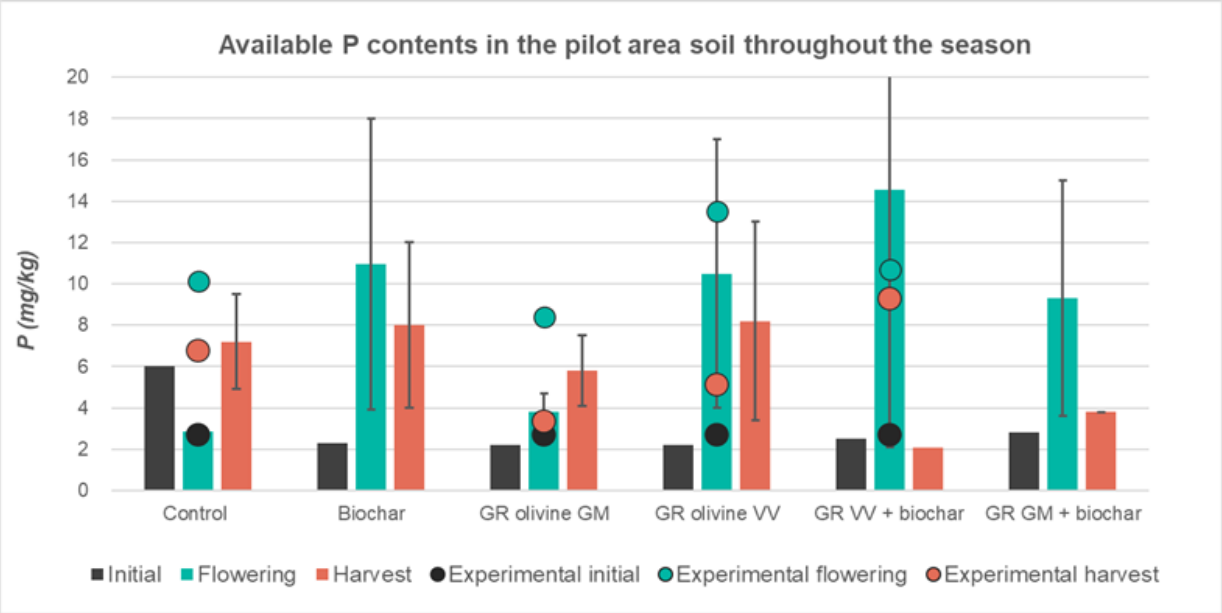


Figure 10.8 Average available phosphorus concentrations in the soil of the pilot (columns) before rock dust application, during the flowering stage and before the harvest. Error bars represent the standard errors over 2 replicates. Round data points represent the average available P contents observed in the experimental area in the 4 treatments in common with the pilot area.

Section summary

Compared to the experimental area where there were 4 soil sample replicates for each treatment, the limited number of only 2 replicates in the pilot area results in less reliable results of the statistical tests.

There is less soil property variability between the treatments at flowering stage and before harvest in the pilot area than observed in the experimental area. Significant differences between treatments are thereby mainly observed in pseudo total heavy metal contents. It seems, however, that these differences are reflecting soil heterogeneities inherent to the large pilot area rather than true variability caused by SRP addition.

Despite the lower reliability of statistical analysis on the pilot area soil data, the same seasonal patterns are observed as in the experimental area. Whereas Cr contents follow the same trend as the soil pH, being significantly lower at flowering compared to initial and harvest values, Ni shows the opposite trend with peak values at flowering. Calcium and lead soil contents increase significantly from April to the end of July and then stagnate or slightly increase at harvest.

Macrorhizon soil water

Due to the **single replicate** for each of the pilot treatments it is **not possible** to perform **statistical analysis** on these data. Table 10.8 thus summarises the macrorhizon water sample data observed throughout the season without indication of the statistical significance of any variability. Below follows a brief comparison of these macrorhizon water data with the statistically better-defined data from the experimental area.

Water volume: The total volume of soil water sampled from the 6 macrorhizons in each plot was recorded throughout the season, except for the first sampling on 13 May 2021, and is shown in Figure 10.9. Varying between 5 and 160 mL, the pilot water volumes show a **larger range** than the ones collected in the experimental area (up to 80mL). There are often **larger water volumes** collected than in the experimental area, which is not only due to the one extra macrorhizon but also to spatial variation in the soil properties. In the **first part of August**, however, distinctly **smaller water volumes** were collected likely due to maximum summer heat and plant growth. A similar, but less clear, pattern of smaller sample volumes in the period of **maximum evapotranspiration** is also observed in the experimental area. Lower sample volumes from 6 August onwards are the reason for the absence of K^+, Ca^{2+}, Mg^{2+},HCO_3^- or CO_3^{2-} concentration data in some pilot treatments (see Table 10.8)

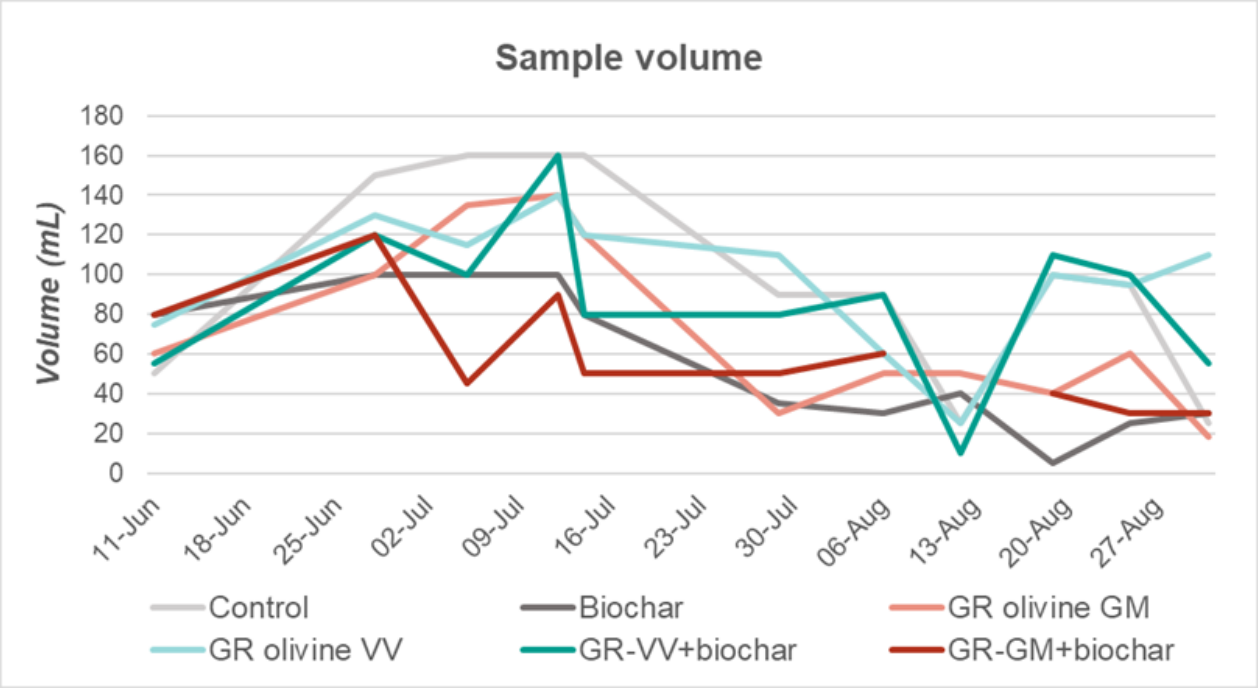


Figure 10.9. Average volume of soil water collected with macrorhizons for each of the 6 pilot treatments throughout the eleven last sampling sessions.

	13 May	11 June	28 June	05 July	12 July	14 July	29 July	06 Aug	12 Aug	19 Aug	25 Aug	31 Aug
Control												
Volume (mL)		50	150	160	160	160	90	90	25	100	95	25
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0	2000	0	0	0
HCO_3^- (µmol/L)	3999	5998	4499	4499	4999	6398	5998	6198	6998	5199	5499	3999
CA (µmol/L)	3999	5998	4499	4499	4999	6398	5998	6198	10998	5199	5499	3999
pH	8.25	8.05	7.78	7.80	8.00	7.95	8.10	8.00	8.30	8.02	8.19	8.23
EC (µS/cm)	1247	1565	1884	1658	1143	1188	1334	1301	1664	1308	1153	1354
Ca^{2+} (µmol/L)	2280	2460	5586	4060	853	2215	1510		2108	1844	1610	1487
K^+ (µmol/L)	152.2	19.2	42.5	28.1	111.0	24.8	24.0		18.7		4.3	16.6
Mg^{2+} (µmol/L)	2138	2831	1836	885	702	1905	1887		3008	2017	1697	2125
Ni (µg/L)	10.00	17.50	19.06	16.39	19.57	7.88	7.30	10.06	22.40	12.28	9.42	11.75
Cr (µg/L)	1.01	0.60	6.93	3.20	3.69	2.40	2.44	2.29	2.11	2.29	2.70	2.16
Biochar												
Volume (mL)		80	100	100	100	80	35	30	40	5	25	30
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0	1500		0	0
HCO_3^- (µmol/L)	4999	6998	7498	4999	5798	5399	3999	5998	5499		4999	7998
CA (µmol/L)	4999	6998	7498	4999	5798	5399	3999	5998	8498		4999	7998
pH	8.29	8.05	7.98	7.70	8.20	8.18	8.00	8.16	8.32	8.46	8.21	8.26
EC (µS/cm)	1024	1228	2020	2220	990	1088	1444	1545	1461	1395	1684	1667
Ca^{2+} (µmol/L)	2280	5586	6122	8880	1496	1854	1912		2103		1615	1899
K^+ (µmol/L)	54.7	42.5	38.1	79.6	31.5	29.2	34.0		18.7		2.3	12.3
Mg^{2+} (µmol/L)	1658	1836	2126	1070	1734	1731	2431		1804		2999	3291
Ni (µg/L)	4.35	24.57	18.11	14.46	5.61	3.24	7.56	7.48	27.37	8.69	15.25	13.83
Cr (µg/L)		4.45	5.55	2.22	1.32	1.11	3.38	3.01	4.82	3.75	1.73	1.86
GR olivine GM												
Volume (mL)		60	100	135	140	120	30	50	50	40	60	18
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0	0	0	0	
HCO_3^- (µmol/L)	4499	6998	3999	3999	5599	6598	5998	5998	5998	3999	6198	
CA (µmol/L)	4499	6998	3999	3999	5599	6598	5998	5998	5998	3999	6198	
pH	8.09	8.06	7.89	7.90	8.17	8.14	8.25	8.05	8.17	8.17	8.30	
EC (µS/cm)	859	1438	1841	2080	1002	1198	1307	1311	1233	1309	1448	1297
Ca^{2+} (µmol/L)	1933	2632	5332	5510	1506	2009	1629		2127	1956	2104	1780
K^+ (µmol/L)	391.2	45.8	64.5	56.5	24.8	29.2	25.8		21.0			14.3
Mg^{2+} (µmol/L)	1275	2434	2874	2579	1646	1731	1792		1804	1985	2283	1987
Ni (µg/L)	10.41	53.32	14.14	11.42	10.72	4.98	15.43	13.93	21.44	14.22	17.93	22.15
Cr (µg/L)	0.29	3.85	7.37	6.06	5.79	0.51	1.44	1.55	2.63	2.06	2.09	2.08

Table 10.8. Values of the different soil solution properties measured in the macrorhizon water samples of the pilot area for each of the 12 sampling sessions. One replicate per treatment per sampling.

	13 May	11 June	28 June	05 July	12 July	14 July	29 July	06 Aug	12 Aug	19 Aug	25 Aug	31 Aug
GR olivine VV												
Volume (mL)		75	130	115	140	120	110	60	25	100	95	110
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0	1000	0	0	0
HCO_3^- (µmol/L)	7998	9997	3999	3999	4999	6798	5998	5599	6498	4399	4999	7698
CA (µmol/L)	7998	9997	3999	3999	4999	6798	5998	5599	8498	4399	4999	7698
pH	8.35	8.54	7.85	7.80	8.16	7.97	8.00	8.00	8.30	8.03	8.21	8.12
EC (µS/cm)	1188	1295	1561	1512	936	1208	1231	1341	1580	1155	1170	1297
Ca^{2+} (µmol/L)	2280	2093	5033	6900	2134	2194	1727		2523	1873	2084	2307
K^+ (µmol/L)	76.0	15.9	77.8	47.6	42.5	35.8	27.9		32.0		14.3	18.7
Mg^{2+} (µmol/L)	1959	2376	2379	1185	1639	1826	1673		2528	1671	1736	2243
Ni (µg/L)	9.55	20.09	9.95	24.13	20.61	11.36	24.50	9.35	113.23	21.12	14.67	10.13
Cr (µg/L)	2.62	5.24	3.28	1.20	4.86	3.81	1.69	1.45	3.60	5.58	1.61	1.42
GR olivine VV + biochar												
Volume (mL)		55	120	100	160	80	80	90	10	110	100	55
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0		0	0	0
HCO_3^- (µmol/L)	4999	4999	6998	3499	4999	6598	6798	5599		4999	5399	5998
CA (µmol/L)	4999	4999	6998	3499	4999	6598	6798	5599		4999	5399	5998
pH	7.79	7.79	7.90	7.80	8.05	8.12	8.13	8.03	8.24	8.04	8.23	8.06
EC (µS/cm)	1705	2650	1967	1606	980	1852	1399	1375	1425	1374	1262	1433
Ca^{2+} (µmol/L)	3532	4355	6429	6225	2105	2357	1972			2094	2354	2226
K^+ (µmol/L)	426.7	118.4	80.1	33.5	35.8	38.1	42.2				8.4	18.7
Mg^{2+} (µmol/L)	2836	5013	3587	1761	1675	1950	1911			1988	1736	2297
Ni (µg/L)	83.90	65.24	80.14	81.68	28.10	48.84	76.75	52.54	44.72	52.04	7.41	47.40
Cr (µg/L)		3.82	2.45	2.32	1.75	1.91	1.60	1.53	3.06	5.49	1.90	1.70
GR olivine GM + biochar												
Volume (mL)		80	120	45	90	50	50	60		40	30	30
CO_3^{2-} (µmol/L)	0	0	0	0	0	0	0	0		0	2000	0
HCO_3^- (µmol/L)	4999	6998	4999	3999	5599	6598	6998	5399		3999	4999	6998
CA (µmol/L)	4999	6998	4999	3999	5599	6598	6998	5399		3999	8999	6998
pH	8.32	7.99	7.91	8.10	8.14	8.14	8.12	8.06		8.14	8.33	8.14
EC (µS/cm)	1094	1647	1762	1524	1120	1350	1342	1388		1233	1193	1206
Ca^{2+} (µmol/L)	2497	2931	5631		2038		1834			2062	2005	1936
K^+ (µmol/L)	247.6	42.2	40.4		35.8		38.1				16.4	26.9
Mg^{2+} (µmol/L)	1823	2842	3041	1589	1869		1837			1852	2084	1790
Ni (µg/L)	22.97	80.47	39.52	61.20	40.77	55.90	49.89	42.46		34.05		10.71
Cr (µg/L)		5.96	5.43	4.31	18.87	7.45	2.76	1.36		5.13	3.39	1.53

Table 10.8. Continued. Values of the different soil solution properties measured in the macrorhizon water samples of the pilot area for each of the 12 sampling sessions. One replicate per treatment per sampling.

Carbonates (CO_3^{2-}): Carbonate contents are only **first observed** in the macrorhizon water samples from **early August** onwards (Figure 10.10), which is **one month later than** the first carbonate contents registered in the **experimental** soil water. The observed range of CO_3^{2-} concentrations is however similar in the pilots as in the experimental area: 0–2000 µmol/L.

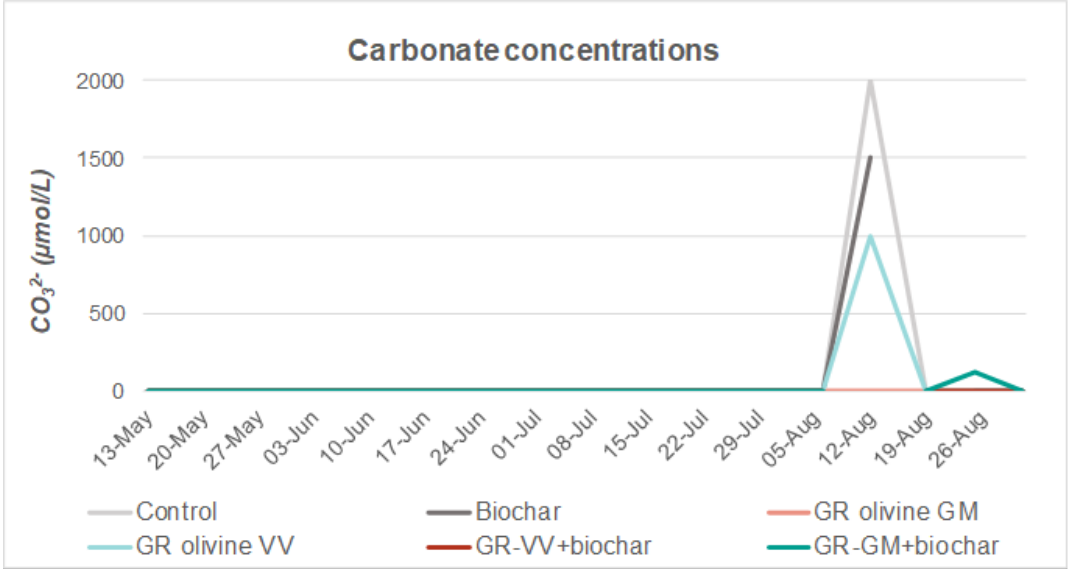


Figure 10.10. CO_3^{2-} concentrations of soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

Bicarbonates (HCO_3^-): Bicarbonate ion concentrations mostly range between 4000 and 10000 µmol/L throughout the entire cotton season (Figure 10.11). The **seasonal trend** observed in the **experimental** area, where HCO_3^- concentrations drop from early July onwards and start to recover again late August, is **not** clearly **recognisable** in the pilot area. As total carbonate alkalinity was calculated from the measured carbonate and bicarbonate concentrations, this parameter also does not show any seasonal trend or variability between the six pilot treatments.

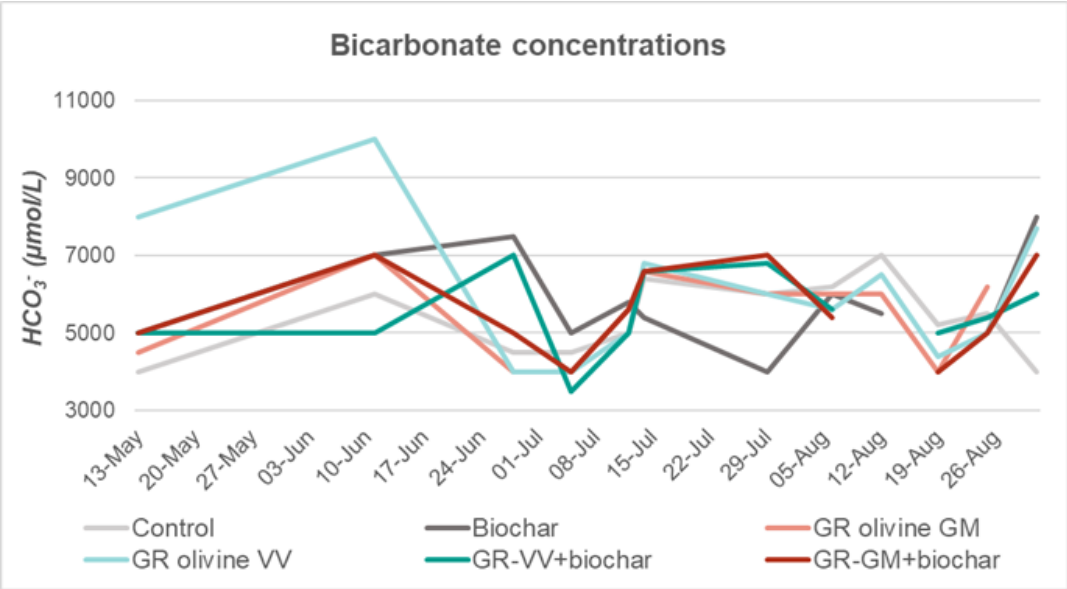


Figure 10.11. HCO_3^- concentrations of soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

pH: The pH of the soil solution (Figure 10.12) was **alkaline** in all treatments and throughout the sampling season, ranging from **7.70 to 8.54**, a slightly larger range than observed across the smaller experimental area. Although less clear, the **seasonal pH trend** observed in the experimental area – decreasing pH from early June until mid-July when pH slowly increases again to its initial levels – is also identifiable in the pilot area. As previously discussed, this might represent addition of nitrogen fertilizer during this time and/or seasonal

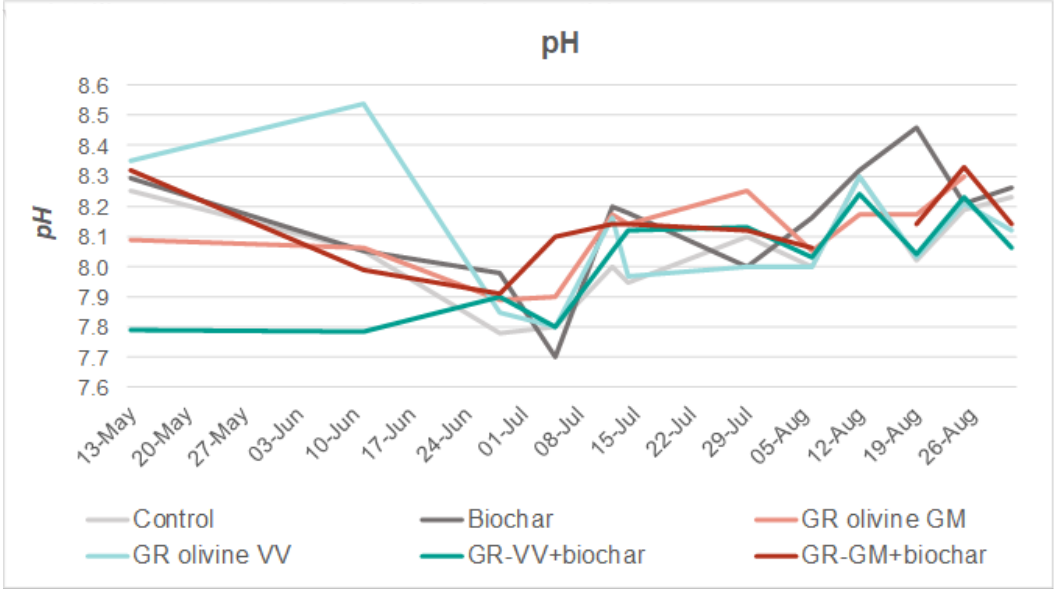


Figure 10.12. pH values of soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

Ca^{2+}, Mg^{2+} and K^{+}: The **seasonal trends** of the basic cations of calcium (Figure 10.13), magnesium (Figure 10.14) and potassium (Figure 10.15) are **similar to** those observed in the macrorhizon water samples from the **experimental area**. Concentrations thereby span somewhat **larger ranges in the pilot area** (Ca^{2+}: 500-9000 µmol/L; K+: 0-420 µmol/L) than in the experimental plots (Ca^{2+}: 1500-6000 µmol/L; K+: 0-100 µmol/L). Only soil water Mg^{2+} concentrations vary within the same range (500 - 5000 µmol/L) across the entire cotton field.

Although **less pronounced**, the opposite **trends** of Mg^{2+} and Ca^{2+} observed in the experimental area (the latter peaking in early July whilst the former reaches the lowest values at the same time) can also be identified in the pilot area. But whereas the experimental plots show K^{+} contents overall decreasing from April through to September with a peak of higher values in early July, only the downward trend is clearly visible in the pilot area. The slight increase of K+ contents at the start of July is thereby probably obscured by **very high initial potassium concentrations** for two of the four olivine rich rock dust treatments.

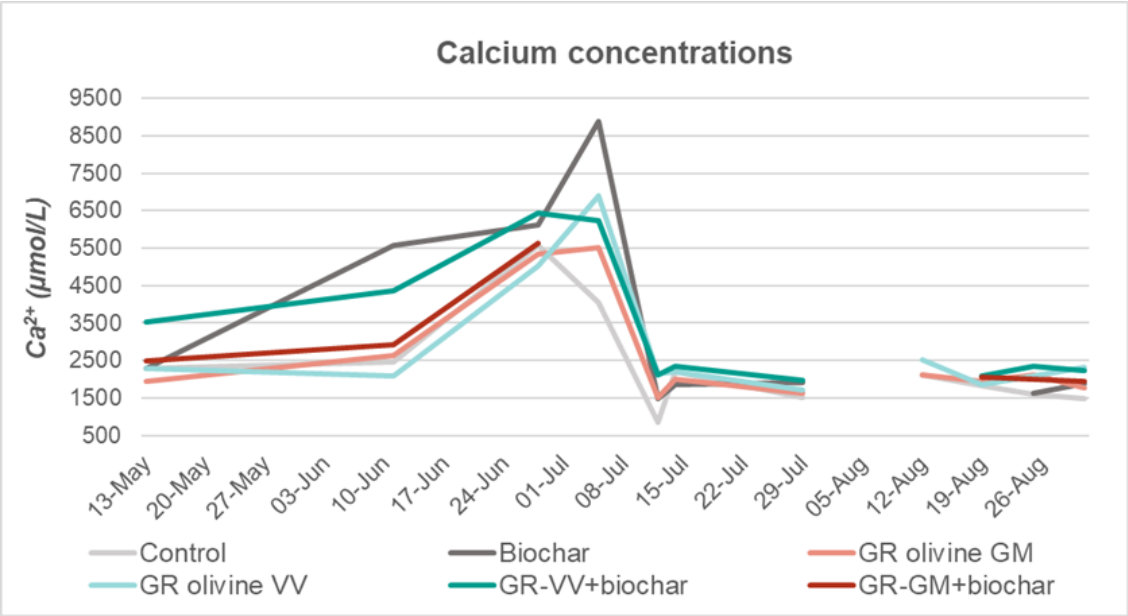


Figure 10.13. Calcium concentrations in the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

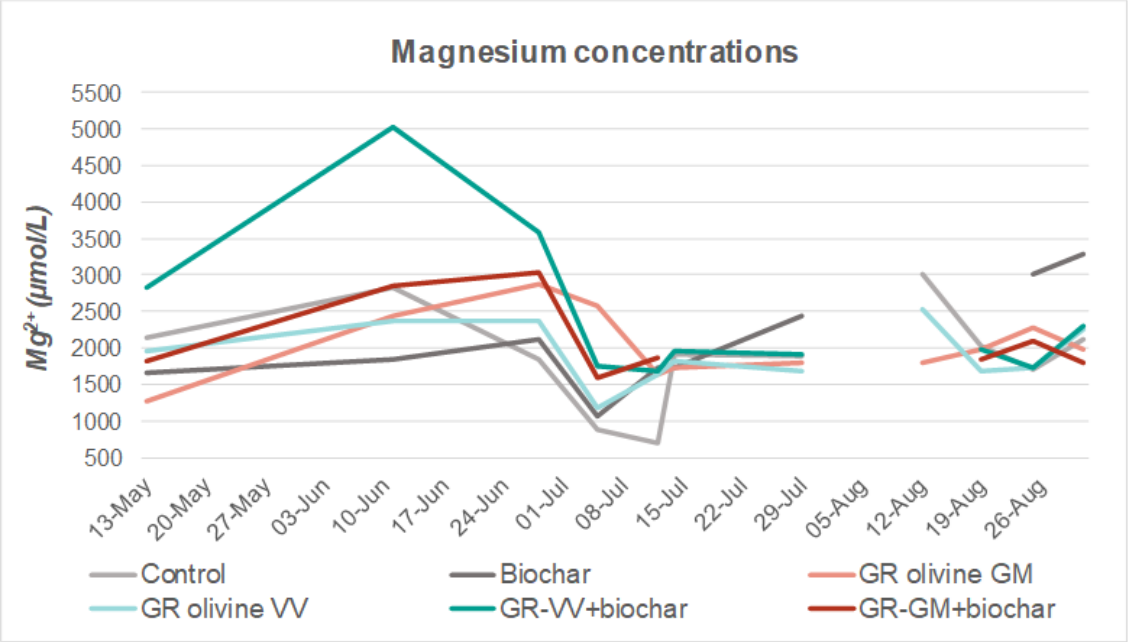


Figure 10.14. Magnesium concentrations in the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

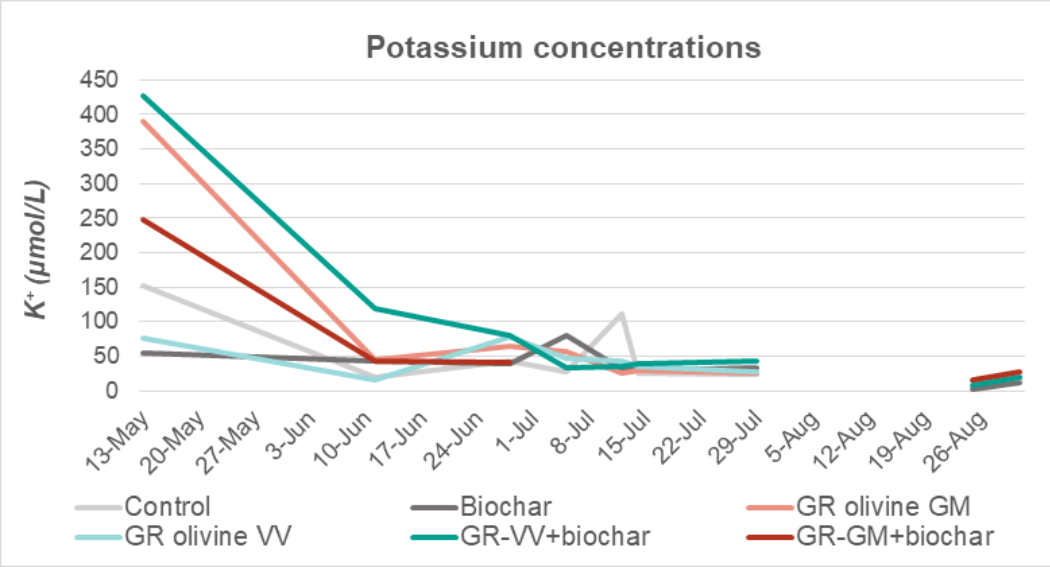


Figure 10.15. Potassium concentrations in the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

Electrical conductivity (EC): Overall, the electrical conductivity of the soil solution shows an **increase from the start of the season** (850-1250 µS/cm) to harvest time (1200-1550 µS/cm) affected by nitrogen fertilizations and nutrients uptake by the plants. The **same** trend is observed **in the experimental area**, albeit at slightly lower values ranging from 700 to 1550 µS/cm. Exception to this general pattern is the Greek olivine rich rock dust from Vitruvit combined with biochar: from mid-May to early July it has distinctly higher EC values than the other 5 treatments (Figure 10.16). This reflects the **distinctly higher** concentrations of **Ca^{2+} and Mg^{2+}**, **and** to a lesser extent **K^{+}**, that this treatment has compared to the other ones during the first part of the season (Figures 10.13, 10.14 & 10.15). It is unclear what could be the reason for these initially higher macronutrient contents of the **GR-VV+biochar** treatment, but it **does coincide with lower pH values** in the first half of the season (Figure 10.12).

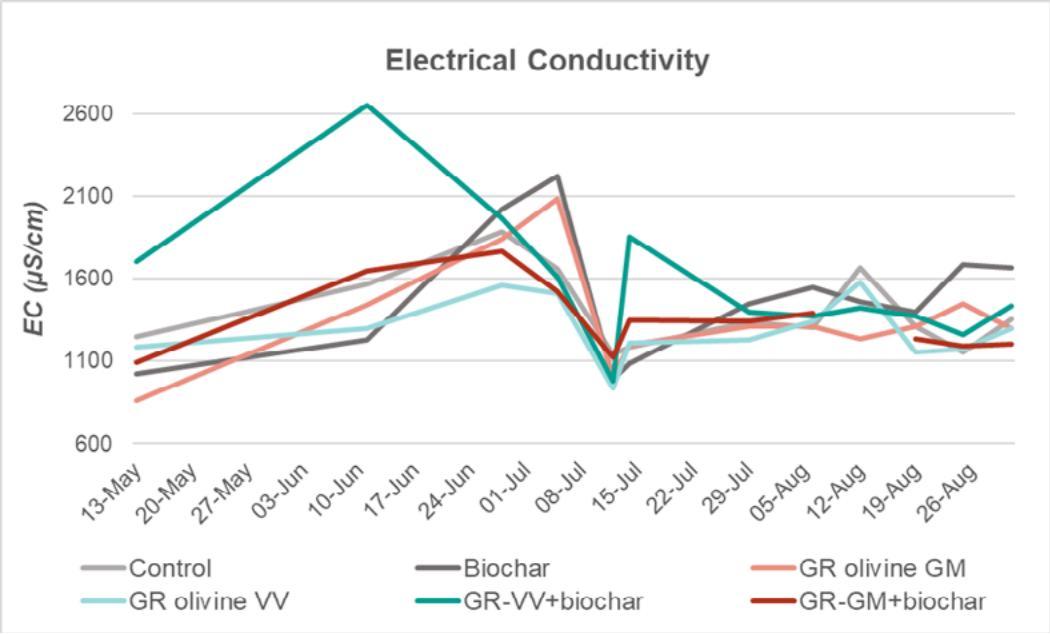


Figure 10.16. EC values of the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

Heavy metals Ni and Cr: Overall, **Ni** concentrations range from 0 to 80 µg/L, a **larger range than** the one observed in the **experimental area** (0-50 µg/L) where olivine rich rock dust application rates were 33 times higher. In the experimental area, Ni soil water concentrations are significantly **higher in** the GR-VV+biochar treatment for the first part of the season, In the pilot area, soil water Ni contents are elevated throughout the season and for both the **GR olivine rich rock dusts combined with biochar** (Figure 9.17). Nickel concentrations in the control, biochar-only and GR-VV treatments are similarly low and the GR-GM treatment has intermediate Ni values.

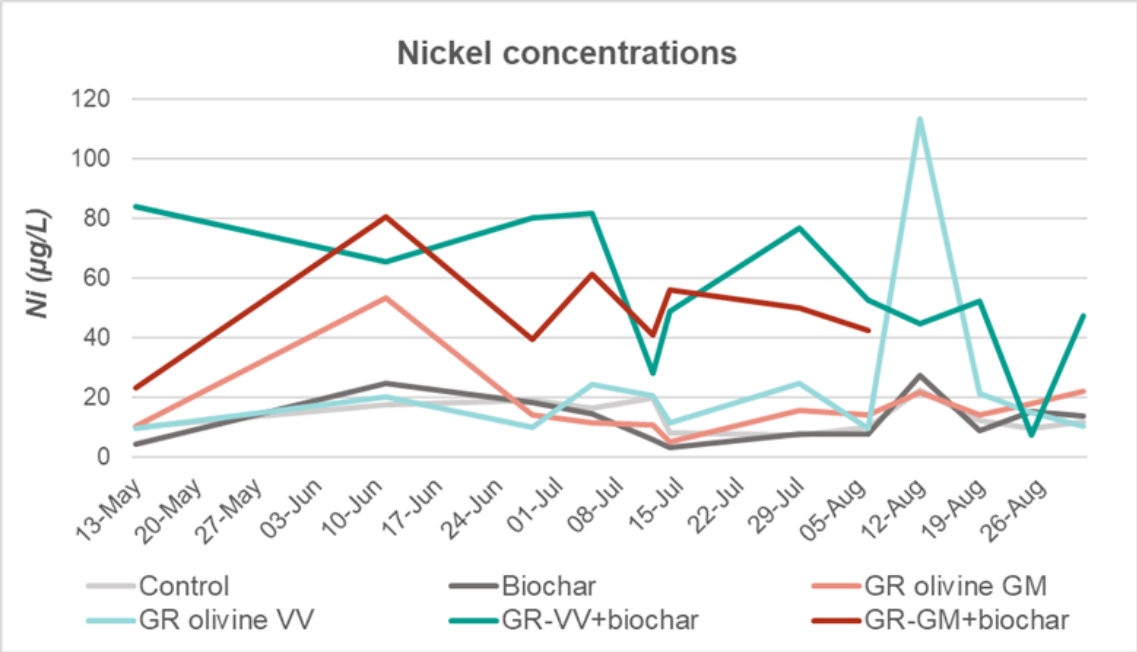


Figure 10.17. Nickel concentrations in the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

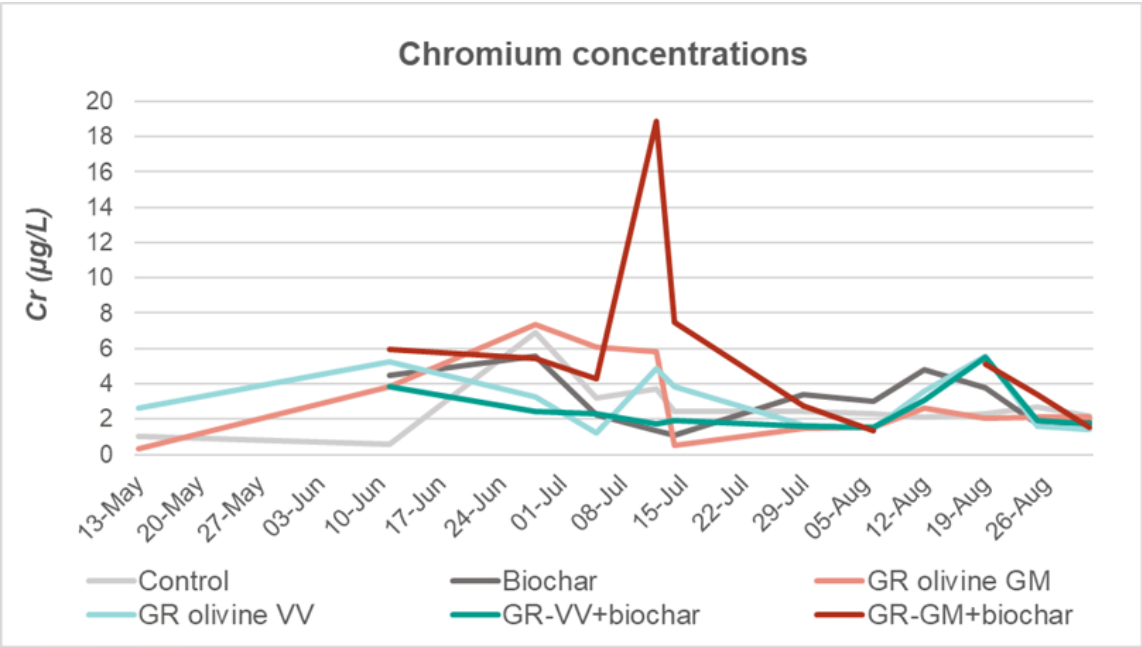


Figure 10.18. Chromium concentrations in the soil water collected with macrorhizons for each of the 6 pilot treatments throughout the 12 sampling sessions.

Contrary to the nickel concentrations, **Cr** in soil water of the pilot area covers a **smaller range** (0-8 µg/L) **than** in the **experimental area** (0-12 µg/L). And whereas higher Cr concentrations are observed in the soil water of the GR-VV+biochar of the experimental area, the olivine rich rock dusts combined **with biochar** generally do **not** show distinctly **higher** amounts of Cr (Figure 10.18).

So although the soil water Ni concentrations show the same trends across the entire field, the Cr contents have a different pattern in the pilot area from the experimental area. The fact that the Ni-Cr containing rock dust is applied at a 33 times lower rate in the pilot area compared to the experimental area makes this even more puzzling. Further experiments need to be carried out to better assess the role of biochar with regards to the fate of Ni and Cr at different SRP application rates.

Section summary

The macrorhizon soil water chemistry data can not undergo statistical analysis as the number of replicates is only 1 per treatment per sampling. Nevertheless, a comparison between the seasonal trends expressed in the experimental and pilot areas is interesting.

Generally, the pilot area soil water solutions show less clear trends across larger data ranges than the experimental area. This might reflect soil heterogeneity across the larger area spanned by the pilot plots, and/or the absence of statistically more balanced averages due to the limited replicates.

Seasonal trends observed in the experimental area for sample volume, pH, Ca^{2+}, Mg^{2+}, K^{+}, EC and Ni are also identified in the pilot plots' soil water. As the olivine rich rock dust application rates are 33 times lower in the pilot area, this might suggest that these soil water chemical properties are mainly reflecting the physical, chemical and biological background processes of the cotton field soil. The addition of nitrogen fertilizer during the cotton growth season is also a likely cause.

The trends for TA, HCO_3^-, CO_3^{2-} and Cr observed in the experimental area are however not (clearly) visible in the pilot area. Especially interesting is the fact that the first detection of carbonate anions is one month later in the pilot area.

In the experimental area, the soil water from the GR-VV+biochar treatment shows significantly higher Ca^{2+}, Mg^{2+}, K^{+} contents at the start of the season and generally higher Ni and Cr concentrations. From the two olivine rich rock dust combined with biochar treatments in the pilot area, only the Vitruvit material reflects the same higher values for Ca^{2+}, Mg^{2+}, K^{+} but Ni contents are elevated for both of them. Chromium, on the other hand, is generally not distinctly higher within any one treatment.

Lysimeter soil water

Table 10.9 presents the results of the analyses of the lysimeter water samples collected from the pilot area on 22 July and 21 September 2021. As we only had one lysimeter for each of the six pilot treatments, **no statistical analysis** can be carried out on these soil water data.

It is nevertheless interesting to **compare** these **soil water geochemical data** to the ones collected from the pilot treatments with macrorhizons. These two sampling methods represent **different time intervals**: whereas the macrorhizons gather water in the ca. 12 hours before the sample is collected, soil water continuously accumulates in the **lysimeters** between two collection times, which is weeks to months. So whereas the **macrorhizon** soil solution data are expected to give an insight into soil solution chemistry at a specific time, the lysimeter samples accumulate the soil solution chemistry over longer periods of time.

The **lysimeter** water data also represent a **different environment** from the **macrorhizon** water data: (1) No irrigation water from early June to late August also means no nitrogen fertilizer was added. (2) The absence of cotton plants within the lysimeters means that no enhancement of rock dust weathering through plant roots and associated micro-organisms could take place.

	Vol. (mL)	CO_3^{2-} (µmol/L)	HCO_3^- (µmol/L)	CA (µmol/L)	pH	EC (µS/cm)	Ca^{2+} (µmol/L)	K^+ (µmol/L)	Mg^{2+} (µmol/L)	Ni (µg/L)	Cr (µg/L)
22-Jul-21											
Control	130	200	4399	8998	8.00	786	1038	32.0	989	51.25	1.00
Biochar	20	2000	1000	3999			314	53.5	217	17.15	0.73
GR olivine GM	50	1000	4999	10997	8.18	940	1076.19	26.35	1092	29.11	3.60
GR olivine VV	25				8.09	263	317	24.3	59		
GR VV + biochar	30	2000	1999	5999	8.13	611	749	168.8	402	20.44	1.49
GR GM + biochar	120	200	5199	10597	7.86	2790	5079	174.7	6154	69.08	0.99
21-Sep-21											
Control	450	400	2199	4799	7.92	2230				34.19	2.82
Biochar	190	300	2199	4699	7.92	2140				20.22	1.90
GR olivine GM	14	600	1999	4599	8.07	1459				20.54	3.04
GR olivine VV	105	700	2299	5299	8.13	2160				74.71	1.20
GR VV + biochar	225	500	2499	5499	7.99	3330				67.70	1.14
GR GM + biochar	85	800	4799	10397	8.31	1322				148.92	0.31

Table 10.9. Soil solution data for the water samples of the pilot treatments collected from the lysimeters. No statistical analysis could be carried out due to the limited number of samples (one replicate per treatment).

It is also interesting to compare the lysimeter soil water chemistry obtained from the experimental treatments with those from the pilot area. Whereas we do not have lysimeter samples for all experimental treatments, we could collect lysimeter soil water from all pilot treatments in both sampling sessions. Table 10.9 suggests there is no correlation between the collected **water volume** and the different soil water properties, as was also observed for the experimental area.

Comparison of the **bicarbonate** (Figure 10.19) and CA data of the lysimeter water with the values observed in the macrorhizon water around the same time shows a rather large variability between treatments and sampling time. Overall, the bicarbonate concentrations are **lower in the lysimeter** than in the macrorhizon soil solutions as well as lower at the end of August compared to the second part of July. The experimental area shows similar trends and HCO_3^- concentration ranges.

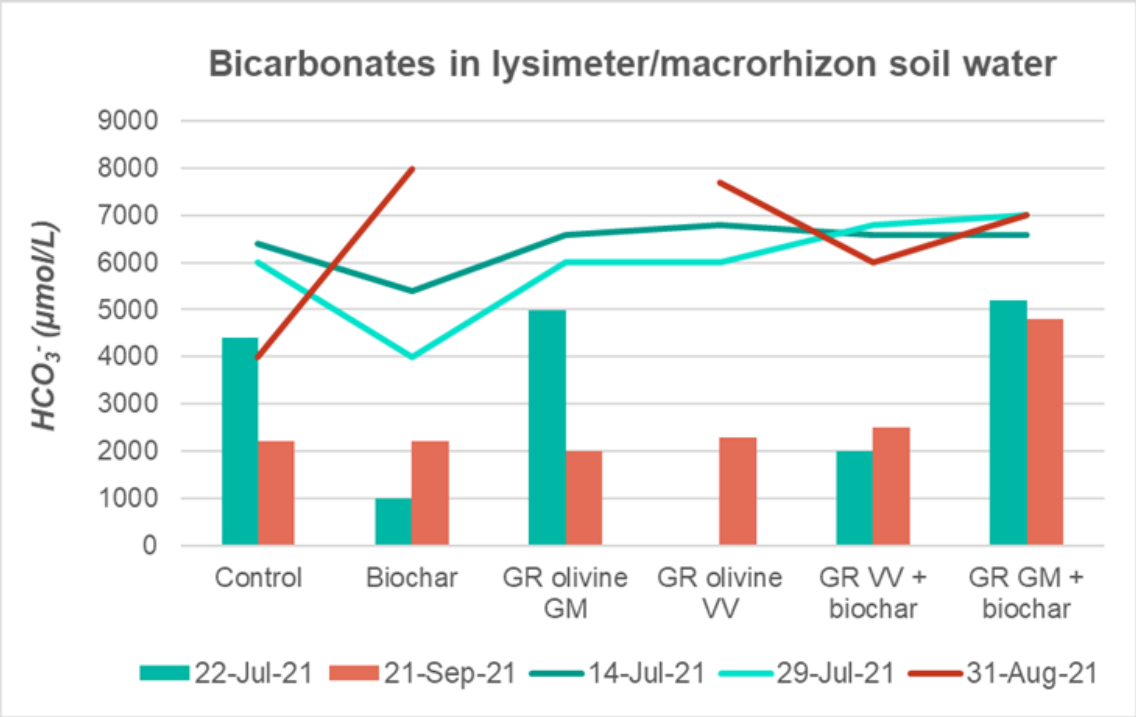


Figure 10.19. Bicarbonate concentration in the soil water from the pilot treatments, collected from lysimeters (bars) and macrorhizons (lines) around similar times.

The **pH** (Figure 10.20) and carbonate concentrations of the pilot treatments show a similar range for the lysimeter water as those in the macrorhizon soil solutions. There does not seem to be any **systematic variability** of pH between treatments or throughout the season. Very similar observations were made for the macrorhizon and lysimeter soil water data of the experimental treatments.

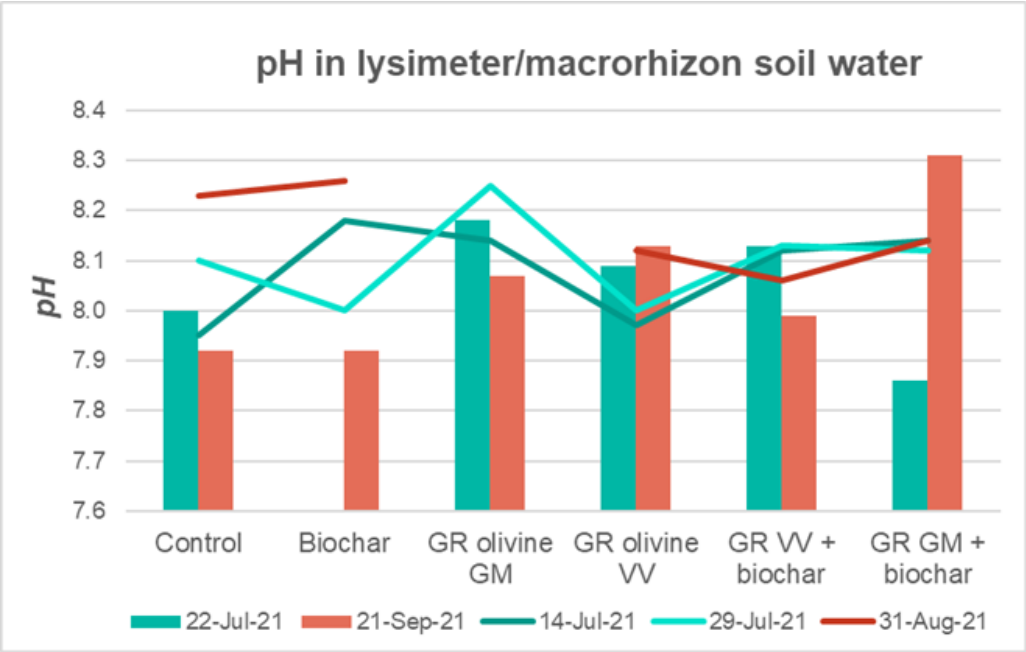


Figure 10.20. pH values of the soil water of the pilot treatments, collected from lysimeters (bars) and macrorhizons (lines) around similar times.

As observed in the experimental area, the **electrical conductivity** of the lysimeter water shows **more variety** than the EC values observed in the macrorhizon water (Figure 10.21). Whereas the EC of macrorhizon water ranges from 1050 to 1850 µS/cm **across treatments and time**, values in the lysimeter water have ranges of 250-2800 µS/cm and 1300-3350 µS/cm for the first and second samplings, respectively. The same was observed within the experimental area, but there the overall range of EC values is much smaller (300-1850 µS/cm).

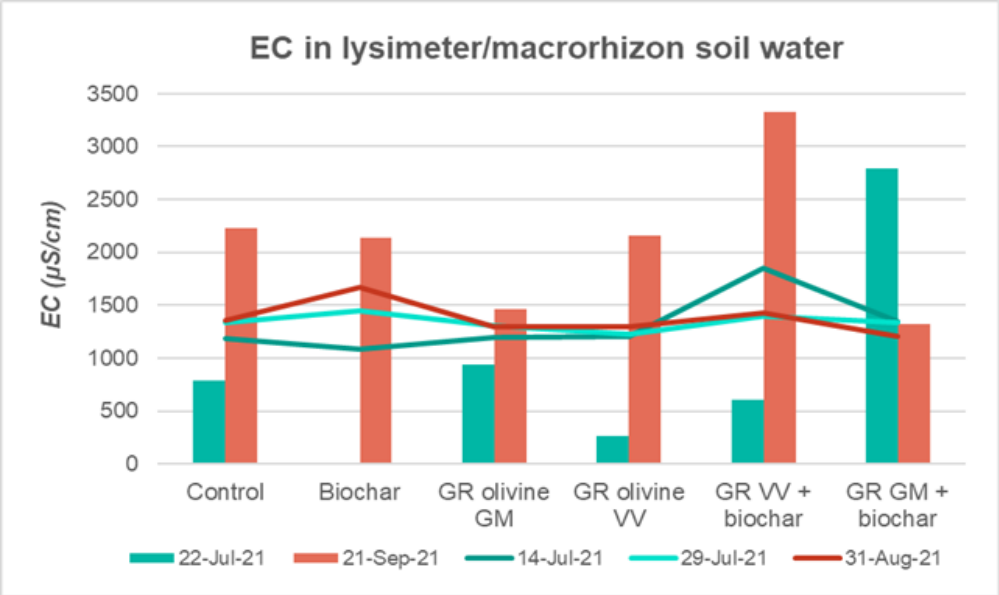


Figure 10.21. EC values of the soil water of the pilot treatments, collected from lysimeters (bars) and macrorhizons (lines) around similar times.

Electrical conductivity is a measure of the amount of **cations** and anions present in the soil water. The Mg^{2+}, Ca^{2+} and K^{+} data for the first lysimeter sampling on 22 July seem to suggest that the EC values of the lysimeter water are mainly **Ca^{2+} and Mg^{2+}** contents. Apart from the anomalously high macronutrient concentrations in the Grecian Magnesite with biochar treatment, Ca^{2+} and Mg^{2+} measured in the **lysimeters** is generally **lower than** in the **macrorhizon** samples collected around the same time (Figure 10.22). Besides the lower concentrations, Ca^{2+} **and** Mg^{2} in the lysimeter soil solutions also show **larger variability between treatments** than in the macrorhizon water. Although similar observations were made for the Mg^{2+} soil water contents in the experimental area, their Ca^{2+} concentrations did not follow this trend.

K^{+} contents in the lysimeter water samples are generally **similar** to those in the macrorhizon water sampled at the same time (10.22). **Only** for the two **olivine** rich rock dust treatments combined **with biochar** is the K^{+} concentration in **lysimeter** water **higher** than in the macrorhizon water. This is probably the result of the exceptionally high initial potassium contents measured in the macrorhizon water samples of both these treatments (Figure 10.15), reflecting the accumulative character of the lysimeter water samples. **Similar** observations were made for the experimental area soil water, **but** there the only treatment with **more K^{+}** in the lysimeter than in the macrorhizon was the DE **basalt** - attributed to this rock dust K-rich mineral contents.

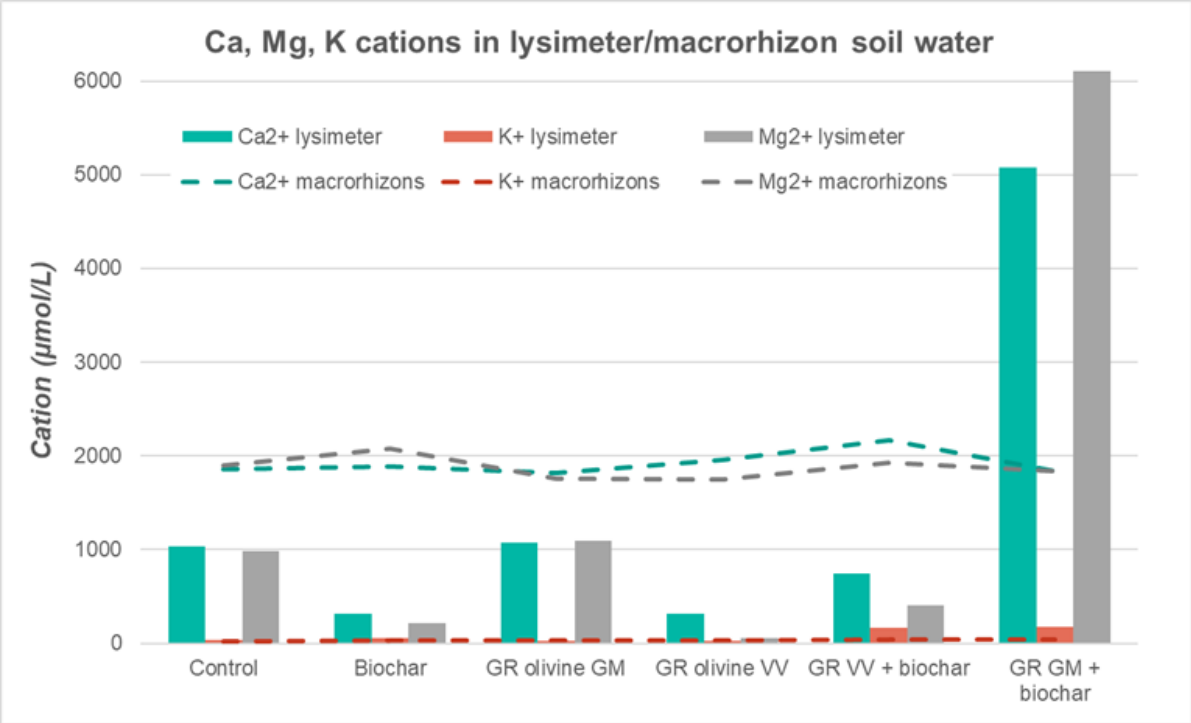


Figure 10.22. Calcium, magnesium and potassium cation concentrations observed in the lysimeter water of the pilot treatments collected on 22 July 2021 (bars) and compared to the Mg2+, Ca2+ and K+ contents in the macrorhizon water collected around the same time (dotted lines).

Overall, **heavy metal** contents observed in the **lysimeter samples** are **similar** to the ones in the **macrorhizon** water (Ni: 22-75 µg/L, Cr:0.3-3.6 µg/L, Figures 10.23 and 10.24 respectively). The only exception is the **higher nickel** concentration of 149 µg/L observed after five months in the Greek olivine **Grecian Magnesite** treatment that also includes **biochar**.

Comparison with the soil water data obtained for the experimental area is particularly interesting for Ni concentrations: although the **pilot treatments** received **33 times less olivine** rich rock dust, the amounts of **Ni** in their lysimeter soil solutions (18-149 µg/L) is generally **2-10 times higher than** in the **experimental area** (7.5-15 µg/L). It is unclear what could be the cause of these counterintuitive Ni concentrations in the soil water of the experimental and pilot areas. The nickel contents of the soil are very similar for the pilot and experimental area, both at the flowering stage (ca. 200-220 mg/kg) and prior to harvest (ca. 160-170 mg/kg). These high background levels of Ni in the cotton field soil are inherited from the soil's source materials which include olivine rich rocks.

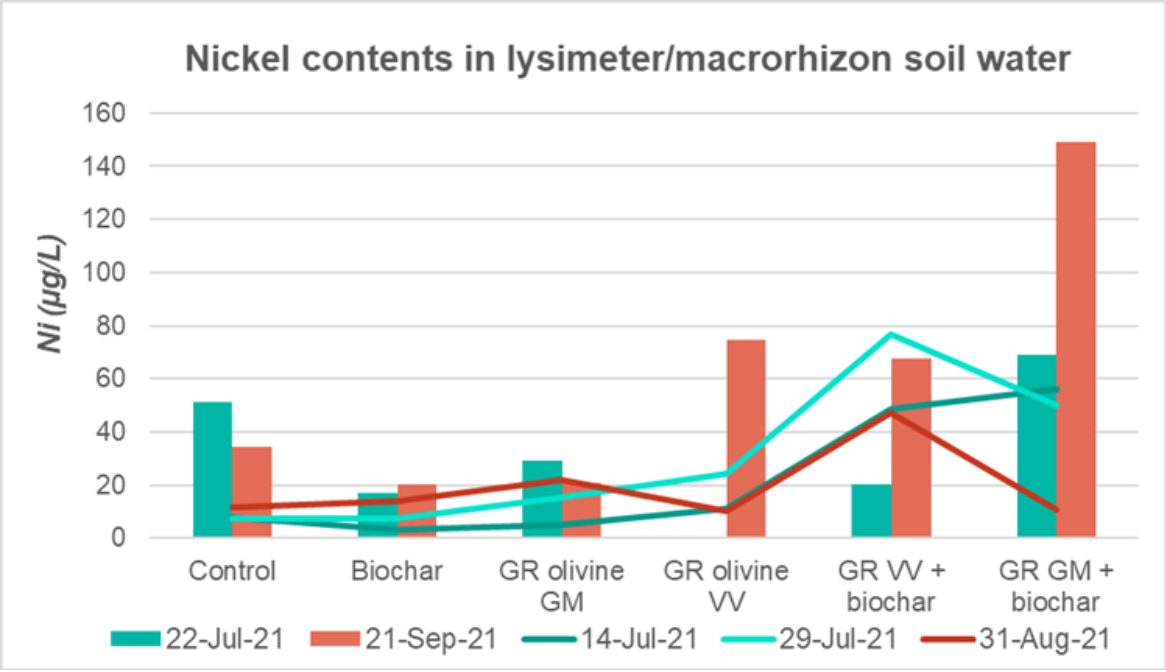


Figure 10.23. Nickel concentrations in the soil water of the pilot treatments collected from lysimeters (bars) and macrorhizons (lines) around similar times.

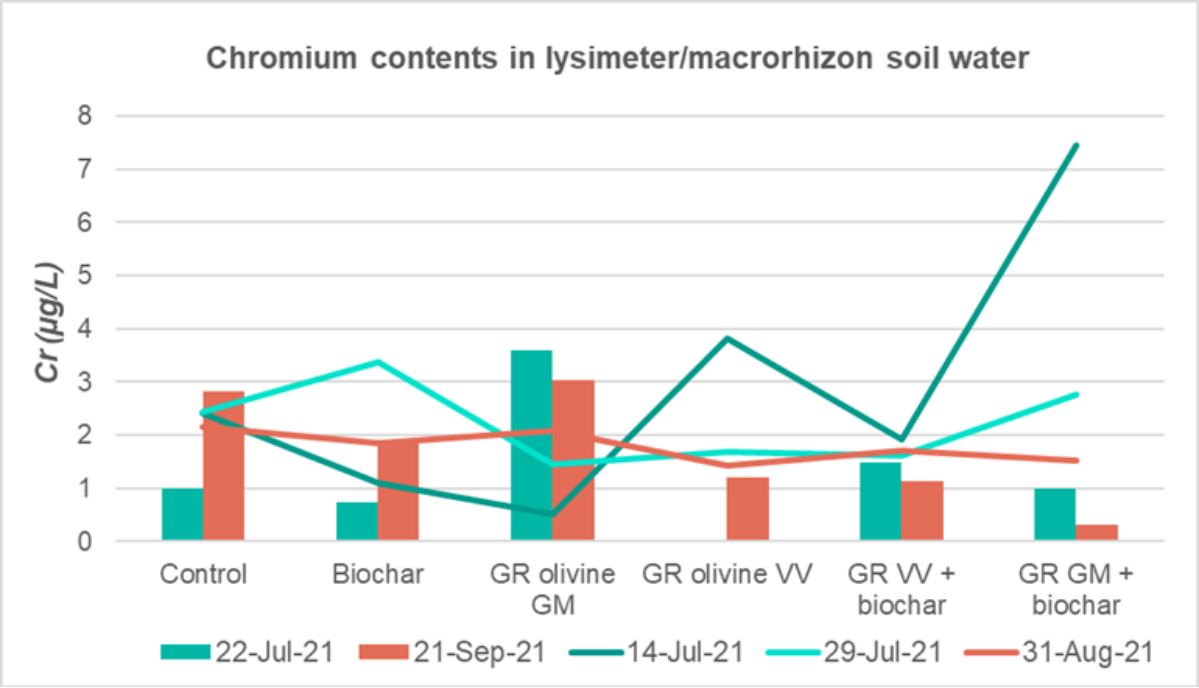


Figure 10.24. Chromium concentrations in the soil water of the pilot treatments collected from lysimeters (bars) and macrorhizons (lines) around similar times.

Section summary

Due to the limited number of samples, the data of the lysimeter water chemistry can not be statistically analysed. Comparison of these data with macrorhizon soil water values collected around the same time as well as with the soil solution data from the experimental area might however reveal some trends.

It is thereby important to understand that the macrorhizon and lysimeter soil solutions represent different environments (with or without fertigation and rhizosphere processes) and specific time windows (accumulated in sampling device 12 hours or multiple weeks to months prior to collection).

In general, the soil water chemistry of the pilot area reflects similar trends as that of the experimental area. However, the pilot data usually show larger value ranges which probably reflect soil heterogeneity in this larger area of the field. Distinct differences between the pilot and experimental area are:

- significantly higher EC values in the pilot treatments
- Mg^{2+} playing a more prominent role in the soil water geochemistry, together with Ca^{2+}, in the pilot treatments
- K^{+} concentrations are higher in lysimeter water of pilot treatments that combine olivine rich rock dust and biochar
- Up to 10 times higher Ni concentrations in the lysimeter (and partially macrorhizon) soil water of the pilot area, despite 33 times lower olivine rich rock dust applications.

Conclusions & recommendations

Conclusions & recommendations

Below we present the main insights gained from the first year of enhanced weathering field experiments, described in detail in the previous chapters. These observations can be grouped into practical lessons learned mainly from the pilot area and scientific knowledge gathered mostly from the experimental area. Based on these preliminary results we then make recommendations for the continuation of the Olivine Project in 2022.

Practical lessons

Our first hands-on experience with rock dust addition to an actively farmed field revealed the importance of site-specific preparation in cooperation with the farmer. The physical characteristics of the rock dust – in our case grain size smaller than 0.25 mm and a high specific density – restrict which of the **farmer's machinery** can be **used for** application. As Doris works a modest total area of fields, he possesses a limited number of farming machinery that we could test. His wheat-sowing machine, although designed to disperse seeds of larger size and lighter weight than our rock dust particles, turned out to be adequate for the **rock dust spreading**. Rock dust was subsequently incorporated into the soil with the farmer's cultivator machine which rips through the soil as it is dragged behind the tractor. A rotary tiller machine with a milling unit would however be able to better homogenize the rock dust into the soil.

It is thereby important to **minimize** the number of runs needed to spread the rock dust. In this particular field, **tractor movement** strongly compacts the soil which has adverse effects on crop growth. Application of biochar, composed of larger and lighter particles than wheat seeds, with the wheat-sowing machine failed as this material scattered much too slow and thus required too many runs across the field. Despite extra tilling carried out prior to cotton sowing, the **soil compaction** in this part of the field resulted into much slower growth and ripening of the cotton. Similar observations were made along the path where the trailer with the rock dust was taken to facilitate manual rock dust spreading. Although the tractor and heavy trailer passed there only once, some delay in cotton growth and ripening was also observed there.

In order to mix the **rock dust** as homogenously as possible with the soil using the cultivator, the material **should be completely dry**. This was the case for 5 out of the 6 rock dusts we applied to the field. The sixth, however, contained about 20% of moisture, which made it much more difficult to spread uniformly over the field as the material clotted together. Upon incorporation of the rock dust into the soil through tillage, all experimental plots with this 6th rock dust were easily recognizable by the up to 7 cm large rock dust aggregates they contained. As soil moisture conditions could have a similar effect, rock dust should only be spread onto a soil that is relatively dry. And once spread onto the field, it needs to be mixed into that soil as soon as possible to avoid it getting wet from precipitation or dew.

Working with such fine and dry materials creates a lot of dust that makes the use of personal protection such as face masks necessary. If possible, rock dust spreading should be carried out on a day when there is little wind to avoid the material being blown away too much. And as explained above, no rain should be expected either when rock dust is added to the field. Exact timing of the different phases of the **EW field experiment** hence depends on the weather. Whereas it is natural for farmers to work their fields **according to the weather**, this is somewhat of a complicating factor for EW research that is otherwise carried out in labs or greenhouses. Weather conditions might also have a profound influence on how workable a soil is, depending on its composition. In the case of our up to 50% swelling clay rich soil, intense or prolonged rainfall turns the field into a sticky mud where no tractor can drive without getting stuck. But after extended time without precipitation the soil dries out and develops large cracks, becoming so hard it cannot be ploughed or tilled. Waiting for the right soil conditions that allow installation of sampling or measuring equipment can thereby be rather frustrating.

Compared to the more controlled environment in a lab or greenhouse, sampling and measuring **equipment suffers from the natural elements** out on an open agricultural field. Intense solar radiation made the plastic of the macrorhizon syringes brittle so that many needed to be replaced throughout the summer season. Small mammals chewed through the macrorhizons' above-ground tubing and in some cases even pulled out the entire inner water sampling tube with the syringe. As for the lysimeters made by our Project Carbdown colleague Ralf Steffens, unfortunately the swelling clay-rich soil on our field turned out to be so heavy that in 10 out of the 14 installed lysimeters the mesh at the bottom of the soil column collapsed into the water reservoir below.

The natural conditions of an EW experiment in an agricultural field with changing seasons and unforeseen animal interactions make it **challenging to collect soil water samples**. Both the volume that can be collected at a single sampling session, and the times that a sampling can be carried out, largely depend on precipitation and evapotranspiration. Most of the 2021 soil water samples were therefore obtained from the macrorhizons right after the irrigation events carried out from early June to late August. As vacuum pressure in the macrorhizons is completely lost after 3-4 hours, we needed to visit the field twice for each soil water sampling. Once to apply vacuum right after irrigation when the soil contained most moisture, and then again the next day to collect the soil water. Overall, most weathering is expected to occur when rainfall is highest in autumn and winter. As we needed to remove the macrorhizons prior to harvest and then had to wait a long time for the weather conditions to be right for ploughing and tillage of the soil, reinstallation of the macrorhizons was only possible late 2021. Soil water data collected during the winter of 2021-2022 will be discussed in the 2022 Progress Report.

Since biochar is a promising material to increase storage time of organically captured carbon as well as to benefit crop growth and to adsorb heavy metals released from olivine dissolution, we included it in some of our treat-

ments. However, the **necessity to activate** the biochar **prior to application** represents a bit of a **challenge for large-scale use** of this material in combination with existing farming practices. In order to avoid that the freshly produced 'sterile' biochar steals away water and nutrients when first mixed into the soil, it should ideally be soaked in compost liquid for up to 2 weeks prior to application. Lack of this material and time led us to mix the biochar with a liquid fertilizer right before application to the experimental plots. As this was both financially and practically (where to contain and mix 4 m^3 of biochar with liquid fertilizer) impossible to do for the pilot area, we opted for the application of a water soluble granular fertilizer right after biochar addition, followed by an intense irrigation event. Ideally, biochar should be manufactured near livestock farming so that it can be mixed with liquid manure or dung before transport to agricultural fields. Further research is however necessary to clarify the complications that might arise when biochar, liquid manure and rock dust are combined. Although mixing rock dust with cattle slurry has been shown to enhance its macro and micro nutrient contents, it also seems to coincide with a significant increase in CH_4 emissions (Swoboda et al., 2021).

All of the above clearly points out the importance of an **excellent cooperation with the farmer** whose field the EW experiment is conducted on. From our own experience, we can say that the active input of Doris during the different steps of the experiment set-up and monitoring was **vital**. He took part in the discussions on how to apply the different materials, suggesting and testing his machinery, providing storage space at the field and on the farm, helping out with logistics of arriving and transporting rock dust, always making himself available to assist us, being as flexible as possible with regards to sowing and harvesting on our part of the field, timely communicating to the IIFC (Institute of Industrial and Forage Crops) researchers about when irrigation, fertigation, pesticide application is carried out or to inform about the local weather or conditions of the field.

Besides the general knowledge that we acquired regarding practicalities of enhanced weathering field trials, we also obtained a lot of experience with how to set up and carry out such field experiments. This information is provided in detail in Chapter 6 and Chapter 7.

Section summary

Enhanced weathering experiments on real agricultural fields require excellent communication and cooperation with the farmer. They know their soil, crops and equipment very well and this knowledge is vital for the practical aspects of the project.

Application of rock dust to the field should involve minimal tractor movement to avoid the negative effect soil compaction has on subsequent crop growth. In order to optimize homogenous mixing into the soil, the rock dust has to be completely dry both when added to and worked into the soil which itself should also have minimal soil moisture. This means that the rock dust has to be spread onto a dry soil and incorporated into it before any rain occurs. The weather is generally a controlling factor in the final timing of the field experiment since ploughing, sowing, irrigation and harvest are all carried out according to the weather.

The natural, open system setting of an agricultural field can take its toll on both the experiment and its equipment. In our case, soil type and dependence on precipitation and irrigation limited the number of times, and volumes, of soil water sampling. Intense solar radiation and chewing mammals destroyed some of the macrorhizons, and a lightning strike prematurely killed off an area of cotton.

Although amending soils with biochar in addition to rock dust is an interesting and potentially synergistic combination of carbon dioxide removal and storage methods, the necessity for the biochar to be activated prior to adding it to the soil creates extra challenges for large-scale application and possible offsetting of some of the positive effects.

Preliminary conclusions

As stated in Chapter 2, enhanced weathering field experiments should be run for prolonged periods of time (at least 2 years and easily up to 5-10 years) in order to yield any scientifically robust results. On the one hand, this is due to a delay in the EW signature appearing in the soil water as the soil adsorbs the initial dissolution products. Upon adding olivine rich rock dust to the field, the soil needs time to reach a new chemical equilibrium. On the other hand, more than one growing season is needed in order to adequately assess any effects on crops and soil. The data collected in 2021 during the first half year of the Olivine Project thus only allow initial interpretation and preliminary conclusions.

From the farmers' point of view, the most important aspect is the effect that the **olivine rich rock dust** might have on his crops. Preliminary results of the first ever EW experiment with cotton suggests there are **no negative effects** for this crop. Both the **yield and quality of cotton** grown on the different experimental and pilot treatments are statistically not different from the cotton in the control plots and the farmer's neighbouring field. Although not statistically significant, the experimental and pilot plots treated with Greek olivine rich rock dust seem to have slightly higher yields than the control plots and plots with other rock dust amendments. Theoretically, one would expect the treatment with Eifelgold basalt powder (a certified natural mineral fertilizer) to result in higher yields. Perhaps the concept of a crop's 'home-field advantage' – defined as a yield advantage resulting from growing a crop variety in the home environment where it is best adapted to – is also applicable for remineralising a soil with local, rather than foreign, rock dusts.

The **nutrient contents** observed in cotton **plants** during blooming, when their nutritional demands are highest, reflect the plants' nutrient uptake from the soil. There was **no statistically significant difference between** the nutrient contents of cotton plants grown in the **various olivine rich rock dust treatments** of the experimental or pilot areas. The **only** exception was the **P** content in the 40 ton/ha experimental area which was distinctly **higher in** the German **basalt** application than in either the control or any of the other rock dust applications without biochar. This likely reflects the presence of 1.5% apatite in the Eifelgold basalt, a phosphate mineral that is absent in all the other olivine rich rock dusts. From these first year experimental results we can preliminary conclude that cotton is a potential EW crop as it does not seem to be affected by the rock dust applications.

Analyses of **soil samples** collected early April prior to rock dust application, during cotton blooming late July and right before harvest mid-September do **not** show **systematic differences between** the various **experimental treatments**. Four months after rock dust application, the soils of the Greek Vitruvit rock dust treatments with and without biochar seemed to have significantly higher exchangeable Ca and CEC values than the other 6 experimental treat-

ments. Total N and available P also seemed to reflect some statistical variations across the experimental area. Two months later, however, the soils from the experimental treatments no longer showed any statistically significant variation in available P and total N contents, and the Norwegian rock dust, German basalt and control had the highest exchangeable Ca and CEC values. The **only** changes observed in the **soil 6 months after 40 ton/ha rock dust application** that might be linked to enhanced weathering are the **increased pseudo total Ni and Cr** contents. At harvest time, these heavy metal contents were lower in the control and German basalt (Ni: 124-129ppm, Cr: 134-135ppm) than in the olivine rich rock dusts (Ni: 144-156ppm, Cr: 140-160ppm).

The soil samples collected from the pilot area did **not** show **statistical differences** between the **1.2 ton/ha treatments** at either flowering stage or harvest. There also were **no increased pseudo total heavy metal** contents of the olivine rich rock dust treatments in the pilot area 6 months after application. This is likely due to the 33 times lower application rate compared to the experimental area where some increase in pseudo total Ni and Cr was observed. This indicates that application of ultramafic rock dusts at the currently allowed levels is safe to do with regards to heavy metal contamination of the soil. However, since higher application rates represent greater carbon dioxide capture potential, more EW field experiments across different soil and climate conditions are needed to further assess the safety of using ultramafic rock dusts at higher application rates.

When comparing soil analyses of the same experimental **40 ton/ha** treatment taken at different times, some **statistically significant seasonal variabilities** emerged. The clearest was the concave pattern of the soil's lower pH during summertime, which seemed to correlate with seasonal trends of EC, P, Pb, Ni, Zn and Cr. CEC and exchangeable Ca and K often reflected a continuous increase or decrease throughout the cotton growing season. As these seasonal patterns were the same for the rock dust treatments and the control, they likely reflected **natural seasonal variation** in chemical, physical and biological processes in combination **with management** operations **of** the **cotton cultivation**, but **not** the dissolution of added **olivine rich rock dusts**. Although **similar seasonal trends** could be seen in the soil of **1.2 ton/ha** treatments in the pilot area, they were **less clear**.

Overall, it seems that the different soil parameters monitored throughout this first cotton growing season only reflected natural seasonal variations, soil heterogeneity and crop management practices. Apart from somewhat increased pseudo total Ni and Cr contents observed at the end of the season in the 40 ton/ha ultramafic rock dusts, the soil did not show any effects from the added olivine rich rock dusts. Although somewhat disappointing, these results are not surprising. The top 30 cm of the cotton field soil represents a weight of about 4950 ton of soil in one hectare, in which we mixed 1.2 ton or 40 ton per hectare of olivine rich rock dust that is expected to completely

dissolve only over a couple of decades. Hence it is logical that after **rock dust additions representing <1.35wt% of the soil**, the **limited mineral dissolution** that occurred **in the first 6 months** is not easily discernible from the soil's natural background signal and variability therein. Additionally, this particular type of soil with a lot of swelling clays, a high pH and elevated inorganic carbon content is expected to further delay dissolution of added rock dusts.

Soil water could only be collected with artificial roots (**macrorhizons**) during 12 sampling sessions: one after intense rainfall mid-May and eleven throughout irrigation from early June until the end of August. In the experimental area we could thereby collect up to 4 replicate samples for each of the 8 treatments. Statistical analysis of the data showed little to **no significant variability between** the eight different **treatments within** a single **sampling session**. It is however interesting to note that despite the lower rock dust application in the **pilot area** (1.2 ton/ha) **compared to** the **experimental area** (40 ton/ha), **similar to higher Ni** concentrations were measured in the former (2-80 µg/L, once ca. 110µg/L) compared to the latter (2-40 µg/L, twice up to ca. 60µg/L). Current drinking water limits for Ni are set by the World Health Organization (WHO) to 70µg/L and by the Environmental Protection Agency (EPA) in the US to 100µg/L.

When studying an experimental treatment's **macrorhizon soil water** chemistry throughout the 12 sampling moments, some **seasonal trends** emerged. The pH sharply decreased during the second part of June before it started to gradually recover from early July onwards - similar to the seasonal trend observed in the soil data. Whereas bicarbonate (HCO_3^{-}) concentrations followed the same trend, soil water EC and concentrations of Ca^{2+} and K^{+} showed the opposite pattern with a peak in late June. Carbonate (CO_3^{2-}) contents are only observed in the soil water samples of the experimental area from early July onwards. Although the soil water chemistry in the pilot treatments spanned larger value ranges, it did show similar seasonal patterns – the only difference was a one month delay of the first occurrence of carbonates. We attribute the larger spread in the soil water data of the pilot area to the fewer number of replicates sampled across an overall larger area (compared to the experimental area), effectively reflecting more strongly the soil's natural heterogeneity. As the same seasonal patterns were recognizable in soil water from both experimental and pilot treatments, including the control plots, they most likely **reflect natural processes** such as evapotranspiration **and** the nitrogen **fertigation** the farmer carried out in June-July.

Collection of **soil water** percolating through the 30 cm top layer of the soil into dug-in **lysimeters** was less successful as these instruments could not receive irrigation water. **Only two times** there was enough water in the lysimeters **for some of the treatments** to be **collected**, once in late July and once in late September. Compared to soil water sampled with macrorhizons, soil water in the lysimeters (1) represents water collected merely through

gravity over weeks to months, instead of extracted from the soil by applying vacuum pressure over a couple of hours, (2) did not receive irrigation and hence nitrogen fertilizer in early summer, and (3) cannot reflect root related biological influence on rock weathering as there were no cotton plants inside the lysimeters.

Hence, **lysimeter soil water** represents a **different environment and time-frame from the** above discussed **macrorhizon soil water**. Moreover, as there was only one lysimeter installed for each treatment, no statistical evaluation is possible for the very limited data retrieved from them. Comparison of the lysimeter soil water data to soil water geochemistry sampled with macrorhizons around the same time shows either similar, lower or higher values for particular parameters, and sometimes overall much larger value ranges. Interestingly, **lysimeter soil water** of the **pilot treatments** had overall **higher Ni concentrations** (18-149 µg/L) **than** the **experimental area** (7.5-15 µg/L) – the same trend as already observed in the macrorhizon soil water. From the data collected so far, it is unclear what might cause seemingly higher Ni concentrations in soil water from the 1.2 ton/ha application rate in the pilot area compared to the experimental area where 40 ton/ha of rock dust was applied. The soil's background Ni contents were statistically the same in both the pilot and experimental area, albeit relatively high due to the geology of the wider region and the soil genesis.

Six months after rock dust application, little to no significant differences were observed between the nutrient uptake of the cotton, soil or soil water of the untreated control plots and of the treatments. The difficulty of identifying the dissolution of the added rock dust suggests that we were **too optimistic** hoping to distinguish between the enhanced weathering signals of **six different olivine rich rock types**. The mafic rock dust, the Eifelgold basalt from Germany, might be recognisable through the higher P nutrient uptake in the cotton grown in it. The 5 ultramafic olivine rich rock dusts, however, could not be distinguished from one another. Only in case of higher application doses of 40ton/ha they seem discernible from the control and basalt through increased pseudo total Ni (and Cr) in the soil 6 months into the field trials. Compared to lab and pot EW experiments, **field trials** clearly represent a more **complex environment** that obscures the enhanced weathering signal, and they **need** to be carried out over **longer periods**. Testing different silicate rock dusts with the aim to assess their respective effects on enhanced weathering is therefore best done in closed systems until the EW dynamics in a natural, open system are better understood from simpler EW field trials.

Biochar, a more stable form to store carbon than biomass, can positively influence a soil's structure resulting in more water and nutrient storage capacity as well as increased microbiological activity. Besides enhancing rock weathering through these indirect effects, biochar might also be a heavy metal sink adsorbing released Ni and Cr. For these reasons, we enthusiasti-

cally added the combination of **Greek olivine rich rock dusts with biochar** as an extra parameter to our first field scale EW experiments. Addition of biochar to our field trials was also interesting from an agricultural point of view as so far little to no trials in similar soil and climate conditions have been carried out.

As mentioned above, including the biochar in our EW field trials required different fertilisers to be used for the biochar treatments in the experimental area and the pilot area. This difference in fertilization is likely the reason why the biochar treatment in the experimental area seems to have a somewhat higher yield than the corresponding rock dust treatment, but this is not observed in the pilot area. There does **not** seem to have been any statistically significant **effect of** the **biochar on** the **cotton yield or quality** in the first season after addition to the soil. Comparing the Greek rock dust treatments with and without biochar addition, the **plant P content** seems to be somewhat **higher with biochar** – a trend that is statistically significant in the experimental area. Since treatments including biochar have the same pseudo total Ni and Cr content as the other ultramafic olivine rich rock dusts , biochar does **not** seem to have any **effect on the soil's** composition in the first 6 months after application.

The only macrorhizon soil water parameter that showed distinct differences between some treatments in more than one sampling session is the **Ni concentration**. In the experimental area, the **Greek** Vitrivut **rock dust with biochar** treatment repeatedly had **significantly higher** Ni contents than the same rock dust without biochar, the control or the basalt treatment. The limited number of replicate samples collected from the pilot area one did not allow for statistical evaluation of soil water chemistry variability between the different treatments. Nevertheless, both treatments that combined biochar with Greek olivine rich rock dust also often showed higher Ni soil water contents than any of the other 4 pilot treatments.

The same observations were made for the lysimeter water samples. The overall highest concentration of Ni in soil water - an extreme outlier value of 281µg/L in comparison to up to 80 µg/L observed throughout the season – is observed late July in the lysimeter sample from the experimental treatment with biochar. The second highest outlier Ni concentration, 149 µg/L, was measured in lysimeter soil water collected late August from a pilot biochar treatment. Although Cr soil water concentrations do not show the same trend as Ni, the highest Cr amount - an outlier value of 59 µg/L compared to usual concentrations of up to 8 µg/L – was detected in macrorhizon soil water from the experimental biochar treatment late August. At this point, the observed Ni increase in soil water is neither statistically confirmed for all biochar treatments nor for every sampling session. However, it definitely shows that more research needs to be carried out on the effect of biochar application on the mobility of Ni in clayey soils.

Section summary

The first cotton crop grown in combination with olivine rich rock dust applications did not show any statistically significant effects on either its yield or its quality. The plants' nutrient uptake also seemed unaffected by the addition of these materials. Only the P nutrient content was somewhat higher in cotton grown in the 40 ton/ha Eifelgold basalt treatment, likely reflecting the presence of the phosphate mineral apatite in this rock type.

Six months after application of the rock dusts, the only observable difference in the soil was slightly higher amounts of Ni (and Cr) in the ultramafic treatments compared to the control and basalt. This trend only showed in the higher application dose of 40 ton/ha and not in the 1.2 ton/ha treatments, suggesting that it is a chemical signature of the enhanced weathering that happened over this time.

Soil water sampled during the period from mid-May to late August did not seem to reflect any effect from the olivine rich rock dust addition. The only visible trend was higher Ni contents in soil water collected from the pilot area compared to soil water from the experimental treatments. Since this was also observed in the untreated plots and as the pilot area received 33 times less rock dust than the experimental area, this is not likely an effect of the added rock dusts.

In general, the overall larger pilot area with a single replicate for each treatment showed larger ranges of analysed parameter values, and less clear trends, than the overall smaller experimental area with 4 replicates for each treatment. We believe that this systematic wider data spread in the pilot area reflects both soil heterogeneity sampled across a bigger area and a larger statistical uncertainty.

Nevertheless, both experimental and pilot treatments clearly showed similar seasonal patterns in their soil and soil water composition. As these temporal trends were observed across treatments and control alike, they are thought to represent natural changes in the biological, chemical and physical processes throughout the cotton-growing season in combination with crop management practices such as fertigation.

Comparison of soil or soil water data collected at a specific date did not show any statistically significant variability between the different treatments in the pilot or the experimental area. It thus seems that none of the parameters that we hoped would reflect the EW signal and allow us to track CO_2 removal (pH, EC, TA, HCO_{3^-}, CO_3^{2-}, Ca^{2+}, Mg^{2+}, K^{+}) showed any relevant changes up to 6 months after the olivine rich rock dust application.

The lack of a clear chemical signature of the enhanced weathering going on during the first 6 months of the experiment is probably due to a combination of multiple factors. First, the natural chemistry of an open system agricultural field largely obscures any emerging signal from the gradual dissolution of rock dust addition that represents <1.35 weight% of the soil it was mixed into. Second, it is known from more straightforward closed system lab experiments that observation of the EW signature in soil water is delayed due to re-equilibration of the soil after rock dust addition, resulting in initial adsorption of the EW products to soil particles. Lastly, both the soil type we used and the climate we work in are not optimal for enhanced weathering, which is thought to work best in the more sandy, low pH, better drained and nutrient-poor soils of the humid tropics. Although our clayey, high pH and carbonate rich soil is not optimal for EW, preliminary results from a simultaneously carried out Carbon Drawdown field experiment in a more EW appropriate soil in Bramstedt, Germany, also shows the absence of a clear chemical EW signature in the first half year.

Despite the fact that the biochar application did not show a statistically significant increase in cotton yield as may be expected, it did seem to lead to a higher P uptake by the cotton plants during flowering. Surprisingly, both the pilot and experimental treatments that combine biochar with olivine rich rock dust often show elevated amounts of Ni in the soil water. It is unclear how biochar might affect Ni mobility in this particular soil.

Recommendations for 2022

Based on the above presented preliminary results, we recommend both the continuation of the cotton field experiment for a second year as well as the start of a completely new EW field experiment.

Since cooperation with the cotton farmer is excellent and we now gathered the know-how on rock dust application, sampling of different materials and growing season specifics for this particular field and crop it would be relatively easy to **carry out** the **2021 cotton field experiment for a second year**. A second year of the same EW cotton experiment is necessary to solidify the preliminary results obtained regarding the absence of any effect of the olivine rich rock dust on the cotton crop yield or quality. From a scientific point of view, it is very valuable and interesting that in this field there are olivine rich rock dust additions that have already been weathering for one year.

However, as we could generally not make a distinction between the different olivine rich rock dust treatments, there is no need to **re-apply** all 6 different materials. Instead we propose to carry out a second round of SRP addition **in the spring of 2022**, reapplying only the **two Greek olivine rich rock dusts** to the different treatments that they were part of in 2021. This means 40 ton/ha addition of Grecian Magnesite rock dust to the four plots in the experimental area (without biochar), and to the two appropriate plots (with and without biochar) in the pilot area at a dose of 1.2 ton/ha. Likewise, the Vitruvit rock dust will be re-applied at 40 ton/ha in both the experimental treatments in the experimental area (with and without biochar) and at 1.2 ton/ha in the respective pilot plots with and without biochar. This second round of rock dust addition represents in the pilot area the practice of annual SRP application as is for example commonly done with fertilizing, liming,... whilst in the experimental area it increases the possibility of seeing the EW chemical signal in soil and soil water.

As **biochar** is supposed to be added to a soil only once in a certain amount of time due to its prolonged effect, we can assess its **potential effects** on crop or enhanced weathering **after one year settling in the soil**. The respective control plots will also keep their role in the second year of this EW field experiment. This effectively means that whereas the same number of samples and analyses will be carried out in the pilot area, efforts in the experimental area will be halved as the 8 treatments will be reduced to 4. Besides soil sampling, the 4 other experimental treatments with EU rock dusts will not be monitored in 2022. Cotton will again be sown all across our 2 ha of the field.

This **second year of the experiment** will **shed more light on** the observations of the first year, whereby we are particularly interested to see whether:

→ The Greek olivine rich rock dusts show any significant **effect on cotton yield and quality** in a second growing season.

- → The trend of **higher amounts of pseudo total Ni (and Cr)** contents **in** the **soil of** the **40 ton/ha treatments** persists and maybe builds up throughout the second year.

- → **Seasonal patterns** observed in 2021 **in** the **soil and soil water** of all treatments will be visible again throughout the 2022 growing season and how they might be different.

- → **Any** of the **soil or soil water parameters** besides Ni or Cr starts to **reflect** an **enhanced weathering** signal in the second year after another rock dust application.

- → The **systematic difference** between the **pilot** area **and experimental area**, with larger soil water data ranges for the former, persists also in the second year. We are thereby especially curious to see if also in the second year the **soil water Ni** contents will overall be higher in the pilot plots than in the experimental area.

- → The **biochar** has any effects on cotton, soil or soil water during the second growing season and if any of its effects suggested by our preliminary results – **higher P uptake** by cotton and **higher Ni and Cr** concentrations **in** soil **water** – will again show in the second year. Especially the potential effect of biochar on the mobility of Ni in this type of soil needs further research.

Although continuation of the 2021 cotton field experiment is valuable, preliminary results indicate that the initial design included too many different treatments and a soil which is not optimal for enhanced weathering. Monitoring of the EW process was furthermore limited due to added complications from nitrogen fertilization during summer, the need to remove sampling equipment prior to harvest, the disruption of the soil when cotton plant remains are ploughed into it and dependence on the cotton crop's need for irrigation. We therefore suggest to set up **a second field experiment in 2022** that minimizes some of the above uncertainties and complications:

- → The Institute of Industrial and Forage Crops (IIFC) **in Larisa** has experimental fields with a soil that has lower pH, less clay content, more organic matter content and nearly no carbonates. Theoretically, this **soil** is **better for enhanced weathering** than the clayey calcareous cotton field soil.

- → We propose a more simple set-up involving **only the Greek rock dust** from Vitruvit, which has the overall **highest olivine content, at** two different application doses of **50 ton/ha and 100 ton/ha**. These higher applications combined with a supposedly better soil will hopefully improve the chance of observing an EW signal. At this point we do not want to involve **biochar** as we first and foremost want to understand and quantify the CO_2 removal through the mineral rock dust dissolution.

- In order to minimize the uncertainty of our analytical data stemming from natural soil heterogeneity and to increase the scientific value of our data, we will carry out this new experiment in a **randomized block design with 5 replicates** for each of the 3 treatments (control, 50 ton/ha, 100 ton/ha) organized in plots of 2m by 2m each.

- To **minimize disturbance** of the soil, and the need to uninstall and reinstall **monitoring and sampling equipment** after every harvest and before every new growing season, we opt for a **perennial crop**. **Alfalfa** is a highly researched crop at the Larisa Institute which is left in the soil for 2-5 years whilst only the top part is periodically harvested. This crop furthermore brings its own environmental benefit as it is one of the few livestock food crops that **does not need** any **nitrogen fertilization**. Furthermore, N fixing crops such as alfalfa have a lower pH in their rhizosphere which is beneficial for enhanced weathering (Haque et al., 2019).

- Our IIFC **colleagues' expertise in growing alfalfa** will help us to correctly prepare the soil, sow the seeds and care for the growing plants. Since the new experiment will be right next to the Institute building, they can give advice and **help** us out **with all practical aspects** of growing alfalfa in this soil, as the farmer does in the cotton field.

- Since the alfalfa in this experiment will be grown in fields that are entirely property of the IIFC, we are **free to decide about fertilization** that might affect the soil water chemistry and **to apply as much irrigation** as we deem necessary for the experiment. The location of the new experiment next to the Larisa Institute furthermore allows us to easily check and maintain it, on a daily basis if needed.

- We would install multiple **lysimeters and macrorhizons** that allow us to **sample soil water** in distinct time frames and from different soil environments. Whereas rock dust would be mixed into the upper ca 20 cm of the soil, we would sample water from a depth of about 17-18 cm, well within the rock dust-soil mixing zone, to increase the possibility of observing the EW signal.

- Finally, we would also install **electronic pH, soil moisture and EC sensors** at the same depth of about 17-18cm to monitor these basic soil parameters throughout the duration of the experiment, which is expected to be up to 2 years. Simultaneous EW experiments of Project Carbdown are already using such sensors in field trials in Germany in the hope that a change in chemistry due to EW can be picked up by (one of) these parameters.

- Besides regular **soil water sampling and** analysis, we will also carry out periodic **sampling of soil and alfalfa crops** to be analysed for the same parameters as assessed in the cotton field experiment. This way we aim to both monitor the CO_2 removal through EW in this new experiment and identify the potential effects of the added ultramafic rock dust on the soil and crop.

Section summary

We propose to continue the cotton field experiment for a second year and to reapply only the two Greek olivine rich rock dust materials. From an agricultural perspective, any effects of EW with olivine rich rock dusts on crops need to be assessed for at least two subsequent years. With regards to the CDR potential of EW in this particular setting, continuation of the cotton field experiment might show a clearer EW signal in the second year as well as confirm the preliminary results from the first year. We are thereby interested to see if (1) the soil's elevated Ni content in the 40 ton/ha treatments, believed to reflect 6 months of EW, will persist and perhaps even increase, (2) the systematic differences in soil and soil water data obtained from pilot and experimental area are maintained, (3) the same seasonal patterns in soil and soil water will be observed, and (4) the addition of biochar to the soil indeed results in higher Ni concentrations in soil water.

As our first experience with an EW field experiment showed that it was probably too complex (many different added materials; influence of soil heterogeneity over large area; not the most appropriate soil type; soil water limited by precipitation and irrigation; soil processes disturbed by fertigation, harvest and subsequent ploughing,...) we suggest to set up a new experiment in 2022 that reduces these complexities. It would be a smaller field experiment next to the Institute of Industrial and Forage Crops in Larisa where the soil is deemed better for EW. The crop would be the perennial livestock food alfalfa which provides for its own nitrogen needs, and we would apply only one Greek olivine rich rock dust at two higher application doses. This new experiment would have 5 replicates per treatment and a sprinkler irrigation system that we can use as we want. Besides soil, plant and soil water sampling (with both lysimeters and macrorhizons) we plan to also install electronic soil sensors to continuously monitor pH, EC and soil moisture.

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Four-legged Olivine Project team member Prima.

Group photo taken when the Project Carbdown team could finally get together for the first time in July 2022.

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Appendix A

Appendix A – Preliminary soil analyses

Soil parameter	1st core 0-20 cm	1st core 20-40 cm	2nd core 0-20 cm	2nd core 20-40 cm	Profile A1, 0-40cm	Profile C1, 40-80cm	Profile C2, >80cm
Sand (%)	22	20	18	28			
Clay (%)	51	57	47	51			
Silt (%)	27	23	35	21			
Soil texture type	Clay	Clay	Clay	Clay			
pH (H_2O 1:1) (25°C)	8.3	8.5	8.6	8.5	8.4	8.7	8.8
EC 25°C (µS/cm)	403	446	419	457	366	466	743
$CaCO_3$ (%)_ Equivalent	23	25	23	25	22	26	26
Soil organic matter (%)	1.5	0.62	0.81	0.44	0.93	0.69	0.56
P ($_{Olsen}$) (mg/kg)	3.7	2.2	3.2	5.2	2.7	2.3	2.5
N (Kjeldahl) (g/100g)	0.091	0.053	0.083	0.056	0.098	0.053	0.045
K (cmol+/kg εδ.), exchangable	0.54	0.34	0.47	0.34	0.46	0.27	0.33

The above analyses were carried on soil samples taken during the reconnaissance fieldtrip and first visit of the field in January 2021.

1st and 2nd core = soil collected on 21 January 2021 with a simple soil-sampling auger

Profile A1, C1, C2 = soil collected from soil profile opened with JCB digger on 22 January 2021

Appendix B

Appendix B – Preliminary analyses of Greek olivine rich rock dusts

ANALYSIS REPORT

December 15th, 2020

Your Reference: Various Harzburgite samples
Our Reference: 2011BI

Analysis Requested

The requested analysis is that of 3 samples by various techniques. The list with the samples and the analyses is shown in Table 1.

Analysis

The samples were first oven-dried at 40°C prior to any analysis.

Bulk Mineralogical analysis by X-ray Diffraction (XRD)
For each sample, a representative part was sampled for the determination of the bulk mineralogical composition. The powders were ground in a wet milling device in ethanol. After drying, the samples were treated in a way to avoid preferred orientation and loaded in XRD sample holders. They were measured by X-ray diffraction using CuKα radiation. The subsequent identification was performed by comparison of the positions and intensities of the reflections with those of the minerals in the available databases. The quantification was performed by an in-house method based on the Rietveld method[1]. The quantitative mineralogical composition of the samples is shown in Table 2. The diffraction patterns can be found in Figure 1.

Bulk chemical analysis by X-ray Fluorescence (XRF) - quantitative
A fusion disk was made by mixing a 0.75g of the sample with 9.75g of a combination of lithium metaborate and lithium tetraborate with lithium bromide as a releasing agent.

[1] During a Rietveld refinement, an XRD pattern is 'calculated' based on the structure models of the minerals present as they are found in literature or in databases (ICSD). The calculated pattern is then fitted to the measured pattern by refining the structure parameters etc.. Quantitative phase contents can be derived from the so-called 'scale factors' which are refined during the procedure.

Contact: Rieko Adriaens / Tel. +32 485 187934

Samples are fused in Pt crucibles and poured into Pt molds. Samples are then analyzed on a Panalytical Axios Advanced wavelength dispersive XRF.
The intensities are then measured and the concentrations are calculated against standard reference materials. In general, the limit of detection is about 0.01wt% for most of the elements.
The results of the analysis are shown in Table 3.

Bulk chemical analysis by X-ray Fluorescence (XRF) - screening
The same disk that was used for the fully quantitative analysis, was screened semi-quantitatively for elements that cannot be quantified using the SRM's.
The results of the analysis are also shown in Table 3.

Particle Size analysis by laser diffraction
The grain-size distribution of the samples was measured using laser diffraction after wet dispersion in water in a Coulter LS13 -320, using an Aqeuous Liquid Module. Ultrasounds were used for the sample dispersion. The reported data were obtained by using the Mie theory.
The measurement data and the statistical parameters of the measurements are shown in Tables 4 and 5. The cumulative frequency distributions are also shown in Figure 2.

Scanning Electron Microscopy (SEM)
A fresh fracture surface of sample "SGO-1 2-6mm Fieldcode 21/11/2020" was prepared and glued to a stub with carbon glue. Samples "SGO-2, 0-1mm Fieldcode 21/11/2020" and "SGO-3, <250µm Fieldcode 21/11/2020" consist of loose grains which were dispersed on a stub with carbon glue. The samples were then coated with a 5nm Pt/Pd coating and were mounted in a SEM FEG XL30. The main objective of the analysis is to check the samples for the presence of asbestos or other fibrous materials.
The images and descriptions are shown in Figures 3 to 5.

Table 1: References of the samples and requested analyses.

Your reference	Our reference	Bulk mineralogical analysis by XRD	Particle Size Analysis by laser diffraction	SEM analysis (with focus on potential presence of asbestos)	XRF-main elements	XRF-screening
SGO-1 2-6mm Fieldcode 21/11/2020	2011BI01	X		X	X	X
SGO-2, 0-1mm Fieldcode 21/11/2020	2011BI02	X	X	X	X	X
SGO-3, <250µm Fieldcode 21/11/2020	2011BI03	X	X	X	X	X

Table 2: Quantitative bulk mineralogical compositions of the samples (in weight percentages of the identified minerals).

Mineral	Theoretical formula[2]	SGO-1 2-6mm	SGO-2, 0-1mm	SGO-3, <250µm
Silicates				
Quartz	SiO_2	1.9	1.0	1.2
Olivine	$(Fe,Mg)SiO_4$	42.6	65.1	65.5
Pyroxene	$(Ca,Na)(Mg,Fe)Si_2O_6$	13.0	21.9	20.1
Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	1.5	0.3	0.2
2:1 layer silicates	$Na_{0,3}(Mg,Li)_3Si_4O_{10}(OH)_2$	4.4	2.5	3.6
Talc	$Mg_3Si_4O_{10}(OH)_2$	1.0	0.5	0.4
Serpentine group minerals	$(Mg,Fe)_3Si_2O_5(OH)_4$	33.2	8.7	9.1
Oxides				
Periclase	MgO	2.5		

[2] These formulae are general formulae and do not necessarily correspond to the composition of the minerals in these specific samples.

Table 3: Results of the chemical analysis of the samples as determined by XRF.

Element/Oxide	Unit Symbol	Quantification method	Detection Limit	SGO-1 2-6mm	SGO-2, 0-1mm	SGO-3, <250µm
Al2O3	%	SRM's*	0.01	1.1	0.8	0.82
CaO	%	SRM's	0.01	1.32	0.56	0.56
Cl	%	Internal method		0.018	0.015	0.015
Fe2O3	%	SRM's	0.01	8.82	9.37	9.21
K2O	%	SRM's	0.01	0.04	0.03	0.02
MgO	%	SRM's	0.01	40.64	43.03	43.16
MnO	%	SRM's	0.001	0.126	0.13	0.124
Na2O	%	SRM's	0.01	0.06	0.06	0.04
P2O5	%	SRM's	0.01	0.01	< 0.01	0.01
SiO2	%	SRM's	0.01	41.76	44.16	44.16
SO3	%	Internal method		0.017	0.013	0.014
TiO2	%	SRM's	0.01	0.02	0.01	0.01
Co	ppm	SRM's	40	103	110	117
Cr	ppm	SRM's	50	1938	2175	1985
Cu	ppm	SRM's	40	<40	<40	<40
Ni	ppm	SRM's	30	2279	2405	2460
V	ppm	Internal method		50		
LOI	%			6	1.09	1.48
Total	%		0.01	100.65	100.05	100.37

***Standard Reference Materials (SRM's)**

Table 4: Particle size analysis by laser diffraction: statistical parameters.

	SGO-2, 0-1mm	SGO-3, <250µm
Mean (µm)	206.3	64.47
d10 (µm)	57.61	11.53
d50 (µm)	282.6	95.86
d90 (µm)	656.1	209.4

Table 5: Laser diffraction measurement data (cumulative).

Size (µm)	SGO-2, 0-1mm	SGO-3, <250µm
0.04	0.00	0.00
0.044	0.00	0.00
0.048	0.00	0.00
0.053	0.00	0.00
0.058	0.00	0.01
0.064	0.01	0.01
0.07	0.01	0.03
0.077	0.02	0.05
0.084	0.03	0.08
0.093	0.05	0.12
0.102	0.07	0.17
0.112	0.09	0.22
0.122	0.12	0.29
0.134	0.15	0.36
0.148	0.19	0.44
0.162	0.22	0.52
0.178	0.26	0.62
0.195	0.30	0.72
0.214	0.35	0.82
0.235	0.39	0.93
0.258	0.44	1.05
0.284	0.50	1.17
0.311	0.55	1.30
0.342	0.61	1.43
0.375	0.67	1.58
0.412	0.73	1.72
0.452	0.79	1.87
0.496	0.85	2.02
0.545	0.92	2.17
0.598	0.98	2.34
0.656	1.05	2.50
0.721	1.12	2.66
0.791	1.19	2.82
0.868	1.26	2.99
0.953	1.33	3.16
1.047	1.40	3.33
1.149	1.47	3.50
1.261	1.55	3.67
1.384	1.63	3.86
1.52	1.71	4.04

1.668	1.79	4.22
1.832	1.87	4.41
2.011	1.96	4.61
2.207	2.06	4.81
2.423	2.15	5.02
2.66	2.25	5.25
2.92	2.36	5.48
3.205	2.47	5.72
3.519	2.59	5.97
3.863	2.71	6.25
4.24	2.84	6.53
4.655	2.97	6.83
5.11	3.11	7.13
5.61	3.25	7.44
6.158	3.39	7.77
6.76	3.53	8.10
7.421	3.67	8.44
8.147	3.81	8.78
8.943	3.95	9.13
9.818	4.08	9.48
10.78	4.21	9.85
11.83	4.34	10.22
12.99	4.47	10.62
14.26	4.60	11.04
15.65	4.73	11.51
17.18	4.87	12.04
18.86	5.02	12.63
20.71	5.19	13.30
22.73	5.38	14.06
24.95	5.59	14.91
27.39	5.83	15.88
30.07	6.11	16.98
33.01	6.44	18.26
36.24	6.83	19.75
39.78	7.29	21.47
43.67	7.83	23.45
47.94	8.46	25.67
52.62	9.19	28.14
57.77	10.03	30.87
63.41	10.98	33.85
69.61	12.07	37.13
76.42	13.31	40.70

83.89	14.71	44.58
92.09	16.30	48.76
101.1	18.08	53.25
111	20.07	58.03
121.8	22.27	63.03
133.7	24.68	68.21
146.8	27.28	73.45
161.2	30.05	78.62
176.9	32.98	83.55
194.2	36.05	88.06
213.2	39.27	91.97
234	42.64	95.11
256.9	46.18	97.41
282.1	49.93	98.88
309.6	53.91	99.63
339.9	58.15	99.91
373.1	62.65	100.00
409.6	67.38	100.00
449.7	72.25	100.00
493.6	77.12	100.00
541.9	81.80	100.00
594.8	86.10	100.00
653	89.87	100.00
716.8	93.00	100.00
786.9	95.46	100.00
863.9	97.29	100.00
948.3	98.56	100.00
1041	99.36	100.00
1143	99.79	100.00
1255	99.97	100.00
1377	99.99	100.00
1512	100.00	100.00
1660	100.00	100.00
1822	100.00	100.00
2000	100.00	100.00

Your Reference: Various Harzburgite samples
Our Reference: 2011BI

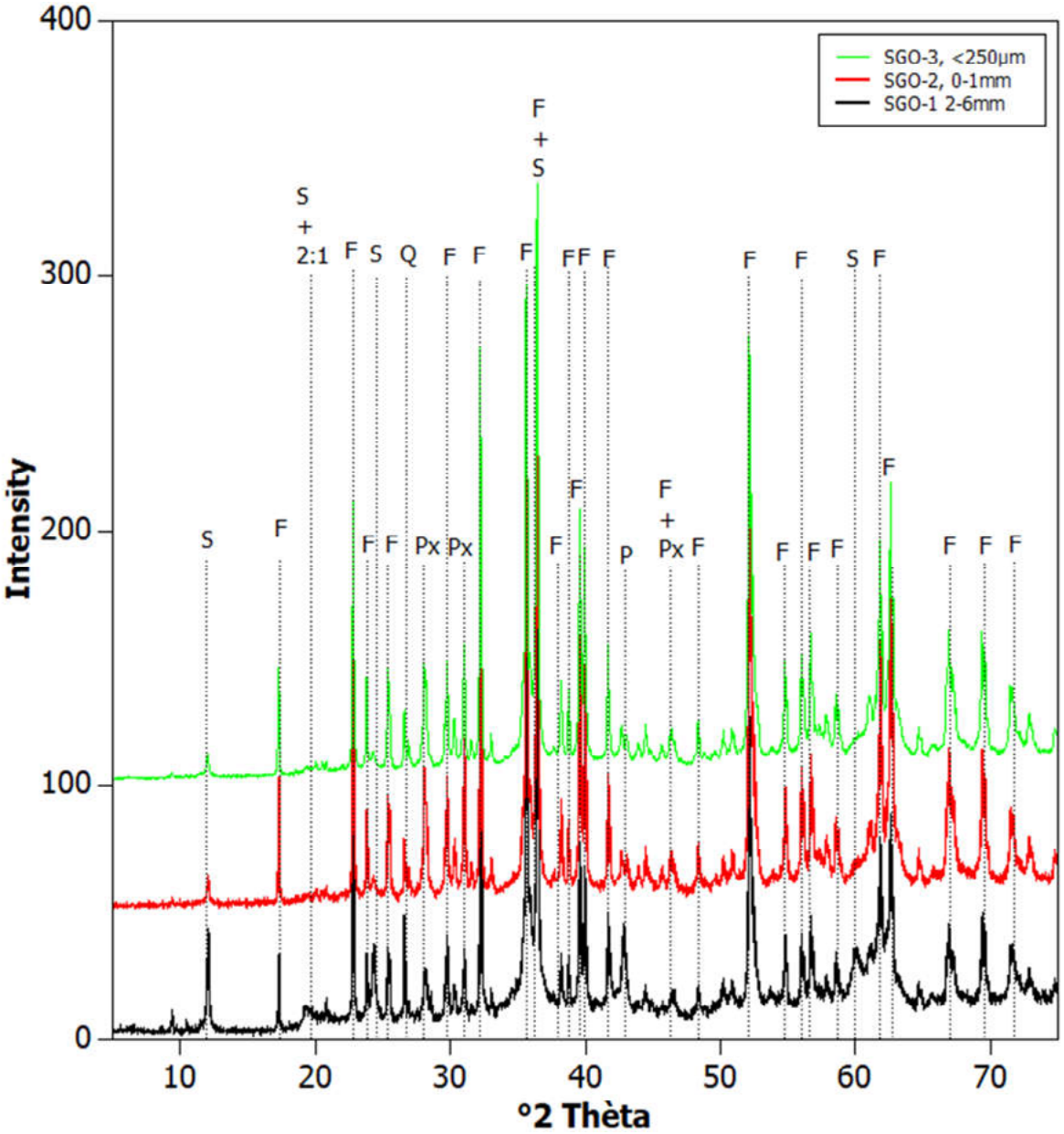


Figure 1: Diffraction patterns of the samples. The main minerals that contribute to the most important reflections are indicated. Serpentine minerals (S), Olivine (F), Pyroxene (Px), 2:1 layer silicates (2:1) and Periclase (P).

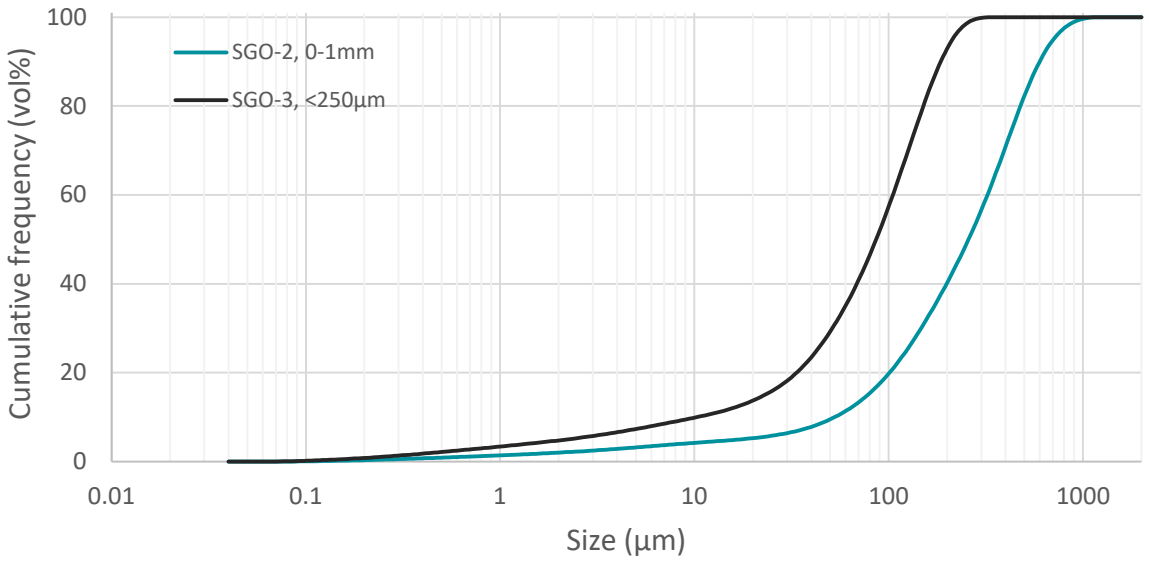


Figure 2: Laser diffraction particle size analysis results.

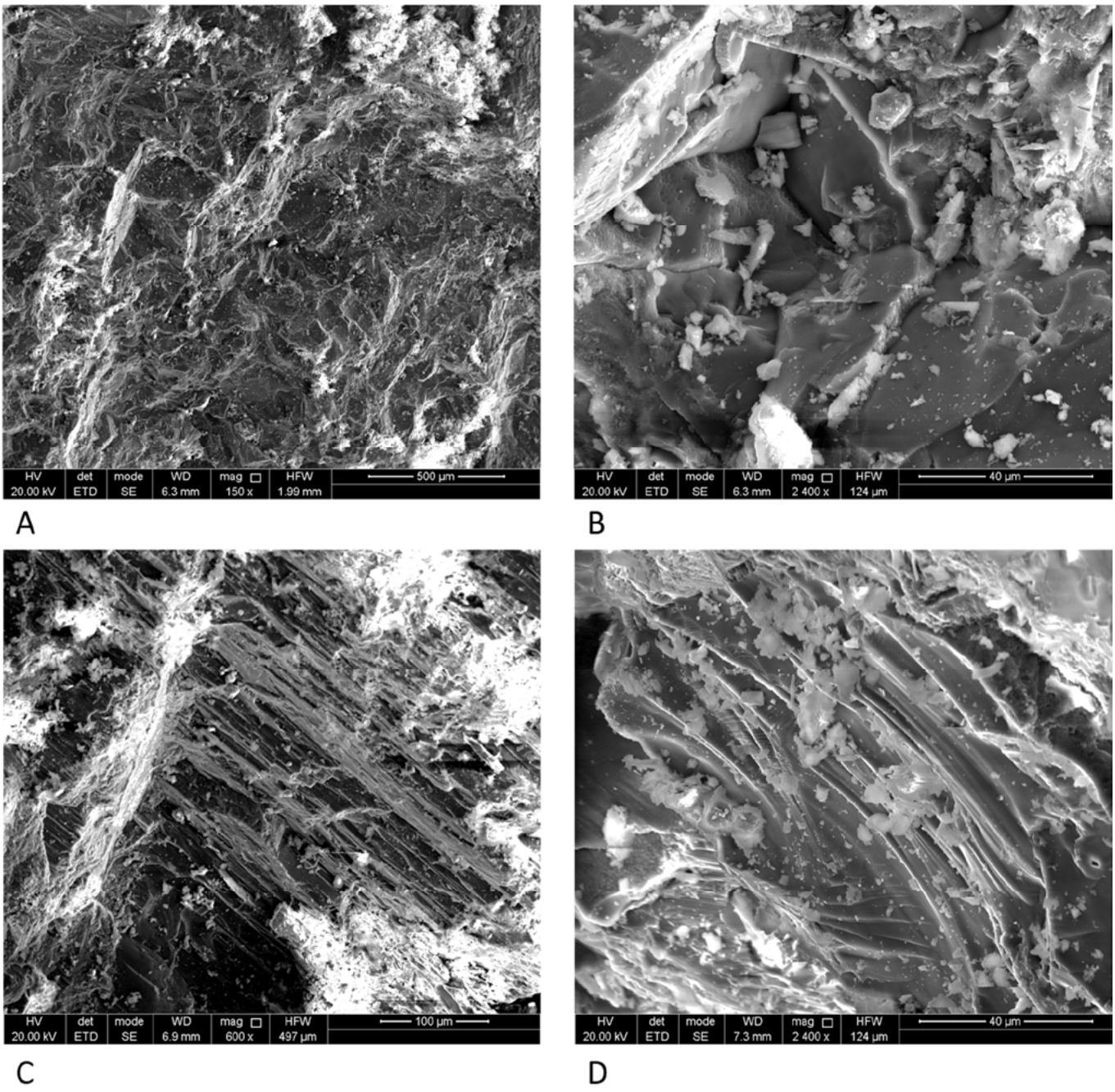
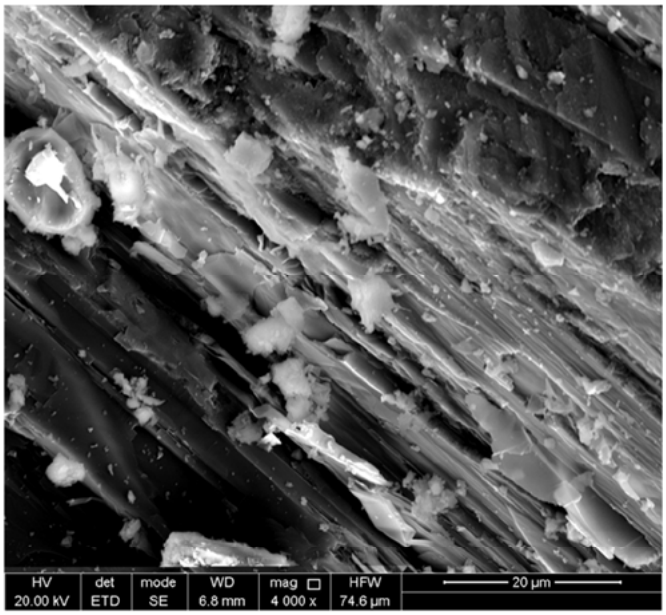


Figure 3: Secondary electron images of sample "SGO-1 2-6mm Fieldcode 21/11/2020". Plate A-H: The sample consists of a dense network of Mg-silicate crystals. Crystals shapes are anhedral although also euhedral crystals are observed (see Plate C, possibly Pyroxene crystal and the cubic crystal Plate G). Plate D, E and F show elongated to columnar structures. Plate H shows a detail of the central part of Plate G with authigenic growth of layer silicates filling up the pore space. No asbestos fibres or particles with a very pronounced fibrous habit were observed.

Your Reference: Various Harzburgite samples
Our Reference: 2011BI



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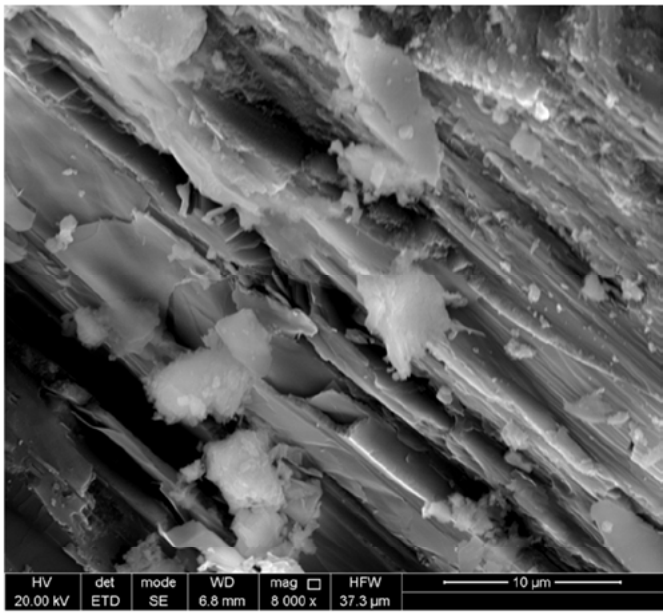

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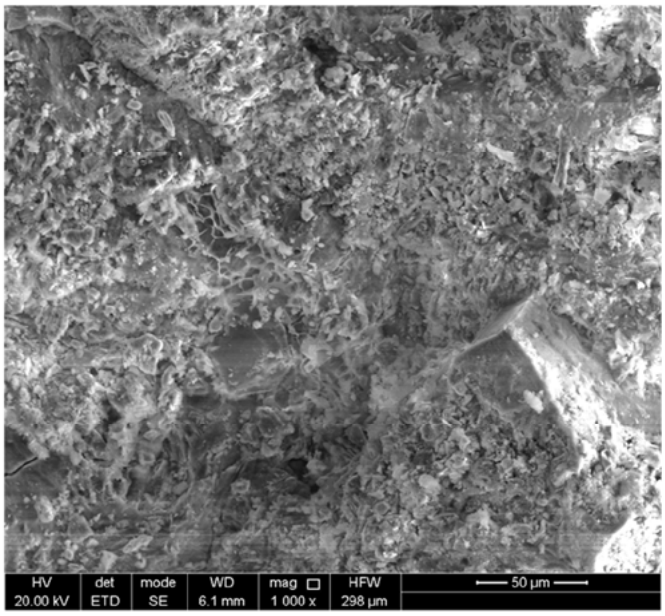

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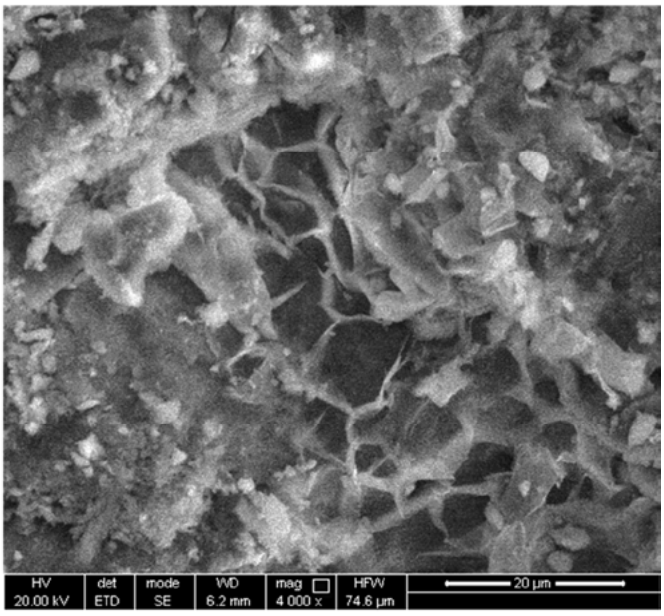


H

Figure 3 (cont.)

Your Reference: Various Harzburgite samples
Our Reference: 2011BI

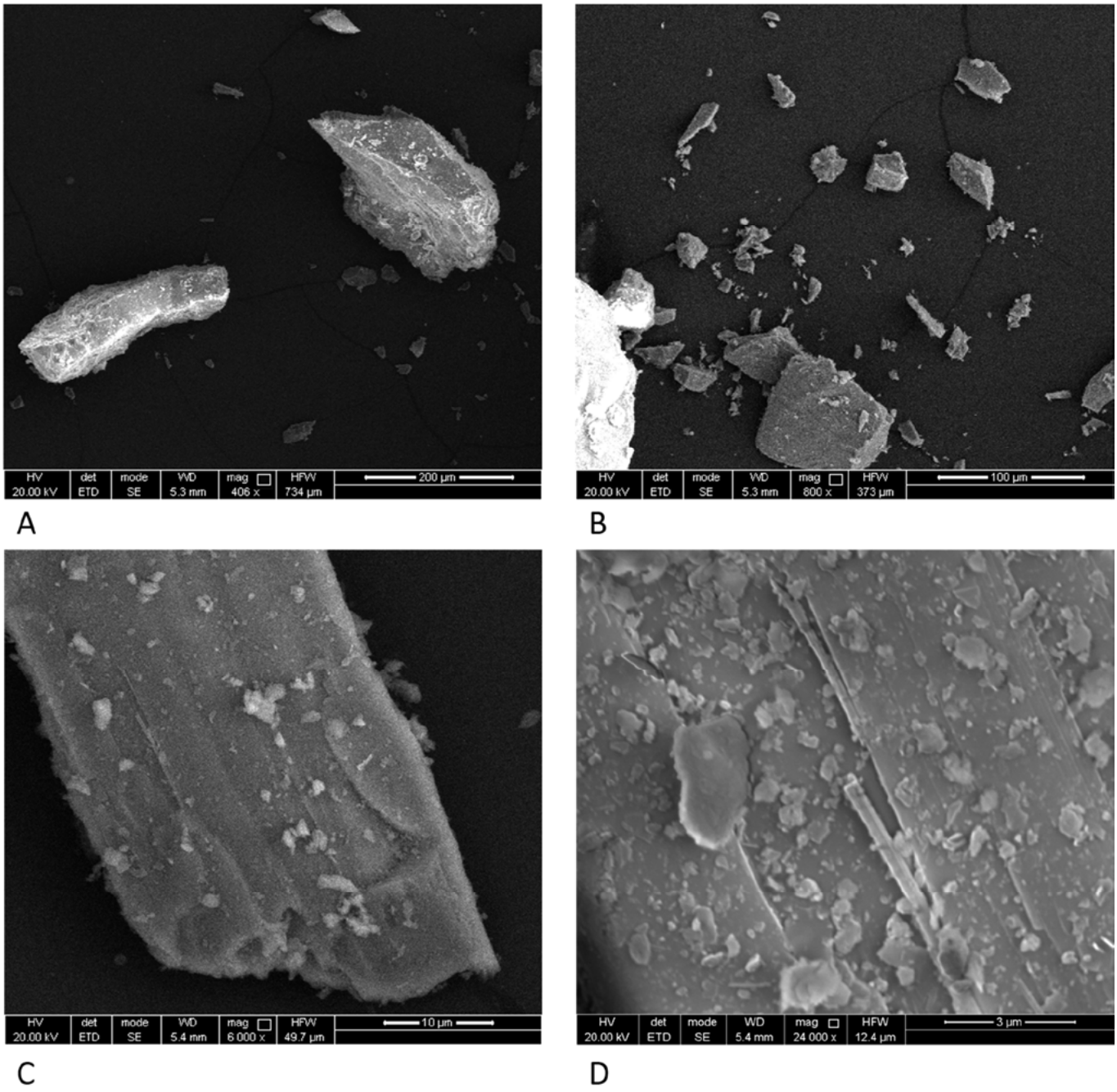
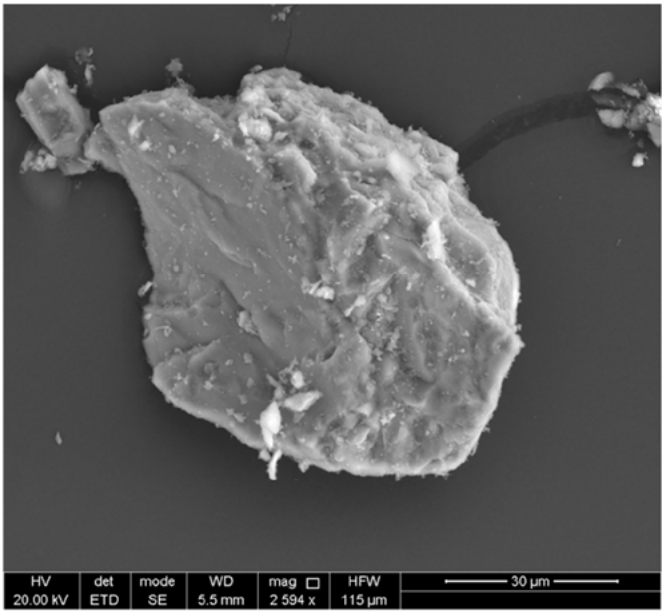


Figure 4: Secondary electron images of sample ”SGO-2, 0-1mm Fieldcode 21/11/2020”. Plate A-H: The sample consists of large grains (up to 1mm, see Plate A), many smaller grains (<100µm, see Plate B, C, E, G) and very fine grains (see Plate F, G and H). No asbestos fibres or particles with a very pronounced fibrous habit could be observed. A few particles display an elongated habit (see Plate D, G and H) but these appear as columnar particles rather than fibrous.

Your Reference: Various Harzburgite samples
Our Reference: 2011BI



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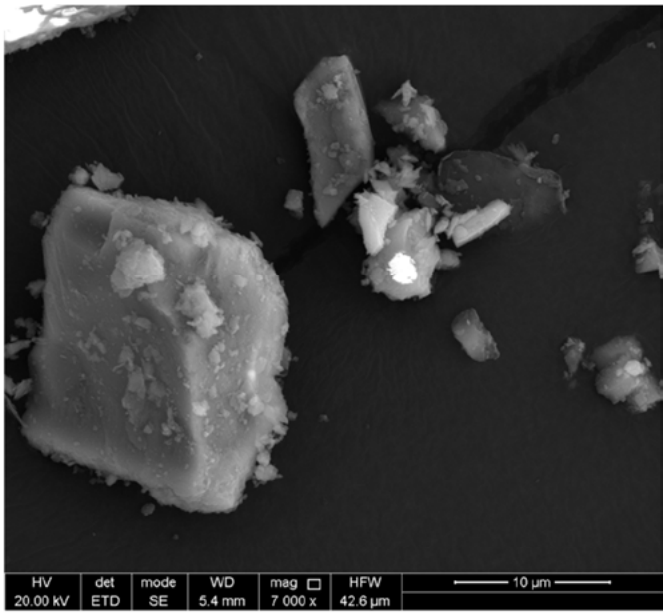

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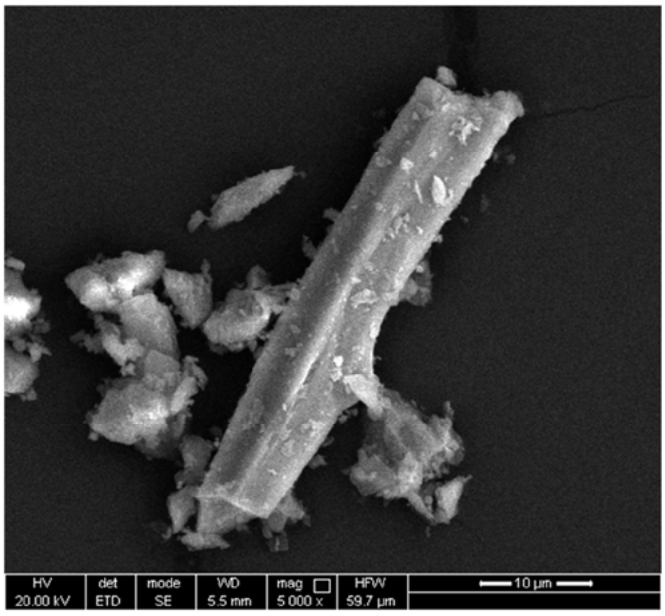

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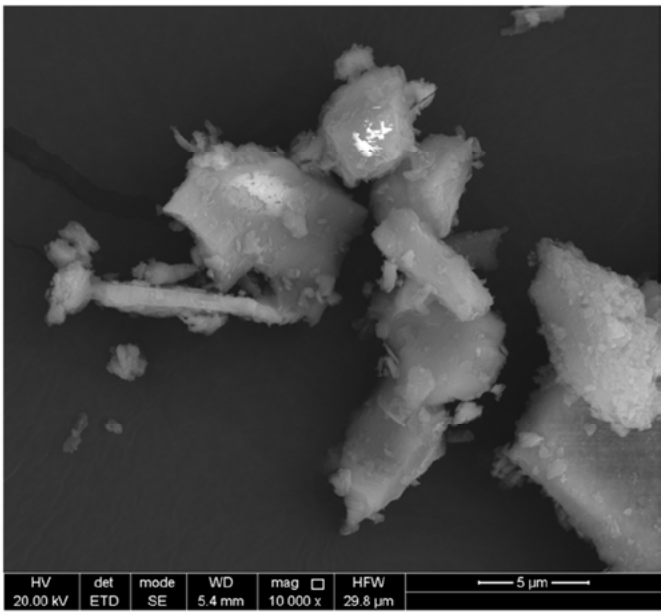

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Figure 4 (cont.)

Your Reference: Various Harzburgite samples
Our Reference: 2011BI

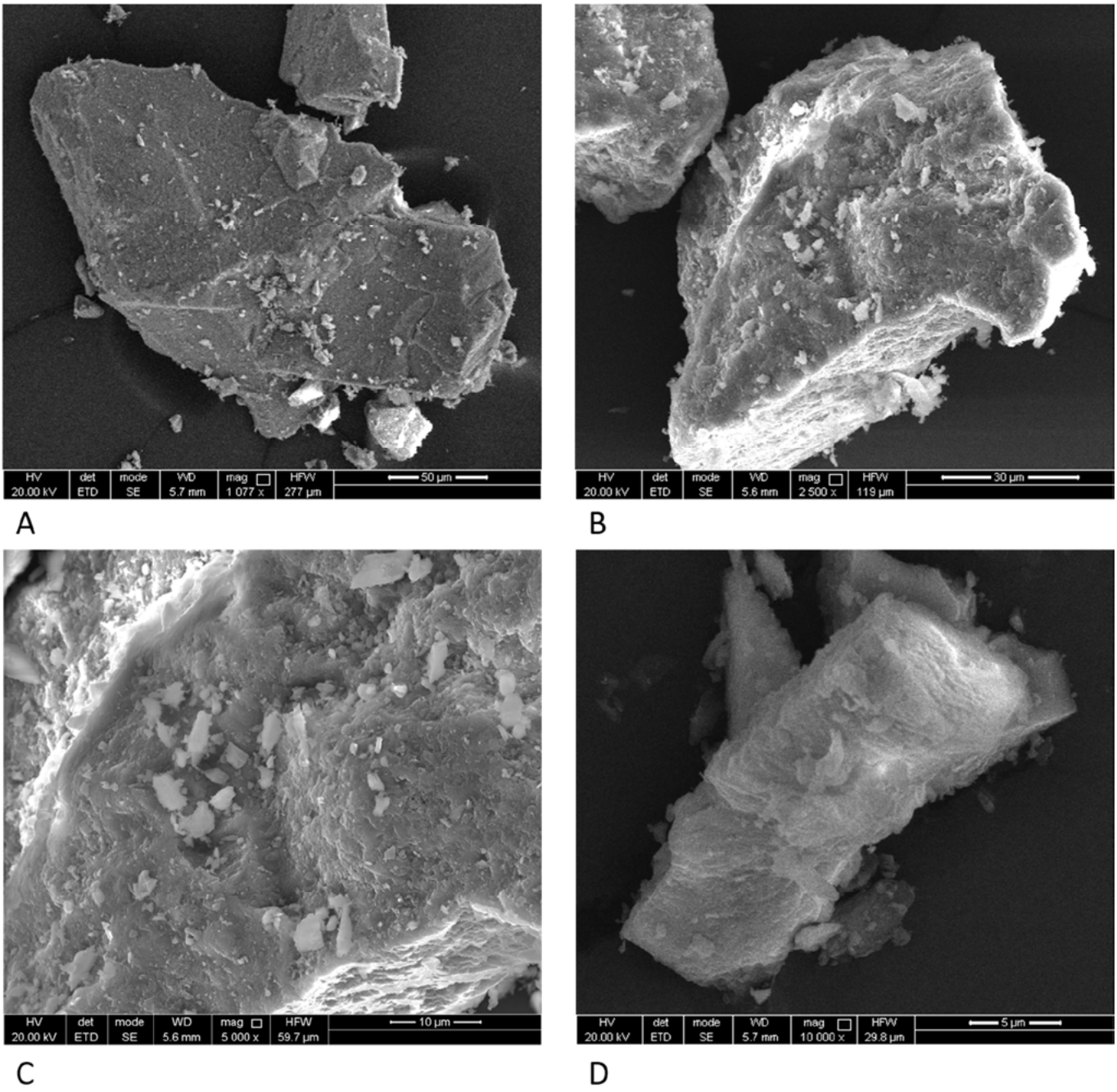
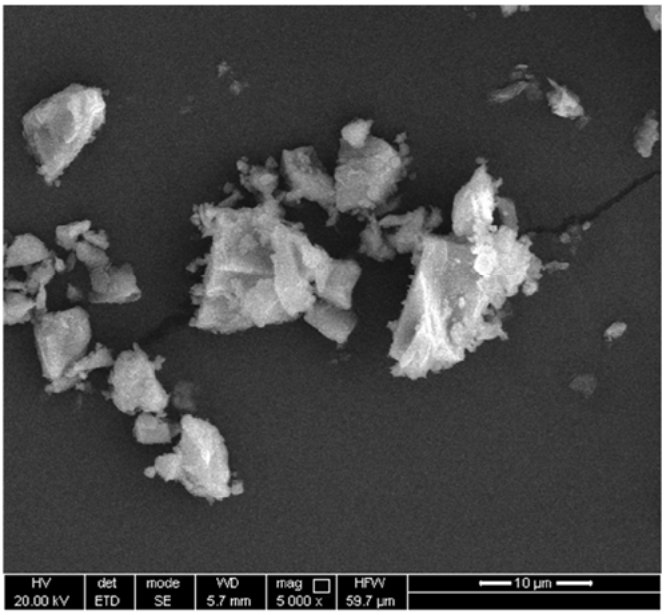


Figure 5: Secondary electron images of sample "SGO-3, <250µm Fieldcode 21/11/2020". The sample consists of medium-sized grains (up to 200µm, see Plate A and B) and many smaller grains (often <20µm, see Plate D, E, F, G and H) and very fine grains (see Plate F, G and H). No asbestos fibres or particles with a very pronounced fibrous habit could be observed. It was observed that a few particles display an elongated habit (see Plate G and H) but these appear as columnar particles rather than fibrous.

Your Reference: Various Harzburgite samples
Our Reference: 2011BI



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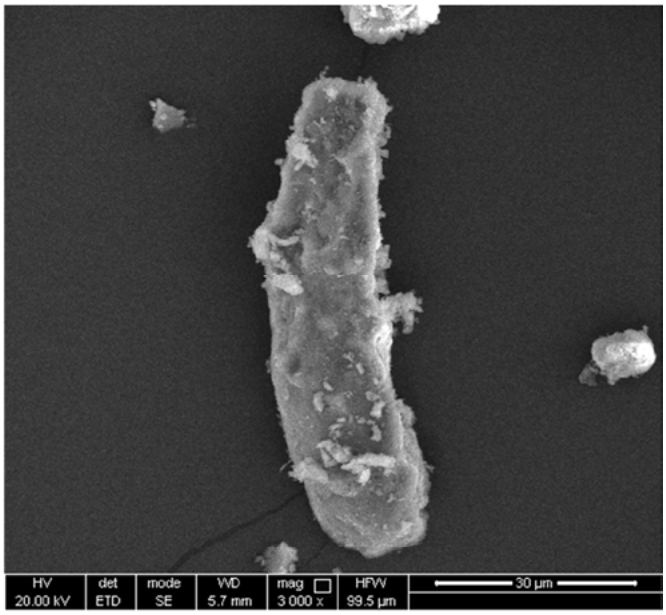

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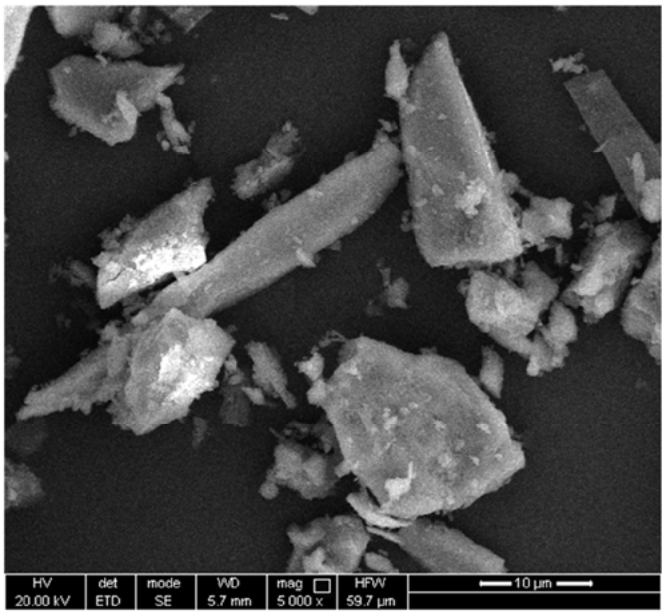

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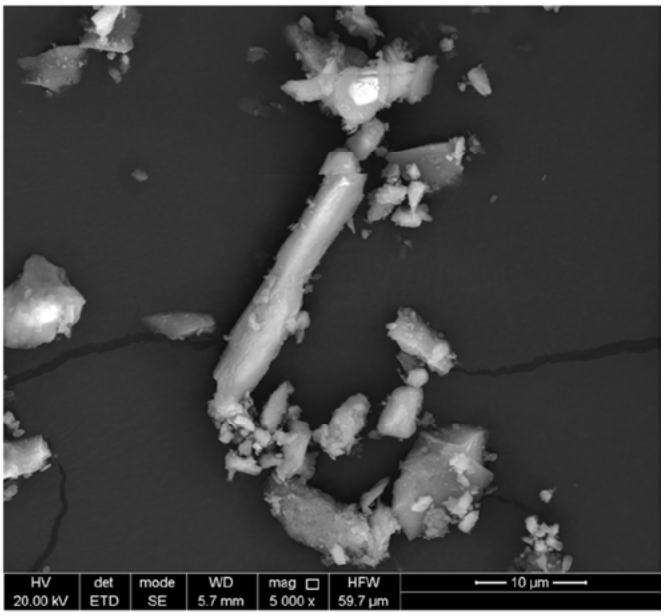

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Figure 5 (cont.)

Appendix C

Appendix C – Analyses of soil and 6 olivine rich rock dusts

ANALYSIS REPORT

July 7th 2021

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

Table 1: Sample list with requested analyses.

Our reference	Your reference	XRF	XRD	PSD	CEC	TIC/ TOC	BET-N2
2104CD01	CS1404 |Composite Soil | Niki 41500 GR	x	x	x	x		X
2104CD02	S1404 #1 |soil sample #1 | GR Niki					x	
2104CD03	S1404 #2 |soil sample #2 | GR Niki					x	
2104CD04	S1404 #3 |soil sample #3 | GR Niki					x	
2104CD05	S1404 #4 |soil sample #4 | GR Niki					x	
2104CD06	S1404 #6 |soil sample #6 | Niki 41500 GR					x	
2104CD07	M-DE (M-DE) |Eiffelgold basalt	x	x	x	x		x
2104CD08	UM-ES |Pasek 'olivine'	x	x	x	x		x
2104CD09	UM-IT |Novo Cives "olivine"	x	x	x	x		x
2104CD10	UM-NO |Greensands | "olivine"	x	x	x	x		x
2104CD11	UM-GR-GM | Grecian Magnesite | "olivine"	x	x	x	x		x
2104CD12	UM-GR-VV |Vitruvit "Olivine"	x	x	x	x		x

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Tel. +32 476 827073

Table 2: Measurement characteristics of the BET analysis.

Parameter	Value
Instrument	Quantachrome Autosorb
Date of analysis	04/06/2021 – 08/06/2021
Date of data treatment	08/06/2021
Operator	A.A.
Sample preparation	Outgassing 2h at 200°C under high-vacuüm
Adsorptive-gas	N_2
Temperature during analysis	77.35K (liquid nitrogen)
Results	Table 8 and Figure 1

Table 3: Measurement characteristics of the CEC measurement.

Parameter	Value
Analysis	Cation Exchange Capacity
General sample handling	Drying at 40°C
Sample preparation	Grinding <500µm, exchange with Co-Hexamine Trichloride
Instrument	Shimadzu UV-1280
Measured by	A.A.
Date of measurement	04/06/2021
Results	Table 9

Table 4: Measurement characteristics of the TOC/TIC analysis.

Parameter	Value
Analysis	Total Organic Carbon and Inorganic Carbon analysis
General sample handling	Each sample was splitted in two representative parts: one for TOC analysis, one for TIC analysis. The parts for TOC analysis were sequentially treated with HCl to remove the inorganic carbon fraction.
Sample preparation	The two parts of each sample were fused at 1600-1800°C and measured using chromatography.
Apparatus	Carlo Erba EA1108 Elemental Analyzer
Date of measurement	26/04/2021
Results	Table 10

Table 5: Measurement characteristics of the bulk XRD analysis.

Parameter	Value
Analysis	Bulk mineralogical analysis by X-ray diffraction
General sample handling	Drying at 40°C, homogenisation by mortar & pestle
Sample preparation	Wet milling and drying
Diffractometer	Bruker D8 Advance, XE-T detector, Cu-Kα radiation
Data treatment methodology	In-house
Interpretation by	Dr. Rieko Adriaens
Date of measurement	07/05/2021
Date of data treatment	16/06/2021
Results	Table 11 and Figures 2-8

Table 6: Measurement characteristics of the XRF analysis.

Parameter	Value
Analysis	X-ray Fluorescence analysis
Sample preparation	Prior to fusion, the loss on ignition (LOI), which includes H2O, CO2, S and other volatiles, is determined from the weight loss after roasting the sample at 1000°C for 2 hours. The fusion disk is made by mixing a 0.75 g equivalent of the roasted sample with 9.75 g of a combination of lithium metaborate and lithium tetraborate with lithium bromide as a releasing agent. The samples were fused in a Pt crucible using an automated crucible fluxer and automatically poured into a Pt mold for casting.
Apparatus	Panalytical Axios Advanced wavelength dispersive XRF
Date of measurement	17/05/2021
Results	Table 12

Table 7: Characteristics of the grain-size analysis.

Parameter	Value
Analysis	Laser diffraction
Sample preparation	Dispersion in water
Apparatus	Fritsch Analysette A-22 NeXt
Use of ultrasonic dispersion	Ja
Model	Mie theory
Interpretation by	Dr. Rieko Adriaens
Date of analysis	17/05/2021
Results	Table 13 & 14 and Figure 9

Table 8: BET specific surface area: results.

Sample	BET area (m^2/g)	Correlation coëfficiënt BET plot	Sample mass (g)
CS1404 |Composite Soil | Niki 41500 GR	51.2	0.999960	1.1170
M-DE (M-DE) |Eiffelgold basalt	13.1	0.999867	1.2457
UM-ES |Pasek 'olivine'	2.4	0.999965	1.6924
UM-IT |Novo Cives "olivine"	4.6	0.999513	1.5042
UM-NO |Greensands | "olivine"	5.0	0.999961	1.5379
UM-GR-GM | Grecian Magnesite | "olivine"	10.8	0.999290	1.9658
UM-GR-VV |Vitruvit "Olivine"	5.9	0.999437	1.6250

Table 9: Cation exchange capacity: results.

Sample	CEC (meq/100g)
CS1404 |Composite Soil | Niki 41500 GR	24.40
M-DE (M-DE) |Eiffelgold basalt	4.67
UM-ES |Pasek 'olivine'	0.19
UM-IT |Novo Cives "olivine"	1.36
UM-NO |Greensands | "olivine"	1.19
UM-GR-GM | Grecian Magnesite | "olivine"	2.33
UM-GR-VV |Vitruvit "Olivine"	1.75

Table 10: Results of the total organic carbon analysis (TOC) and total inorganic carbon analysis (TIC). Results are expressed in weight percentages.

Analysis	Unit	S1404 #1 |soil sample #1 | GR Niki	S1404 #2 |soil sample #2 | GR Niki	S1404 #3 |soil sample #3 | GR Niki	S1404 #4 |soil sample #4 | GR Niki	S1404 #6 |soil sample #6 | Niki 41500 GR
TIC	%	2.56	2.57	2.55	2.62	2.53
TOC	%	0.92	0.74	0.80	0.80	0.93

Table 11: Quantitative bulk mineralogical compositions of the samples (in weight percentages of the identified minerals).

Mineral	Theoretical formula[1]	CS1404 | Composite Soil | Niki 41500 GR	M-DE (M-DE) | Eiffelgold basalt	UM-ES | Pasek 'olivine'	UM-IT | Novo Cives "olivine"	UM-NO | Green sands | "olivine"	UM-GR-GM | Grecian Magnesite | "olivine"	UM-GR-VV | Vitruvit "Olivine"
Silicates								
Quartz	SiO_2	20.8	0.6	0.5	0.8	0.9	0.9	0.6
K-feldspar	$(K,Na)(Si,Al)_4O_8$	1.1	1.9	1.4				
Plagioclase	$(Ca,Na)(Si,Al)_4O_8$	10.9	7.9					
Olivine	$(Fe,Mg)SiO_4$		11.7	24.1	58.6	55.0	47.8	63.6
Pyroxene	$(Ca,Na)(Mg,Fe)Si_2O_6$	0.7	43.4	18.5	26.1	5.5	13.2	19.7
Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	0.6	0.9	5.5	2.8	1.3	0.9	0.4
Epidote	$Ca_2(Fe,Al)_3(SiO_4)_3(OH)$		2.2					
Chabazite	$(Na_2,K_2,Ca,Mg)[Al_2Si_4O_{12}]•6(H_2O)$		2.8					
Analcime	$NaAlSi_2O_6•(H_2O)$		3.8					
Leucite	$KAlSi_2O_6$		4.8					
Nepheline	$(Na,K)AlSiO_4$		3.4					
Carbonates								
Calcite	$CaCO_3$	21.0	0.7	0.4	0.5	0.1	0.1	0.2
Dolomite/Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$	1.5						
Oxides								
Periclase	MgO						2.3	
Anatase	TiO_2	0.1						
Rutile	TiO_2	0.4						
Hematite	Fe_2O_3		2.4					
Goethite	$FeO(OH)$							0.6
Magnetite	Fe_3O_4			1.3				
Spinel	$MgAl_2O_4$			2.2	3.0			
Phosphates								
Apatite	$Ca_5(PO_4)_3(OH,Cl,F)$	0.6	1.5					
Layer silicates								
2:1 layer silicates	$Na_{0,3}(Mg,Fe,Al)_3Si_4O_{10}(OH)_2$	35.3	1.9		0.7		4.2	4.4
Kaolinite	$Al_2Si_2O_5(OH)_4$	3.2						
Chlorite	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$	3.9		0.7	0.7	4.1	0.5	0.9
Talc	$Mg_3Si_4O_{10}(OH)_2$					5.3	0.7	0.1
Serpentine group minerals	$(Mg,Fe)_3Si_2O_5(OH)_4$			45.5	6.8	27.8	29.3	9.6
Amorphous			10.1					

[1] These formulae are general formulae and do not necessarily correspond to the composition of the minerals in these specific samples.

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

Table 12: Results of the chemical XRF analysis of the samples. The Loss on Ignition (LOI) was determined on the fused samples.

Element	Unit	Detection limit	CS1404 |Composite Soil | Niki 41500 GR	M-DE (M-DE) |Eiffelgold basalt	UM-ES |Pasek 'olivine'	UM-IT |Novo Cives "olivine"	UM-NO |Greensands | "olivine"	UM-GR-GM | Grecian Magnesite | "olivine"	UM-GR-VV |Vitruvit "Olivine"
SiO2	%	0.01	46.97	43.31	41.67	43.24	41.18	41.07	43.58
Al2O3	%	0.01	10.58	12.99	2.98	3.16	1	0.82	0.75
Fe2O3	%	0.01	5.06	11.1	8.79	9.61	7.09	9.16	8.9
MnO	%	0.01	0.1	0.168	0.122	0.141	0.086	0.127	0.122
MgO	%	0.01	3.43	9.95	36.23	39.81	44.04	42.09	43.31
CaO	%	0.01	12.8	11.8	2.89	2.21	0.37	0.83	0.58
Na2O	%	0.01	1.34	2.46	0.15	0.05	< 0.01	< 0.01	< 0.01
K2O	%	0.01	1.41	2.75	0.09	0.04	0.07	0.03	0.02
TiO2	%	0.01	0.63	2.6	0.07	0.07	0.02	0.01	< 0.01
P2O5	%	0.01	0.11	0.47	0.01	0.01	0.01	< 0.01	< 0.01
Cr2O3	%	0.01	0.06	0.03	0.41	0.39	0.26	0.44	0.37
V2O5	%	0.003	0.015	0.054	0.009	0.008	< 0.003	0.012	0.005
Co3O4	%	0.005	< 0.005	0.007	0.019	0.017	0.016	0.016	0.015
CuO	%	0.005	0.008	0.021	0.01	0.011	0.007	< 0.005	< 0.005
NiO	%	0.003	0.06	0.026	0.295	0.309	0.335	0.309	0.318
LOI	%		17.55	2.21	6.77	1.71	6.09	5.57	2.33
TOTAL	%		100.1	99.95	100.5	100.8	100.6	100.5	100.3

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

Table 13: Grain-size analysis by laser diffraction: raw data.

Size (µm)	CS1404 | Composite Soil | Niki 41500 GR	M-DE (M-DE) | Eiffelgold basalt	UM-ES | Pasek 'olivine'	UM-IT | Novo Cives "olivine"	UM-NO | Greensands | "olivine"	UM-GR-GM | Grecian Magnesite | "olivine"	UM-GR-VV | Vitruvit "Olivine"
0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.11	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.19	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.24	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.26	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.29	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.32	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.36	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.56	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.62	0.1	0.0	0.0	0.0	0.0	0.0	0.0
0.69	0.2	0.0	0.0	0.0	0.0	0.0	0.0
0.77	0.3	0.0	0.0	0.0	0.0	0.0	0.0
0.85	0.6	0.0	0.0	0.1	0.0	0.0	0.0
0.95	1.1	0.1	0.0	0.1	0.1	0.1	0.1
1.06	1.8	0.2	0.1	0.2	0.1	0.1	0.1
1.17	2.8	0.4	0.1	0.4	0.3	0.2	0.3
1.31	4.0	0.7	0.2	0.7	0.5	0.3	0.4

1.45	5.6	1.1	0.3	1.0	0.9	0.5	0.6
1.62	7.5	1.6	0.4	1.4	1.5	0.7	0.8
1.80	9.6	2.2	0.6	1.9	2.2	1.0	1.1
2.01	12.1	3.0	0.8	2.5	3.0	1.4	1.4
2.23	14.8	3.9	1.1	3.1	4.1	1.8	1.8
2.48	17.7	4.9	1.3	3.9	5.5	2.3	2.2
2.77	20.8	6.0	1.6	4.8	7.0	2.9	2.7
3.08	24.0	7.3	2.0	5.7	8.7	3.5	3.2
3.43	27.2	8.6	2.3	6.6	10.7	4.1	3.7
3.81	30.4	10.1	2.7	7.7	12.8	4.8	4.2
4.24	33.5	11.6	3.1	8.7	15.1	5.5	4.8
4.72	36.5	13.2	3.5	9.8	17.5	6.2	5.4
5.26	39.3	14.8	3.8	11.0	19.9	6.9	6.0
5.85	42.0	16.5	4.2	12.1	22.4	7.6	6.6
6.51	44.6	18.2	4.5	13.2	25.0	8.3	7.2
7.25	47.0	20.0	4.8	14.4	27.5	8.9	7.8
8.07	49.3	21.7	5.1	15.6	30.0	9.6	8.5
8.98	51.6	23.6	5.3	16.9	32.6	10.2	9.2
9.99	54.0	25.5	5.6	18.2	35.1	10.9	9.9
11.12	56.4	27.6	5.9	19.6	37.8	11.6	10.6
12.38	58.9	29.7	6.1	21.1	40.5	12.3	11.5
13.78	61.5	32.1	6.4	22.7	43.4	13.1	12.5
15.34	64.2	34.7	6.7	24.4	46.6	14.0	13.6
17.07	67.1	37.5	7.1	26.3	50.0	15.0	14.8
19.00	69.9	40.7	7.6	28.4	53.6	16.1	16.3
21.15	72.7	44.3	8.1	30.7	57.6	17.4	18.0
23.54	75.3	48.2	8.7	33.3	61.8	18.9	20.0
26.20	77.7	52.5	9.4	36.1	66.2	20.5	22.3
29.16	79.7	57.3	10.3	39.2	70.7	22.4	24.9
32.45	81.4	62.4	11.3	42.7	75.3	24.5	27.8
36.12	82.8	67.8	12.7	46.7	79.7	26.8	31.1
40.20	83.8	73.3	14.3	51.0	83.8	29.5	34.7
44.74	84.7	78.8	16.3	55.8	87.7	32.4	38.6
49.80	85.6	83.9	18.8	61.0	91.0	35.8	42.9
55.43	86.6	88.6	21.9	66.6	93.9	39.6	47.5
61.69	87.8	92.6	25.5	72.4	96.1	43.9	52.4
68.66	89.3	95.6	29.7	78.1	97.8	48.7	57.6
76.42	91.0	97.8	34.4	83.6	98.9	53.9	63.0
85.06	92.8	99.0	39.7	88.5	99.5	59.4	68.5
94.67	94.6	99.7	45.4	92.6	99.8	65.3	73.9
105.37	96.3	99.9	51.3	95.7	100.0	71.2	79.2
117.28	97.7	100.0	57.4	97.9	100.0	77.0	84.0
130.53	98.8	100.0	63.4	99.1	100.0	82.5	88.4
145.28	99.4	100.0	69.2	99.7	100.0	87.4	92.1
161.70	99.8	100.0	74.7	99.9	100.0	91.5	95.0
179.97	99.9	100.0	79.6	100.0	100.0	94.8	97.2
200.31	100.0	100.0	84.0	100.0	100.0	97.1	98.6
222.95	100.0	100.0	87.7	100.0	100.0	98.6	99.4
248.14	100.0	100.0	90.8	100.0	100.0	99.5	99.8
276.18	100.0	100.0	93.2	100.0	100.0	99.8	100.0
307.40	100.0	100.0	95.1	100.0	100.0	100.0	100.0
342.13	100.0	100.0	96.6	100.0	100.0	100.0	100.0
380.80	100.0	100.0	97.6	100.0	100.0	100.0	100.0

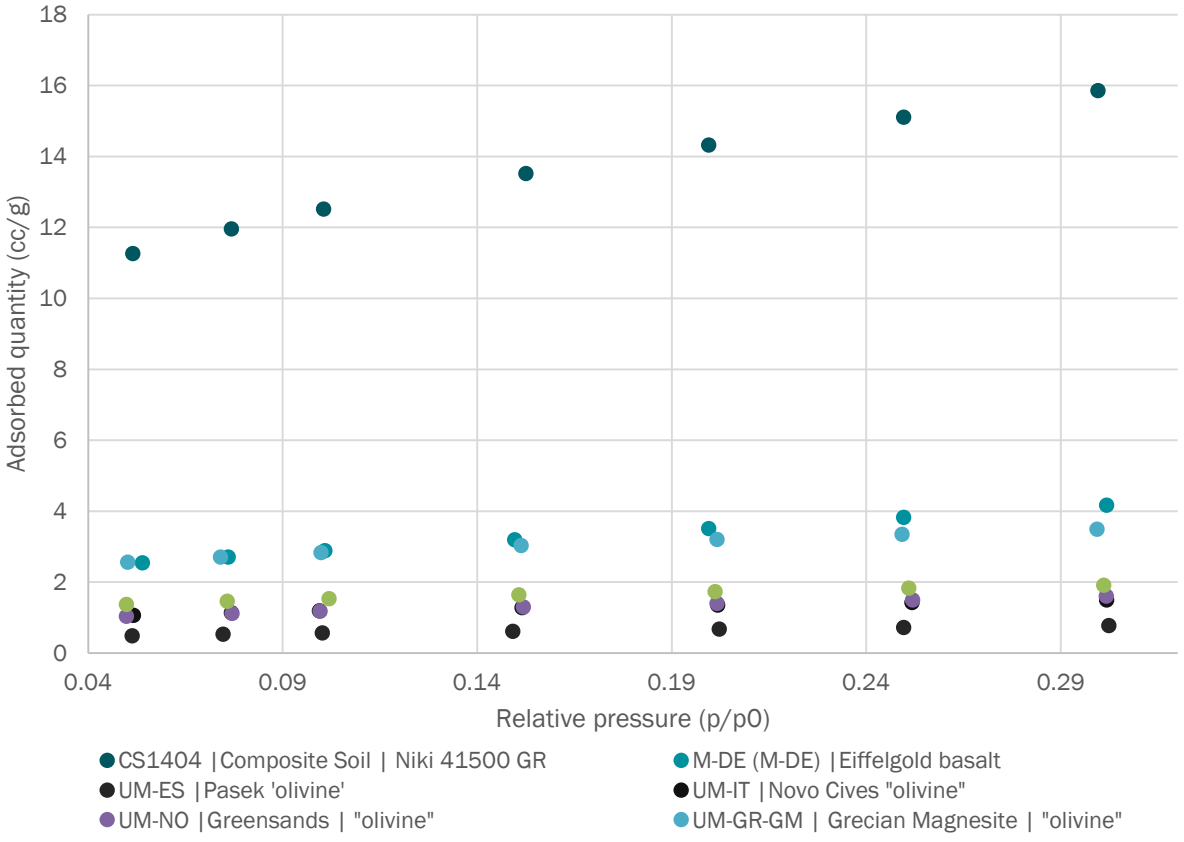
423.83	100.0	100.0	98.4	100.0	100.0	100.0	100.0
471.73	100.0	100.0	99.0	100.0	100.0	100.0	100.0
525.04	100.0	100.0	99.4	100.0	100.0	100.0	100.0
584.37	100.0	100.0	99.7	100.0	100.0	100.0	100.0
650.41	100.0	100.0	99.9	100.0	100.0	100.0	100.0
723.91	100.0	100.0	100.0	100.0	100.0	100.0	100.0
805.72	100.0	100.0	100.0	100.0	100.0	100.0	100.0
896.77	100.0	100.0	100.0	100.0	100.0	100.0	100.0
998.11	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1110.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1236.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1376.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1531.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1704.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1897.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2111.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 14: Statistical parameters of the laser diffraction measurements of the samples.

Parameter	CS1404 | Composite Soil | Niki 41500 GR	M-DE (M-DE) | Eiffelgold basalt	UM-ES | Pasek 'olivine'	UM-IT | Novo Cives "olivine"	UM-NO | Greenlands | "olivine"	UM-GR-GM | Grecian Magnesite | "olivine"	UM-GR-VV | Vitruvit "Olivine"
Mean (µm)	22.96	29.43	130.60	45.79	23.02	82.20	71.23
Standard Deviation (µm)	32.96	22.07	100.68	33.87	19.43	58.95	52.02
Skewness	2.16	0.75	1.74	0.67	1.13	0.72	0.89
Kurtosis	4.37	-0.02	4.85	-0.14	1.01	0.14	0.57
d10 (µm)	1.93	3.99	29.75	5.06	3.48	9.10	10.73
d50 (µm)	8.78	25.96	108.53	41.36	18.00	74.45	61.77
d90 (µm)	75.78	60.71	254.72	93.26	50.83	164.06	144.27

Your reference:	Various samples received on 26/04/2021
Our reference:	2104CD_Bis

Figure 1: Isotherms.



Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

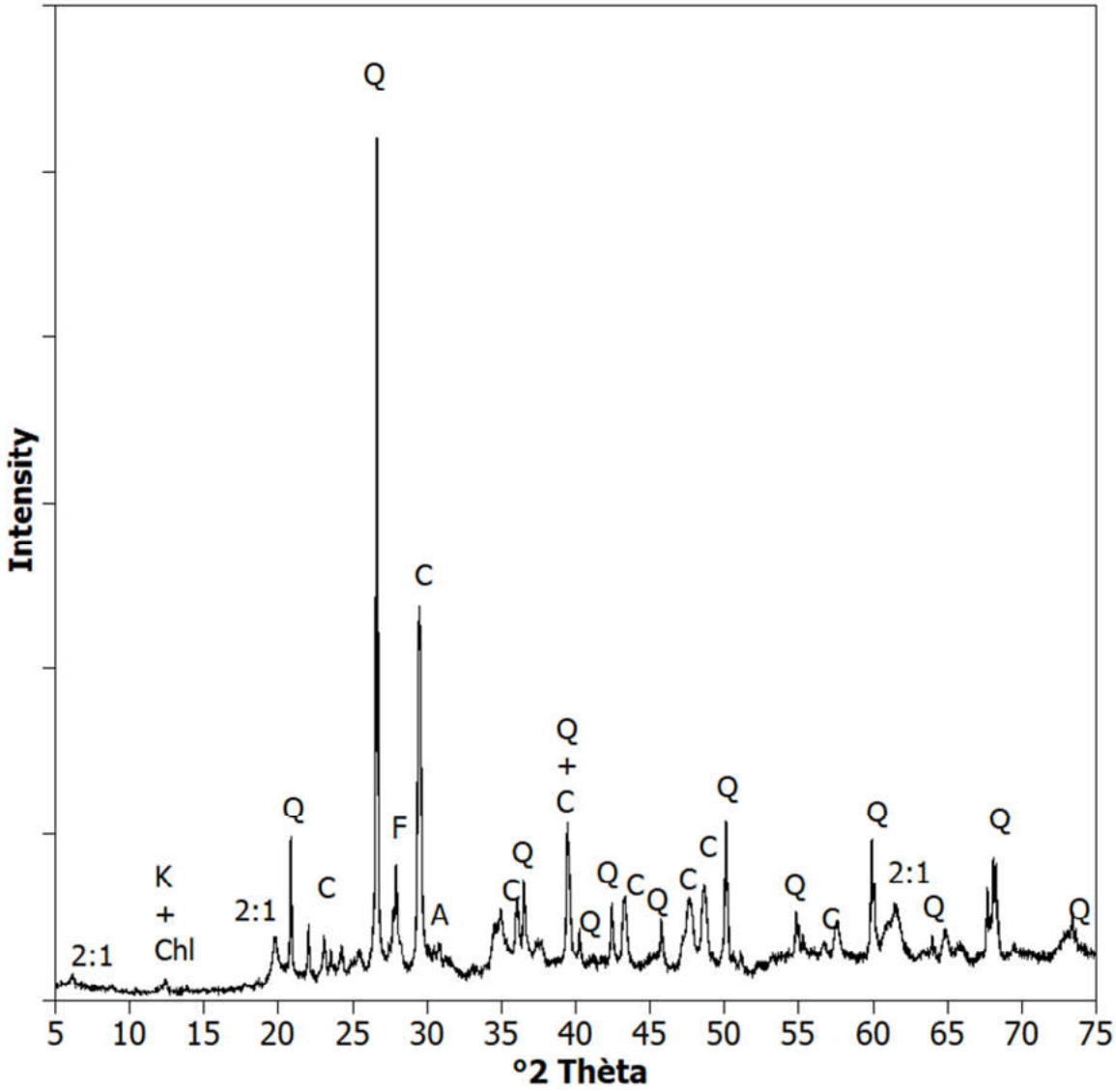


Figure 2: Diffraction pattern of the sample "CS1404 |Composite Soil | Niki 41500 GR". The minerals that contribute to the main reflections are labeled: 2:1 layer silicates (2:1), Quartz (Q), Alkali feldspar and Plagioclase (F), Calcite (C), Dolomite/Ankerite (A), Kaolinite (K) and Chlorite (Chl).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

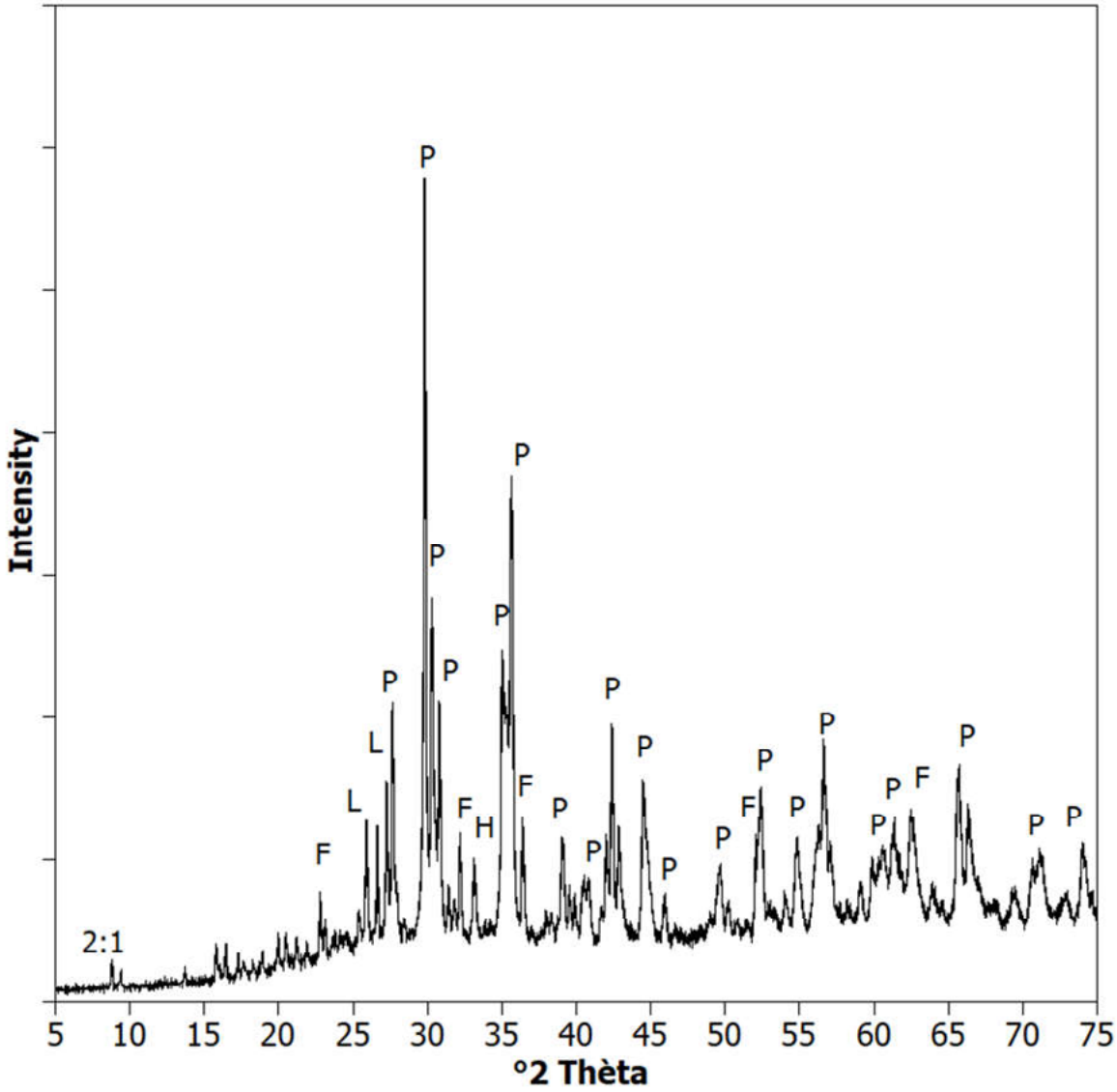


Figure 3: Diffraction pattern of the sample "M-DE (M-DE) |Eiffelgold basalt". The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), Leucite (L), Hematite (H), 2:1 layer silicates (2:1).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

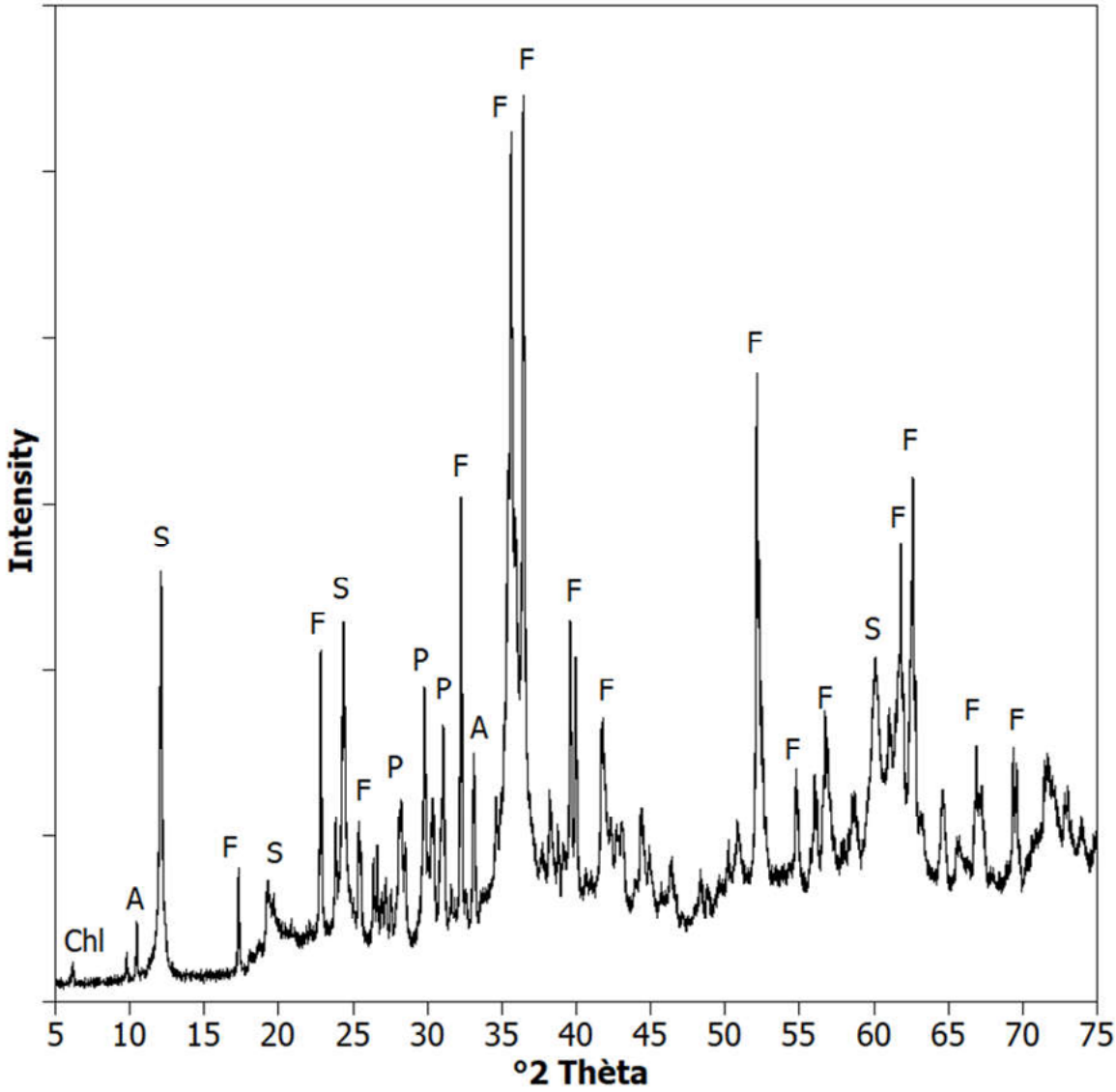


Figure 4: Diffraction pattern of the sample "UM-ES |Pasek 'olivine'". The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), Chlorite (Chl), Serpentine (S).

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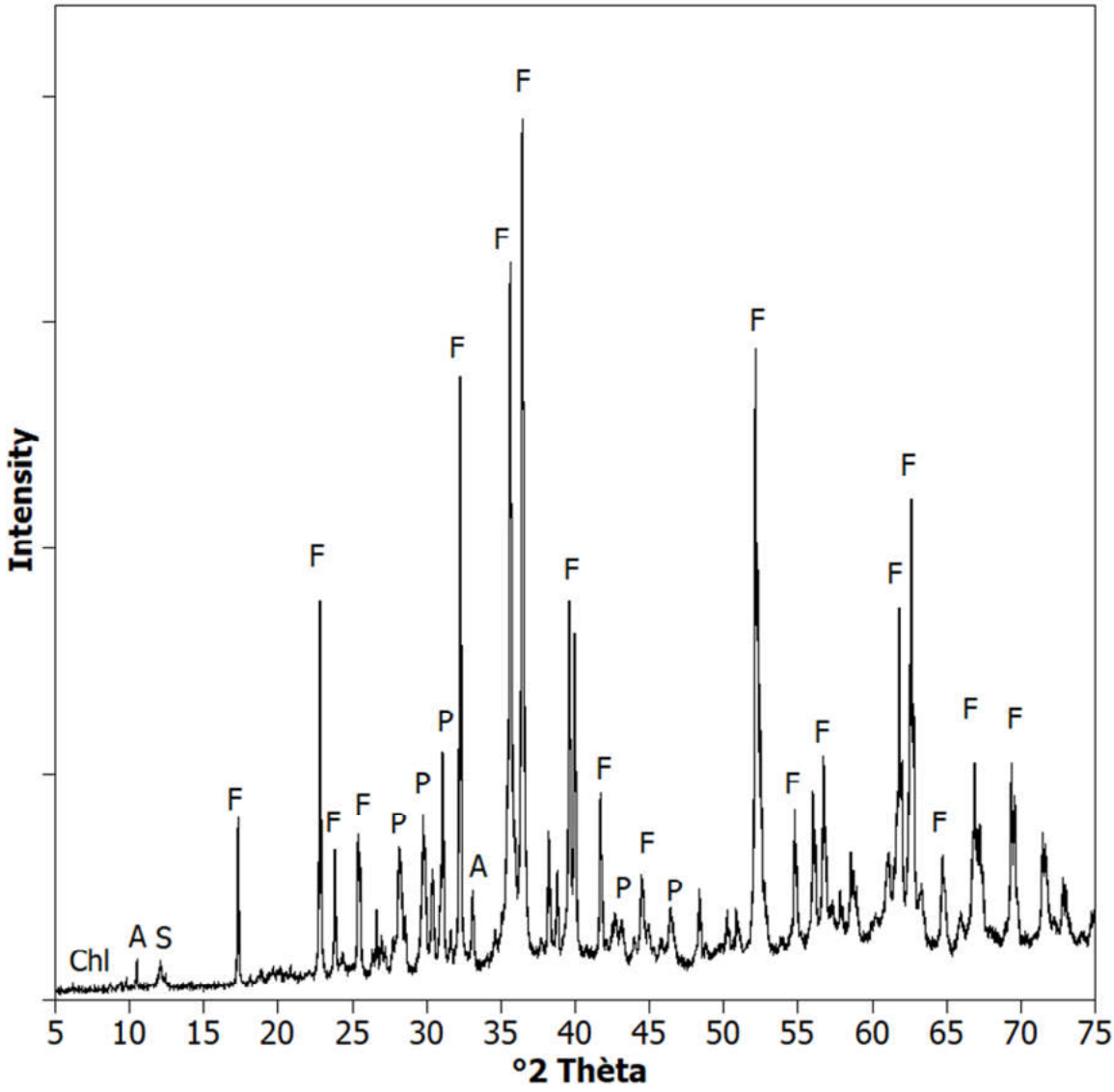

Figure 5: Diffraction pattern of the sample “UM-IT |Novo Cives "olivine"”. The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), Chlorite (Chl), Serpentine (S).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

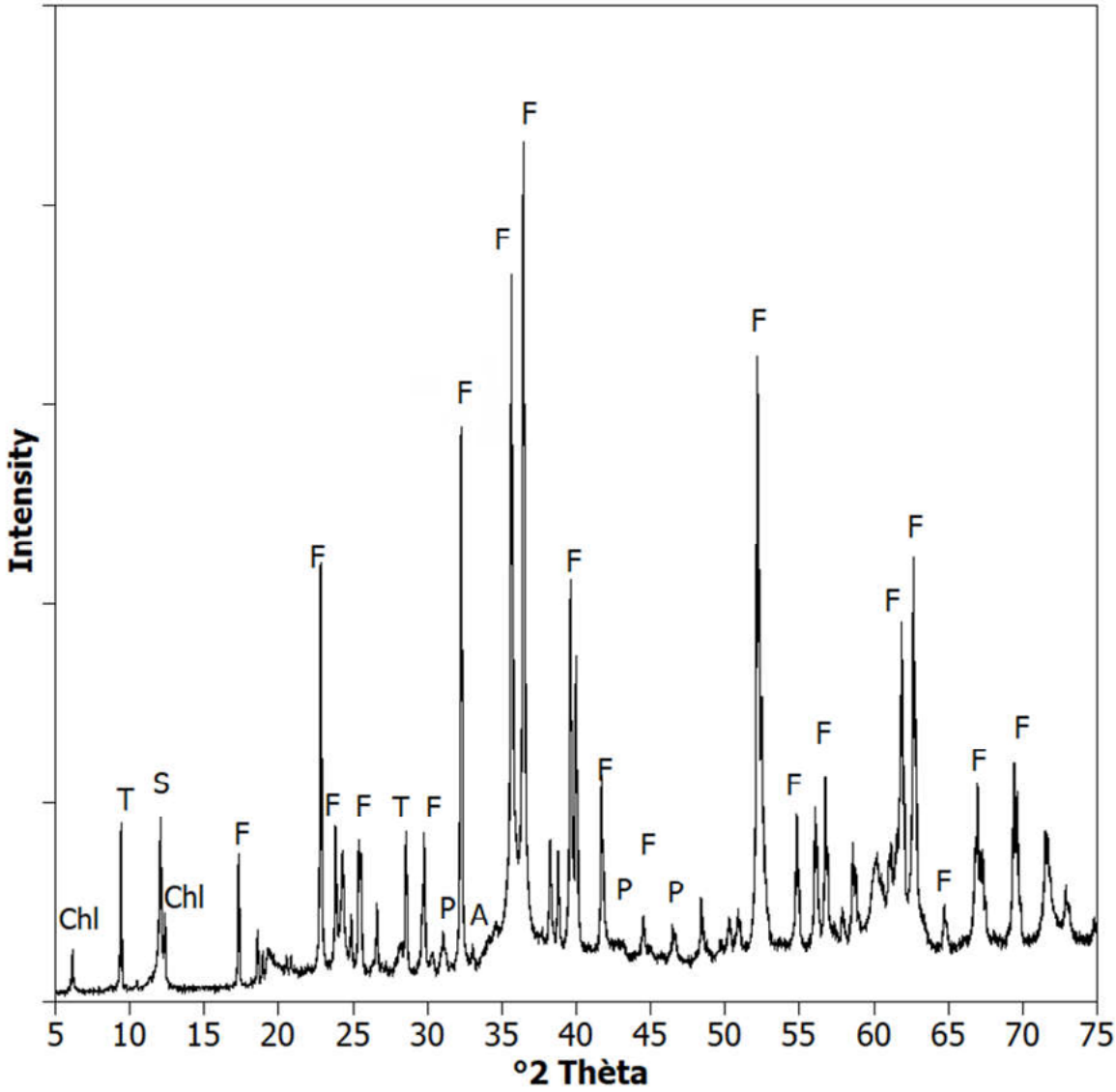

Figure 6: Diffraction pattern of the sample “UM-NO |Greensands | "olivine"”. The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), 2:1 layer silicates (2:1), Chlorite (Chl), Serpentine (S), Talc (T).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

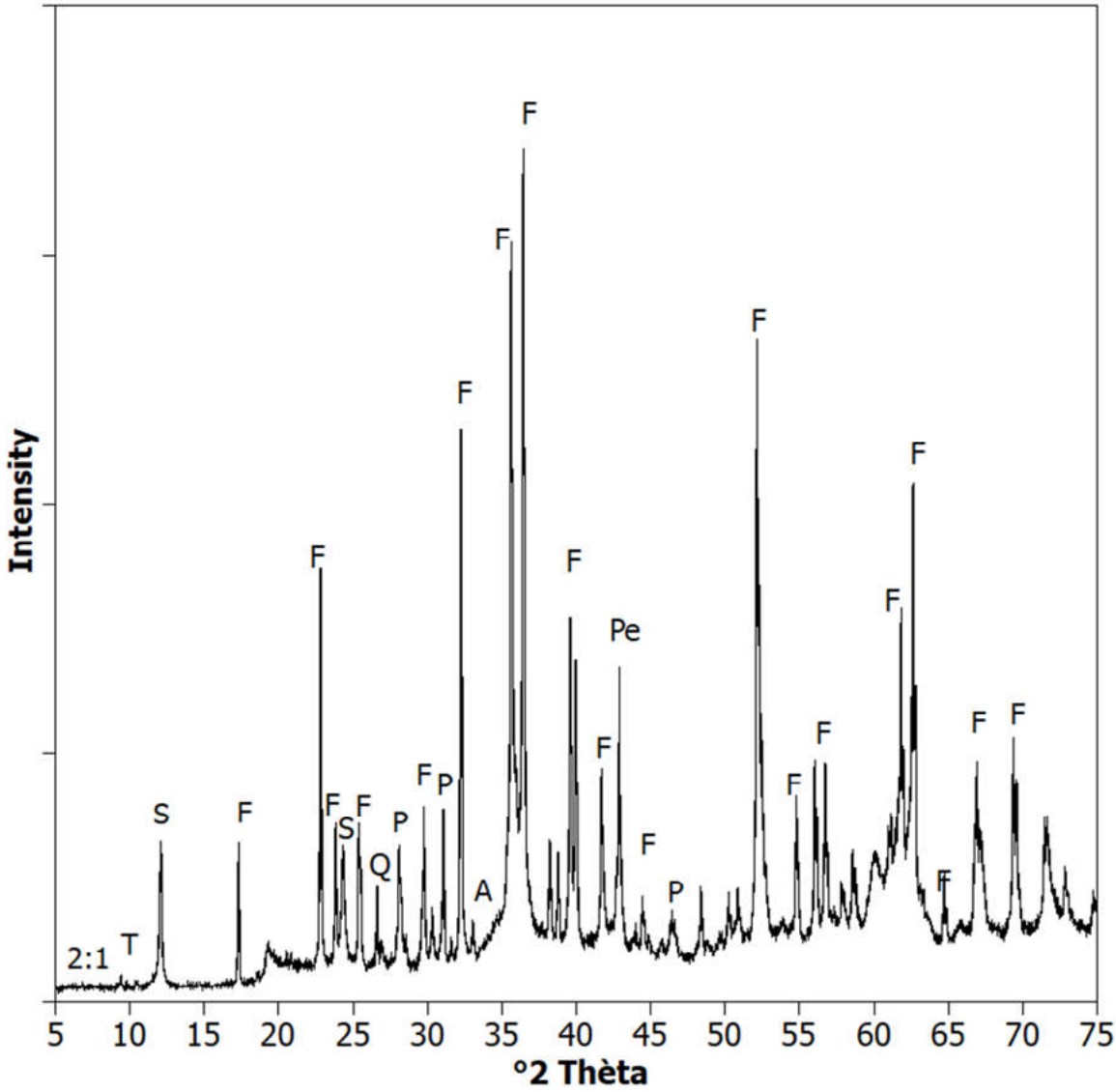

Figure 7: Diffraction pattern of the sample “UM-GR-GM | Grecian Magnesite | "olivine"”. The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), 2:1 layer silicates (2:1), Chlorite (Chl), Serpentine (S), Talc (T), Periclase (Pe).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

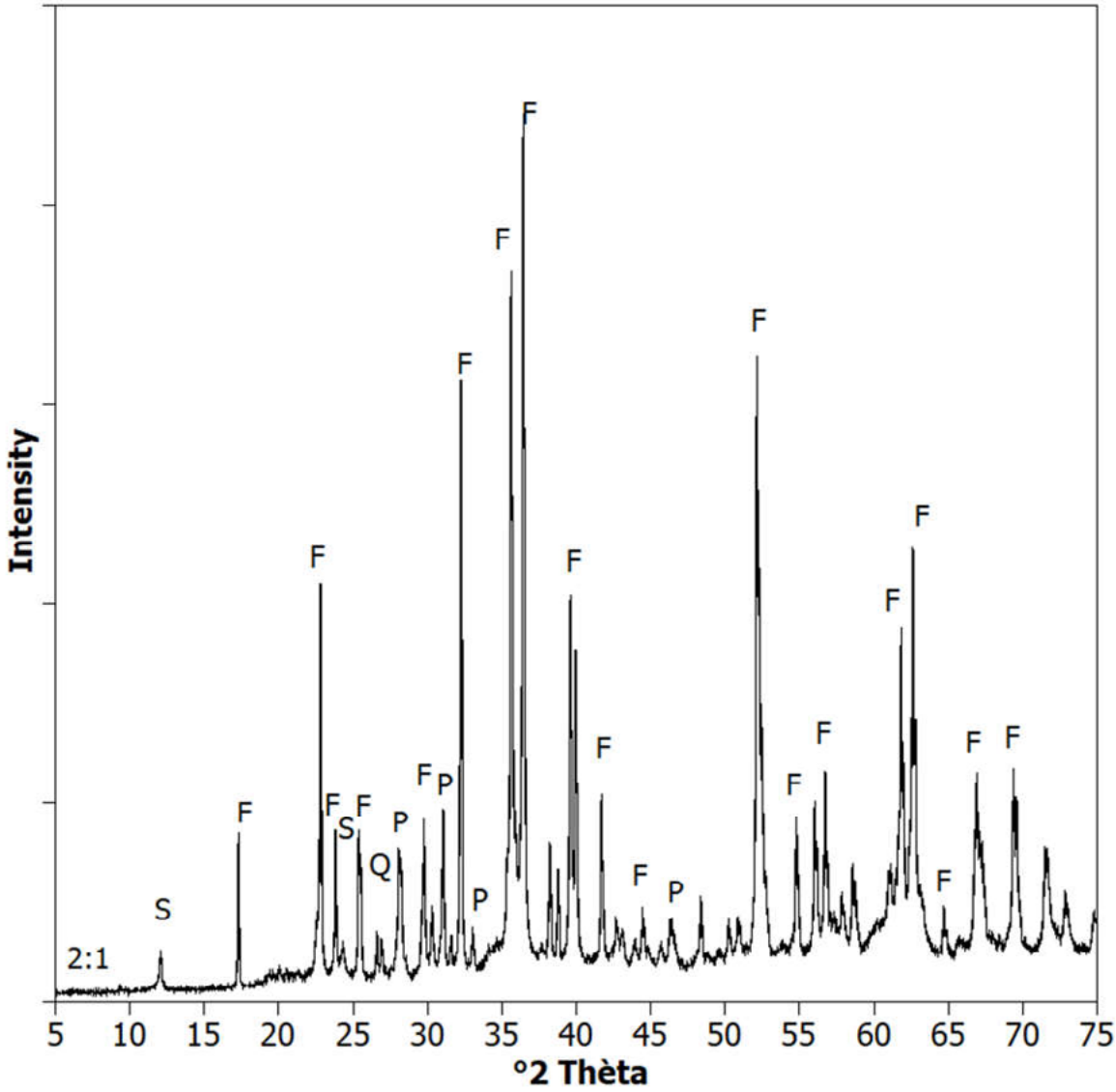

Figure 8: Diffraction pattern of the sample “UM-GR-VV |Vitruvit "Olivine"”. The minerals that contribute to the main reflections are labeled: Forsterite (F), Pyroxene (P), Amphibole (A), 2:1 layer silicates (2:1), Serpentine (S).

Your reference: Various samples received on 26/04/2021
Our reference: 2104CD_Bis

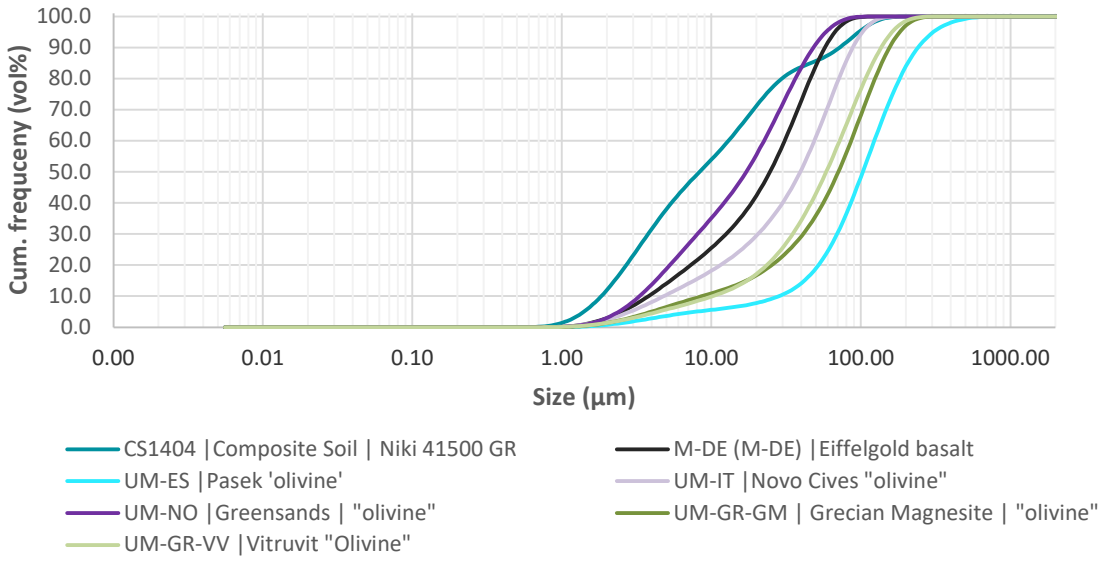

Figure 9: Cumulative frequency distributions of the samples.

Appendix D

Appendix D – Soil analyses throughout cotton season

1. SOIL SAMPLING PRIOR TO ROCK DUST APPLICATION											
	EXPERIMENTAL AREA				PILOT AREA						
Soil parameters	**Control 1**	**Control 2**	**Control 3**	**Control 4**	**Control 1**	**Control 2**	**Biochar**	**GR olivine GM**	**GR olivine VV**	**VV + Biochar**	**GM + Biochar**
Sand (%)	30	20	22	26	26	24	30	28	22	20	24
Clay (%)	52	44	60	56	40	42	42	46	44	38	48
Silt (%)	18	36	18	18	34	34	28	26	34	42	28
pH (H_2O 1:1) (25^oC)	8.3	8.4	8.3	8.4	8.2	8.4	8.5	8.4	8.4	8.4	8.3
EC 25^{o}C (µS/cm)	452	498	557	490	651	473	433	419	429	425	644
$CaCO_3$ _equivalent (%)	24	24	24	23	25	23	23	22	24	23	23
SOM (%)	0.61	0.71	0.7	0.87	0.68	0.87	1.0	1.1	0.71	1.2	2.2
$P_{(Olsen)}$ (mg/kg)	2.9	<2,1	3.7	2.2	<2,1	6.0	2.3	2.2	2.2	2.5	2.8
$N_{(Kjeldhal)}$ (%)	0.057	0.077	0.075	0.081	0.085	0.073	0.071	0.080	0.075	0.084	0.078
NO3-N (mg(NO_3^-N)/kg soil)	3.77	3.87	6.86	4.72	1.45	8.48	4.61	1.42	0.95	0.51	3.40
K (cmol+/kg soil)	0.41	0.36	0.37	0.39	0.38	0.36	0.36	0.31	0.31	0.38	0.36
Na (cmol+/kg soil.)	0.14	0.17	0.13	0.17	0.23	0.17	0.32	0.21	0.41	0.22	0.18
Ca (cmol+/kg soil)	28	29	29	29	29	29	29	29	29	30	30
Mg (cmol+/kg soil)	7.9	8.9	8.0	8.6	9.0	8.4	8.3	8.3	8.1	8.5	8.1
CEC (cmol+/kg soil)	34	37	35	37	36	36	35	36	36	37	36
Cr (mg/kg)	130.0	133.4	132.6	148.2	133.6	134.1	132.5	122.8	125.3	128.2	117.9
Cu (mg/kg)	25.9	26.8	26.1	26.8	27.0	26.2	26.5	26.0	26.1	26.0	25.8
Ni (mg/kg)	147.0	148.2	145.0	152.5	144.9	143.1	143.5	134.5	136.6	136.9	133.4
Pb (mg/kg)	5.4	5.4	5.0	5.5	5.0	4.6	4.7	4.7	4.4	4.4	4.0
Zn (mg/kg)	41.3	46.3	35.1	36.0	35.9	33.3	34.6	32.2	32.6	33.3	32.3

2. SOIL SAMPLING DURING FLOWERING STAGE																
EXPERIMENTAL AREA – PART 1																
Treatment	**Control**				**DE Basalt**				**NO olivine**				**ES olivine**			
Replicate	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Sand (%)	15	35	15	17	13	19	19	15	17	17	13	21	15	17	17	21
Clay (%)	39	47	37	44	47	47	48	47	43	39	43	51	41	48	45	43
Silt (%)	46	18	48	39	40	34	33	38	40	44	44	28	44	35	38	36
pH (H_2O 1:1) (25^oC)	8.1	8.2	7.9	8.2	8.1	8.2	8.2	8.2	8.1	7.9	8.2	8.1	8.2	8.2	8.2	8.2
EC 25^{o}C (µS/cm)	710	640	1160	627	995	679	539	605	640	1032	611	860	635	684	655	661
$CaCO_3$ equivalent (%)	25	25	26	21	26	26	25	27	24	23	29	24	26	27	25	25
SOM (%)	1.1	1.0	<0,39	0.59	0.43	0.67	0.71	0.64	0.44	1.3	0.54	<0,39	<0,39	<0,39	0.90	1.2
$P_{(Olsen)}$ (mg/kg)	10	11	4.5	15	5.0	6.7	3.5	4.2	15	12	9.5	5.2	11	20	4.4	28
$N_{(Kjeldhal)}$ (%)	0.088	0.084	0.077	0.090	0.082	0.085	0.080	0.077	0.088	0.081	0.073	0.080	0.075	0.091	0.094	0.087
NO3-N (mg(NO_3^- N)/kg soil)	3.44	12.39	3.65	26.49	2.25	36.45	2.95	6.60	23.66	5.60	11.83	9.98	4.50	30.49	3.19	35.19
K (cmol+/kg soil)	0.49	0.57	0.51	0.56	0.48	0.51	0.54	0.54	0.62	0.53	0.52	0.47	0.53	0.69	0.56	0.73
Na (cmol+/kg soil.)	1.17	0.95	0.99	1.02	1.06	0.95	0.77	0.88	1.07	0.89	1.38	0.98	1.11	0.96	0.90	0.92
Ca (cmol+/kg soil)	34	34	33	36	34	30	31	34	35	35	33	34	35	36	33	36
Mg (cmol+/kg soil)	9.1	9.1	8.8	8.7	9.1	7.7	8.3	9.0	9.2	9.2	8.9	8.9	10	9.0	8.2	9.3
CEC (cmol+/kg soil)	42	43	41	43	43	37	38	42	44	44	42	42	45	44	42	46
Cd (mg/kg)	0.09	0.09	0.13	0.07	0.15	0.12	0.15	0.13	0.15	0.10	0.14	0.16	0.16	0.21	0.18	0.21
Cr (mg/kg)	230.0	223.3	213.3	214.2	216.0	228.1	228.5	211.5	213.3	206.9	201.6	209.9	206.8	200.7	193.7	201.0
Cu (mg/kg)	29.8	28.4	29.2	28.2	28.3	29.4	28.9	27.8	29.7	28.5	30.1	27.2	29.0	28.8	26.6	29.5
Ni (mg/kg)	248.6	239.9	248.3	234.0	235.4	245.6	297.0	245.3	239.7	237.7	245.1	250.6	243.1	237.2	281.7	237.3
Pb (mg/kg)	8.8	9.0	8.8	8.8	8.6	9.2	9.3	9.1	9.5	8.8	9.0	8.2	8.7	8.6	7.8	8.8
Zn (mg/kg)	51.6	49.0	48.7	45.7	45.8	49.1	47.2	44.8	45.1	42.6	44.0	41.7	43.4	42.6	40.9	42.6

2. SOIL SAMPLING DURING FLOWERING STAGE																
EXPERIMENTAL AREA – PART 2																
Treatment	**IT olivine**				**GR olivine GM**				**GR olivine VV**				**GR olivine VV + biochar**			
Replicate	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Sand (%)	11	21	19	21	17	13	17	23	17	15	23	13	19	17	17	19
Clay (%)	45	49	39	39	45	45	43	37	42	49	49	45	45	39	47	45
Silt (%)	44	30	42	40	38	49	40	40	42	36	28	42	36	44	36	36
pH (H_2O 1:1) (25°C)	8.0	8.1	8.1	8.3	8.0	8.1	8.1	8.1	8.1	8.1	8.3	8.1	8.1	8.1	8.1	8.1
EC 25°C (µS/cm)	845	680	629	640	971	805	900	720	580	655	555	685	770	720	635	650
$CaCO_3$ equivalent (%)	25	24	26	24	25	24	26	22	24	25	25	24	26	24	24	23
SOM (%)	0.92	0.69	0.87	0.87	0.67	0.82	0.74	0.71	1.2	0.74	0.81	0.74	1.0	1.0	1.1	0.78
$P_{(Olsen)}$ (mg/kg)	2.4	3.1	3.8	3.9	2.5	2.1	19	10	16	4.1	<2,1	32	26	2.8	10	4.0
$N_{(Kjeldhal)}$ (%)	0.075	0.073	0.067	0.081	0.083	0.083	0.088	0.095	0.097	0.091	0.080	0.084	0.088	0.082	0.090	0.094
NO3-N (mg(NO_3-N)/kg soil)	3.24	1.80	2.14	5.59	2.70	2.45	8.95	18.17	13.27	2.54	4.34	11.90	32.83	2.49	38.52	1.03
K (cmol+/kg soil)	0.43	0.47	0.58	0.58	0.51	0.50	0.62	0.54	0.58	0.53	0.39	0.55	0.64	0.43	0.56	0.48
Na (cmol+/kg soil.)	0.88	1.00	0.75	0.85	0.92	0.98	0.82	0.90	0.89	0.94	0.97	0.86	0.92	0.93	1.31	0.98
Ca (cmol+/kg soil)	34	36	36	35	34	35	34	40	38	40	39	41	38	40	41	41
Mg (cmol+/kg soil)	8.8	9.9	9.8	9.8	8.8	8.9	9.1	10.0	9.2	9.1	8.7	9.5	8.1	9.4	9.6	10
CEC (cmol+/kg soil)	43	46	46	45	42	43	42	49	46	47	47	50	45	47	50	50
Cd (mg/kg)	0.22	0.04	0.05	0.07	0.06	0.01	0.07	0.08	0.05	0.17	0.14	0.26	0.23	0.24	0.26	0.24
Cr (mg/kg)	192.2	99.8	103.4	117.7	105.7	103.5	100.8	105.5	110.7	103.3	99.4	98.4	99.8	99.6	95.7	89.4
Cu (mg/kg)	27.8	29.0	31.4	31.0	28.1	28.8	28.4	30.3	29.0	28.5	28.2	27.2	26.8	25.4	26.5	26.4
Ni (mg/kg)	260.7	204.1	233.7	211.2	211.8	228.7	222.1	228.5	220.0	204.9	230.8	234.6	195.3	241.2	200.7	219.8
Pb (mg/kg)	7.8	8.9	9.4	9.5	8.7	9.2	9.1	9.8	10.1	10.1	9.4	10.2	9.4	10.2	10.2	9.8
Zn (mg/kg)	39.9	48.7	52.3	50.7	46.3	47.4	47.3	48.8	49.1	50.0	46.8	48.1	45.1	45.0	46.3	44.5

2. SOIL SAMPLING DURING FLOWERING STAGE												
PILOT AREA												
Treatment	**Control**		**Biochar**		**GR olivine GM**		**GR olivine VV**		**GR olivine VV + biochar**		**GR olivine GM + biochar**	
Replicate	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Sand (%)	15	23	21	23	11	21	25	15	15	13	11	19
Clay (%)	46	50	40	38	44	40	42	50	43	46	46	46
Silt (%)	39	27	39	39	45	39	33	35	42	41	43	35
pH (H_2O 1:1) (25°C)	8.1	8.2	8.2	8.2	8.0	8.2	8.1	8.1	7.9	8.2	8.1	8.3
EC 25°C (µS/cm)	1033	616	708	602	1033	629	935	765	1096	667	885	746
$CaCO_3$ equivalent (%)	24	26	25	25	23	25	26	19	30	30	25	27
SOM (%)	0.81	0.94	1.0	1.2	0.81	1.0	1.0	1.3	1.2	1.1	1.5	1.1
$P_{(Olsen)}$ (mg/kg)	3.1	2.6	18	3.9	4.7	2.9	4.0	17	2.1	27	3.6	15
$N_{(Kjeldhal)}$ (%)	0.094	0.087	0.095	0.095	0.089	0.085	0.085	0.092	0.077	0.082	0.095	0.075
NO3-N (mg(NO_3-N)/kg soil)	7.26	2.20	11.05	17.37	9.55	13.61	12.95	18.66	8.72	9.69	8.53	22.56
K (cmol+/kg soil)	0.52	0.45	0.51	0.42	0.45	0.49	0.47	0.54	0.43	0.62	0.48	0.50
Na (cmol+/kg soil.)	0.90	1.08	0.94	0.99	0.99	1.29	0.79	0.94	0.86	0.90	0.99	1.17
Ca (cmol+/kg soil)	40	38	40	39	41	41	36	41	40	40	42	38
Mg (cmol+/kg soil)	8.7	8.4	9.1	8.5	9.4	9.7	7.7	9.4	8.8	9.1	9.5	9.3
CEC (cmol+/kg soil)	47	44	48	46	49	49	42	49	48	47	51	47
Cd (mg/kg)	0.28	0.21	0.23	0.20	0.20	0.27	0.27	0.16	0.17	0.17	0.21	0.15
Cr (mg/kg)	92.9	86.6	87.9	85.0	83.4	94.9	89.5	74.6	83.6	85.5	76.5	93.8
Cu (mg/kg)	27.1	25.7	27.3	25.7	25.3	26.1	25.7	24.4	25.0	24.0	22.2	21.9
Ni (mg/kg)	221.5	218.6	218.1	196.7	192.6	233.5	222.2	201.6	211.2	209.3	188.8	261.5
Pb (mg/kg)	10.4	9.6	10.3	10.7	10.7	10.9	11.3	10.8	11.3	11.4	11.0	10.8
Zn (mg/kg)	45.4	44.6	45.2	45.4	42.1	45.4	45.2	41.6	40.6	40.4	38.7	39.3

3. SOIL SAMPLING BEFORE HARVEST																
EXPERIMENTAL AREA – PART 1																
Treatment	**Control**				**DE Basalt**				**NO olivine**				**ES olivine**			
Replicate	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
pH (H_2O 1:1) (25°C)	8.4	8.3	8.1	8.2	8.2	8.3	8.2	8.3	8.3	8.5	8.4	8.3	8.3	8.3	8.4	8.4
EC 25°C (µS/cm)	437	423	1047	597	556	412	605	470	643	398	429	631	451	515	394	463
$CaCO_3$ equivalent (%)	22	22	6	22	21	21	19	19	22	22	22	22	20	22	22	21
SOM (%)	1.1	1.1	1.2	0.99	1.3	1.1	1.2	1.0	0.96	0.80	1.1	0.88	1.0	0.99	1.1	0.96
$P_{(Olsen)}$ (mg/kg)	5.6	13	6.4	<2,1	7.5	13.0	<2,1	<2,1	<2,1	5.3	<2,1	<2,1	<2,1	2.6	<2,1	<2,1
$N_{(Kjeldhal)}$ (%)	0.089	0.082	0.092	0.085	0.089	0.083	0.120	0.078	0.078	0.082	0.110	0.210	0.082	0.082	0.820	0.089
NO3-N (mg(NO_3^- N)/kg soil)	12	12	18	1.3	17	2.7	1.4	2.2	1.7	15	2.2	3.6	0.60	2.2	4.0	2.8
K (cmol+/kg soil)	0.47	0.45	0.38	0.34	0.54	0.47	0.41	0.30	0.31	0.41	0.35	0.46	0.35	0.47	0.40	0.30
Mn (cmol+/kg soil.)	1.9	1.6	1.4	2.0	1.5	2.3	2.2	1.8	2.0	1.8	1.8	1.8	1.9	1.8	2.1	2.3
Ca (cmol+/kg soil)	41	41	44	45	44	44	43	43	45	43	45	44	42	42	42	41
Mg (cmol+/kg soil)	9.1	8.3	9.7	9.8	9.8	9.5	9.5	10.0	10	10	9.3	9.9	9.5	8.9	9.5	9.5
CEC (cmol+/kg soil)	48	46	50	52	52	52	48	50	50	51	50	51	48	48	46	47
Cd (mg/kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.01	0.04	0.04	0.03	0.01	0.04	0.04
Cr (mg/kg)	137.8	149.3	142.6	153.2	145.1	146.9	143.5	140.0	160.2	150.8	145.0	143.4	195.6	135.6	136.6	132.2
Cu (mg/kg)	28.8	28.8	30.2	30.5	30.5	29.1	29.5	28.8	30.0	30.1	29.3	29.6	30.6	28.9	27.9	29.4
Ni (mg/kg)	137.2	153.2	137.1	162.3	131.8	153.1	153.6	154.7	149.2	154.2	139.8	151.1	169.7	125.1	157.2	126.6
Pb (mg/kg)	6.0	6.0	5.8	6.0	6.1	6.2	6.0	7.0	6.6	7.3	6.7	7.4	7.5	7.1	6.8	7.2
Zn (mg/kg)	43.1	41.6	55.1	45.4	43.7	41.8	40.6	43.4	47.2	42.6	41.8	43.0	42.7	42.5	41.6	43.3

3. SOIL SAMPLING BEFORE HARVEST																
EXPERIMENTAL AREA – PART 2																
Treatment	**IT olivine**				**GR olivine GM**				**GR olivine VV**				**GR olivine VV + biochar**			
Replicate	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
pH (H_2O 1:1) (25°C)	8.3	8.4	8.5	8.4	8.2	8.3	8.3	8.4	8.3	8.4	8.3	8.4	8.4	8.3	8.3	8.3
EC 25°C (µS/cm)	537	474	419	390	555	550	699	463	451	481	455	449	491	503	475	467
$CaCO_3$ equivalent (%)	23	21	22	21	20	22	22	11	20	22	22	21	21	21	22	20
SOM (%)	0.78	0.86	1.6	1.1	1.1	0.9	1.0	1.2	1.1	0.85	0.92	<0,39	0.79	0.80	1.0	0.89
$P_{(Olsen)}$ (mg/kg)	19	<2,1	<2,1	2.6	7.4	<2,1	<2,1	<2,1	14	2.4	<2,1	<2,1	<2,1	25	5.2	4.8
$N_{(Kjeldhal)}$ (%)	0.140	0.078	0.082	0.091	0.087	0.096	0.081	0.077	0.085	0.081	0.870	0.077	0.076	0.081	0.091	0.085
NO3-N (mg(NO_3^- N)/kg soil)	4.1	1.5	2.7	24	2.2	2.7	2.0	2.4	25	4.6	2.0	1.9	2.4	13	14	17
K (cmol+/kg soil)	0.63	0.35	0.51	0.54	0.51	0.35	0.35	0.35	0.50	0.40	0.39	0.35	0.35	0.49	0.49	0.43
Mn (cmol+/kg soil.)	1.8	2.0	2.1	2.3	2.4	1.7	2.3	1.9	1.8	2.2	2.3	1.8	2.0	1.9	1.9	2.6
Ca (cmol+/kg soil)	33	42	39	38	43	42	42	43	41.00	41.00	41.00	42.00	40.00	39.00	41.00	41.00
Mg (cmol+/kg soil)	7.1	9.8	8.0	7.4	10	9.6	10	10	11	10	10	9.9	9.6	9.4	10	9.8
CEC (cmol+/kg soil)	33	42	39	38	43	42	42	43	50	49	47	49	46	47	47	48
Cd (mg/kg)	0.06	0.05	0.08	0.09	0.09	0.08	0.06	0.05	0.05	0.07	0.10	0.13	0.10	0.13	0.14	0.13
Cr (mg/kg)	132.4	134.9	125.9	133.6	130.4	132.1	134.6	138.6	137.4	145.9	144.0	138.2	140.0	134.9	131.9	136.3
Cu (mg/kg)	29.3	29.9	30.1	29.5	29.2	28.4	27.2	28.5	28.3	28.1	28.1	27.6	27.5	27.5	28.1	29.2
Ni (mg/kg)	175.3	168.9	132.4	131.8	134.1	120.1	158.4	126.1	148.4	139.9	150.0	139.2	147.7	149.6	120.3	127.2
Pb (mg/kg)	7.3	7.0	7.4	7.7	8.0	8.3	8.6	9.1	9.7	9.9	10.5	10.6	10.9	11.1	11.2	11.5
Zn (mg/kg)	43.4	42.2	41.3	41.6	42.4	39.9	39.9	41.0	41.7	39.8	41.4	39.2	38.8	38.6	39.8	40.6

3. SOIL SAMPLING BEFORE HARVEST												
PILOT AREA												
Treatment	**Control**		**Biochar**		**GR olivine GM**		**GR olivine VV**		**GR olivine VV + biochar**		**GR olivine GM + biochar**	
Replicate	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
pH (H_2O 1:1) (25°C)	8.2	8.5	8.2	8.3	8.1	8.3	8.2	8.4	8.3	8.3	8.3	8.3
EC 25°C (µS/cm)	679	438	670	670	556	593	570	500	513	601	625	478
$CaCO_3$ equivalent (%)	22	22	22	21	21	22	21	18	22	22	21	22
SOM (%)	1.2	0.82	0.90	1.0	0.92	0.75	1.0	0.80	1.0	0.89	0.50	0.94
$P_{(Olsen)}$ (mg/kg)	9.5	4.9	4.0	12	7.5	4.1	13	3.4	<2,1	2.1	3.8	3.8
$N_{(Kjeldhal)}$ (%)	0.098	0.075	0.087	0.080	0.083	0.084	0.084	0.063	0.086	0.088	0.075	0.091
NO3-N (mg(NO_3-N)/kg soil)	3.9	4.8	23	12	1.7	4.0	2.8	1.2	1.3	13	2.6	6.9
K (cmol+/kg soil)	0.46	0.47	0.49	0.47	0.42	0.38	0.47	0.35	0.39	0.41	0.37	0.47
Mn (cmol+/kg soil.)	2.3	2.0	1.9	2.2	2.2	2.4	2.2	2.3	3.3	2.2	2.2	2.2
Ca (cmol+/kg soil)	42	42	41	41	41	41	41	40	41	40	39	40
Mg (cmol+/kg soil)	9.3	9.3	8.9	8.9	10	9.5	8.9	10	10	10	10	9.4
Cd (mg/kg)	0.16	0.12	0.15	0.20	0.20	0.20	0.20	0.22	0.21	0.20	0.22	0.22
Cr (mg/kg)	131.9	126.9	123.4	124.8	118.4	134.1	140.7	129.7	125.5	133.0	126.3	130.5
Cu (mg/kg)	28.3	26.6	27.6	27.4	27.3	27.7	29.0	27.9	27.1	26.8	26.2	25.2
Ni (mg/kg)	125.6	122.0	119.2	122.0	121.4	122.6	117.4	115.7	111.9	112.6	111.1	115.1
Pb (mg/kg)	11.7	11.1	11.7	11.9	11.7	11.6	11.9	13.2	14.3	14.3	14.1	14.2
Zn (mg/kg)	40.8	38.8	41.7	52.3	38.8	40.3	40.8	37.7	38.8	39.3	38.8	47.0

Appendix E

Appendix E – GPS Coordinates of sampling locations

List of the exact locations in the field where soil water, soil, plant tissue and cotton were sampled throughout 2021. Coordinates are expressed in Geographic Coordinate System EGSA'87.

The ID numbers of the experimental plots represent row_treatment, where rows are parallel to the 100 m width of our part of the field, with 1 starting at the bottom. Treatments are 1 - control, 2 - DE basalt, 3 - NO olivine, 4 - ES olivine, 5 - IT olivine, 6 - GR olivine GM, 7 - GR olivine VV, 8 - GR olivine VV + biochar.

ID numbers for the pilot areas are pilot xxx where xxx stands for bioch - biochar, contol - control, grec mag – GR olivine GM, vitruvit – GR olivine VV, vitruvit bio – GR olivine VV + biochar, grec mag bio – GR olivine GM + biochar.

ID	**X**	**Y**		***ID***	**X**	**Y**
1_5	388746	4376526		***3_8***	388752	4376471
1_2	388750	4376520		***3_7***	388756	4376464
1_1	388755	4376513		***4_3***	388714	4376502
1_4	388759	4376507		***4_8***	388719	4376497
1_6	388763	4376500		***4_7***	388723	4376490
1_7	388768	4376493		***4_5***	388728	4376484
1_8	388773	4376487		***4_6***	388733	4376477
1_3	388777	4376480		***4_4***	388737	4376470
2_7	388736	4376518		***4_1***	388740	4376462
2_4	388740	4376512		***4_2***	388745	4376456
2_3	388745	4376505		***pilot bioch1***	388697	4376491
2_1	388749	4376499		***pilot bioch2***	388705	4376478
2_8	388753	4376492		***pilot contol1***	388682	4376480
2_5	388756	4376484		***pilot contol2***	388691	4376467
2_6	388762	4376478		***pilot grec mag 1***	388664	4376466
2_2	388766	4376471		***pilot grec mag 2***	388672	4376454
3_6	388725	4376510		***pilot vitruvit 1***	388648	4376454
3_1	388729	4376504		***pilot vitruvit 2***	388656	4376441
3_5	388734	4376497		***pilot vitruvit bio1***	388631	4376442
3_4	388738	4376491		***pilot vitruvit bio2***	388640	4376429
3_2	388743	4376485		***pilot grec mag bio 1***	388618	4376432
3_3	388747	4376478		***pilot grec mag bio 2***	388623	4376417

Appendix F

Appendix F – Cotton yield

Treatment_replicate	Yield (kg/ ha)	*Treatment_replicate*	Yield (kg/ ha)
Control_1	3163.2	*GR olivine VV_4*	3961.4
Control_2	3184.2	*GR olivine VV + biochar_1*	4789.5
Control_3	5084.2	*GR olivine VV + biochar_2*	4824.6
Control_4	5449.1	*GR olivine VV + biochar_3*	5186.0
DE Basalt_1	4142.1	*GR olivine VV + biochar_4*	4831.6
DE Basalt_2	4355.0	*Pilot Control _1*	3898.2
DE Basalt_3	4796.5	*Pilot Control _2*	4324.6
DE Basalt_4	4126.3	*Pilot Control _3*	4154.4
NO olivine_1	4089.5	*Pilot Biochar_1*	4440.4
NO olivine_2	3521.1	*Pilot Biochar_2*	3298.2
NO olivine_3	3814.6	*Pilot Biochar_3*	3780.7
NO olivine_4	3833.3	*Pilot GR olivine GM_1*	4280.7
ES olivine_1	3410.5	*Pilot GR olivine GM_2*	4284.2
ES olivine_2	4293.0	*Pilot GR olivine GM_3*	5428.1
ES olivine_3	3221.1	*Pilot GR olivine VV_1*	3784.2
ES olivine_4	3922.8	*Pilot GR olivine VV_2*	4498.2
IT olivine_1	2980.7	*Pilot GR olivine VV_3*	4733.3
IT olivine_2	5177.2	*Pilot GR-VV + Biochar_1*	3891.2
IT olivine_3	3935.1	*Pilot GR-VV + Biochar_2*	4743.9
IT olivine_4	2657.9	*Pilot GR-VV + Biochar_3*	4293.0
GR olivine GM_1	4047.4	*Pilot GR-GM + Biochar_1*	4328.1
GR olivine GM_2	5152.6	*Pilot GR-GM + Biochar_2*	3963.2
GR olivine GM_3	4503.5	*Pilot GR-GM + Biochar_3*	5068.4
GR olivine GM_4	4061.4	*Doris'field_1*	4668.4
GR olivine VV_1	4380.7	*Doris'field_2*	4354.4
GR olivine VV_2	4171.9	*Doris'field_3*	4240.4
GR olivine VV_3	4410.5		

Yield observed across experimental plots (4 replicates for each treatment), pilot area (3 replicates for each treatment) and the farmer's own cotton crop next to our experiment (Doris' field – 3 replicates).

Yield (kg/ha) calculated from the amount of cotton (kg) we manually collected for each 3m long by 2 cotton rows wide replicate area.

Appendix G

Appendix G – Cotton quality

COTTON QUALITY - EXPERIMENTAL AREA – PART 1													
Treatment	**Lint weight %**	**Seed weight %**	**SCI**	**Moisture %**	**Micronaire**	**Maturity**	**UHML mm**	**Length uniformity**	**SFI**	**Strength**	**Elongation**	**Reflectance %**	**yellowness +b**
Control-1	45.00	54.00	162	7.1	5.08	0.87	30.87	85.3	7.5	36.7	8.3	77.6	8.7
Control-2	45.00	54.00	157	6.7	4.86	0.86	29.43	85.0	7.6	35.9	9.1	76.3	8.3
Control-3	47.00	52.00	146	7.2	4.62	0.85	29.63	82.7	8.5	35.5	8.8	75.2	7.8
Control-4	46.28	53.00	150	7.2	4.57	0.85	30.65	83.7	8.5	34.3	8.8	75.7	7.9
DE Basalt-1	47.35	52.65	133	7.4	4.86	0.86	29.62	81.7	8.2	32.9	9.2	76.6	8.6
DE Basalt--2	45.29	54.71	143	6.9	5.08	0.86	29.69	84.2	8.1	33.3	9.0	75.5	8.1
DE Basalt--3	47.17	52.83	129	6.7	5.16	0.86	28.79	82.7	7.9	32.0	9.3	75.4	7.7
DE Basalt--4	44.63	55.37	145	6.9	4.50	0.85	28.80	83.0	8.4	34.4	9.1	76.5	8.3
NO olivine-1	46.25	53.75	154	7.0	4.31	0.84	30.57	83.9	8.0	34.4	9.3	76.3	8.2
NO olivine-2	48.06	51.94	146	7.4	4.62	0.85	29.17	82.7	8.2	35.0	8.8	77.3	8.4
NO olivine-3	47.05	52.95	133	6.9	5.08	0.87	29.17	83.6	8.3	31.8	8.6	73.5	7.5
NO olivine-4	46.84	53.16	129	6.9	4.89	0.85	27.61	82.6	8.6	31.7	9.5	76.6	8.2
ES olivine-1	46.61	53.39	137	6.8	4.73	0.85	28.50	84.1	8.1	31.9	9.0	71.7	7.9
ES olivine-2	45.56	54.44	150	7.5	4.64	0.85	29.61	84.0	7.4	35.8	8.8	71.6	7.9
ES olivine-3	44.94	55.06	153	8.3	4.59	0.85	28.89	84.3	8.4	35.0	9.3	77.4	8.2
ES olivine-4	47.97	52.03	135	7.2	4.93	0.86	28.63	83.3	8.1	33.6	9.2	70.1	7.3
IT olivine-1	44.96	55.04	155	7.1	4.81	0.86	31.31	84.1	8.0	35.7	8.3	75.4	8.2
IT olivine-2	48.53	51.47	133	7.3	4.44	0.85	28.45	81.6	9.2	32.5	9.0	76.9	8.2
IT olivine-3	47.12	52.88	137	6.8	4.66	0.85	28.53	83.1	8.0	33.3	9.0	71.1	7.5
IT olivine-4	47.19	52.81	134	7.4	4.96	0.86	28.41	82.6	8.5	33.4	9.6	74.6	8.2
GR olivine GM-1	46.33	53.67	159	7.1	4.49	0.85	29.78	84.4	7.6	36.3	8.9	77.3	7.7
GR olivine GM-2	48.05	51.95	156	6.9	4.65	0.86	30.02	84.8	7.9	36.1	8.6	72.3	6.9
GR olivine GM-3	45.95	54.05	149	7.2	4.36	0.84	29.85	84.5	7.8	33.0	9.6	71.9	8.0
GR olivine GM-4	47.41	52.59	149	6.7	4.69	0.86	28.25	84.9	7.9	33.8	8.3	76.9	7.8

COTTON QUALITY - EXPERIMENTAL AREA – PART 2													
Treatment	**Lint weight %**	**Seed weight %**	**SCI**	**Moisture %**	**Micronaire**	**Maturity**	**UHML mm**	**Length uniformity**	**SFI**	**Strength**	**Elongation**	**Reflectance %**	**yellowness +b**
GR olivine VV-1	48.53	51.47	137	6.9	4.93	0.86	29.11	83.4	8.3	32.9	8.7	74.8	7.4
GR olivine VV-2	46.57	53.43	149	7.1	4.77	0.86	30.13	83.8	7.7	35.2	8.6	74.3	7.7
GR olivine VV-3	47.41	52.59	153	7.2	4.91	0.86	30.20	83.7	8.0	36.5	8.4	76.1	8.0
GR olivine VV-4	47.42	52.58	136	7.4	4.35	0.85	28.89	82.2	8.8	32.5	9.0	75.3	8.2
GR-VV + Biochar-1	44.07	55.93	161	7.3	4.76	0.86	31.17	85.6	7.8	34.7	8.4	78.2	8.0
GR-VV + Biochar-2	46.30	53.70	162	8.1	4.54	0.85	30.92	85.2	7.6	36.1	9.0	74.6	7.6
GR-VV + Biochar-3	47.57	52.43	148	6.7	4.51	0.85	30.01	83.5	7.9	34.6	9.0	73.6	7.8
GR-VV + Biochar-4	46.67	53.33	143	7.6	4.68	0.86	28.78	82.9	8.0	34.5	8.5	76.3	8.3
COTTON QUALITY - PILOT AREA													
Control 1	46.34	53.66	138	7.0	5.18	0.86	29.40	84.4	7.9	31.4	9.7	77.0	8.5
Control 2	45.54	54.46	154	7.0	4.44	0.85	30.35	84.6	7.8	34.4	8.8	73.5	7.9
Control 3	47.32	52.68	155	7.1	4.14	0.84	29.29	83.7	8.2	35.1	9.2	77.2	8.6
Biochar 1	43.80	56.20	135	7.7	4.59	0.85	29.55	80.4	8.9	35.1	9.1	76.2	8.5
Biochar 2	44.76	55.24	156	6.8	4.76	0.86	30.34	84.9	7.5	35.3	8.0	75.2	7.9
Biochar 3	42.73	57.27	166	7.2	4.77	0.87	31.72	85.5	7.2	36.6	7.6	76.3	8.3
GR olivine GM 1	44.94	55.06	149	7.8	5.10	0.86	28.59	84.8	8.0	34.7	9.4	77.1	8.1
GR olivine GM 2	44.34	55.66	144	7.7	4.98	0.86	29.40	83.0	7.8	35.4	8.6	75.3	8.6
GR olivine GM 3	46.02	53.98	145	6.8	4.90	0.86	29.14	84.1	8.2	33.6	9.0	76.3	8.7
GR olivine VV 1	45.02	54.98	138	7.2	4.76	0.86	29.74	81.8	9.0	34.4	8.5	75.3	8.2
GR olivine VV 2	44.80	55.20	152	7.5	5.08	0.86	30.11	84.8	7.7	35.2	8.9	75.3	8.4
GR olivine VV 3	45.63	54.37	134	7.0	4.99	0.86	28.45	82.4	9.0	33.4	8.8	77.1	8.0
GR-VV + Biochar 1	44.12	55.88	143	7.8	4.52	0.85	29.30	83.1	7.8	33.2	8.3	76.9	8.9
GR-VV + Biochar 2	45.06	54.94	168	7.5	4.61	0.86	31.34	85.9	7.5	36.3	8.2	76.1	8.0
GR-VV + Biochar 3	47.48	52.52	138	6.9	4.95	0.86	29.29	83.5	8.0	32.1	8.6	77.1	8.4
GR-GM + Biochar 1	45.37	54.63	147	6.9	4.55	0.85	29.29	84.3	8.5	32.8	9.2	76.4	8.2
GR-GM + Biochar 2	44.63	55.37	141	7.5	4.83	0.86	29.22	83.1	7.8	34.1	8.6	74.4	7.9
GR-GM + Biochar 3	46.94	53.06	140	7.5	4.96	0.87	29.40	83.1	7.5	33.2	8.1	78.6	8.4

Appendix H

Appendix H – Nutrients in plant tissue

PLANT NUTRIENT CONTENTS – EXPERIMENTAL AREA – PART 1										
Treatments	**P (%)**	**N (%)**	**K (%)**	**Ca (%)**	**Mg (%)**	**Fe (mg/kg)**	**Zn (mg/kg)**	**Cu (mg/kg)**	**Mn (mg/kg)**	**B (mg/kg)**
Control 1	0.20	3.01	0.97	2.86	0.79	163	23	6.3	132	89
Control 2	0.16	2.74	0.76	2.55	0.65	291	24	6.1	112	68
Control 3	0.18	3.36	1.16	3.02	0.84	868	176	9.2	155	83
Control 4	0.16	2.90	1.23	2.80	0.85	181	83	6.6	126	69
DE Basalt 1	0.22	3.42	1.02	3.01	0.76	195	63	9.9	140	63
DE Basalt 2	0.22	3.29	0.96	2.58	0.67	300	281	0.94	119	104
DE Basalt 3	0.20	3.40	1.07	2.99	0.8	309	27	4.6	120	85
DE Basalt 4	0.19	3.01	1.30	2.88	0.78	227	58	6.8	134	57
NO olivine 1	0.20	3.19	0.90	2.83	0.79	456	38	1.2	125	95
NO olivine 2	0.18	2.87	0.77	2.75	0.72	157	24	5.8	120	75
NO olivine 3	0.20	2.82	0.90	2.6	0.76	229	50	6.4	80	64
NO olivine 4	0.16	3.01	0.83	2.79	0.82	158	20	6.3	126	100
ES olivine 1	0.20	3.03	0.88	3.07	0.79	280	103	0.9	130	98
ES olivine 2	0.10	2.77	0.75	1.64	0.44	119	23	3.9	62	44
ES olivine 3	0.17	3.07	0.93	2.86	0.78	176	25	1.5	138	69
ES olivine 4	0.18	3.05	0.89	3.01	0.87	541	153	3.3	155	96
IT olivine 1	0.20	3.11	1.00	2.89	0.76	309	49	7.6	133	64
IT olivine 2	0.19	3.30	1.05	3.25	0.93	193	121	6.2	127	72
IT olivine 3	0.15	2.95	0.74	2.45	0.67	287	22	6.6	87	79
IT olivine 4	0.16	2.80	1.06	2.32	0.6	625	72	8.9	101	75
GR olivine GM 1	0.19	3.16	1.29	2.83	0.75	223	31	6.3	116	66
GR olivine GM 2	0.21	3.39	1.09	2.83	0.84	181	26	6.3	107	75
GR olivine GM 3	0.19	3.38	0.94	2.92	0.86	727	32	7.9	144	72
GR olivine GM 4	0.19	3.46	0.89	2.8	0.75	388	42	3.7	118	90

PLANT NUTRIENT CONTENTS – EXPERIMENTAL AREA – PART 2										
Treatments	**P (%)**	**N (%)**	**K (%)**	**Ca (%)**	**Mg (%)**	**Fe (mg/kg)**	**Zn (mg/kg)**	**Cu (mg/kg)**	**Mn (mg/kg)**	**B (mg/kg)**
GR olivine VV 1	0.20	2.99	0.95	3.14	0.92	187	24	6.6	136	74
GR olivine VV 2	0.21	3.42	1.05	3.04	0.84	362	43	8.7	139	64
GR olivine VV 3	0.19	3.13	0.84	2.74	0.79	450	51	0.81	116	92
GR olivine VV 4	0.16	2.57	0.60	2.64	0.72	168	22	6	115	85
GR olivine VV + biochar 1	0.24	3.40	1.07	3.14	0.75	174	61	6.2	119	65
GR olivine VV + biochar 2	0.22	3.33	0.97	2.94	0.81	250	94	5.1	122	57
GR olivine VV + biochar 3	0.21	3.09	1.33	2.72	0.84	199	59	6.4	101	67
GR olivine VV + biochar 4	0.20	3.23	1.12	3.33	0.95	302	37	9.1	133	74
PLANT NUTRIENT CONTENTS – PILOT AREA										
Pilot Control 1	0.16	3.04	1.08	2.49	0.70	176	24	7.1	105	65
Pilot Control 2	0.18	3.25	1.11	2.83	0.84	614	50	7.5	145	78
Pilot Biochar 1	0.16	2.98	1.00	2.44	0.68	1489	46	6.3	103	67
Pilot Biochar 2	0.20	3.26	0.96	2.41	0.61	183	177	5.5	105	62
Pilot GR olivine GM 1	0.19	2.98	1.22	2.37	0.65	252	35	7.3	95	64
Pilot GR olivine GM 2	0.19	3.22	1.02	2.67	0.77	298	68	7.4	122	71
Pilot GR olivine VV 1	0.19	3.17	1.06	2.93	0.84	194	42	9.1	126	68
Pilot GR olivine VV 2	0.18	3.03	1.15	3.2	0.95	485	102	7.8	139	87
Pilot GR-VV + Biochar 1	0.22	3.42	1.01	2.96	0.83	274	137	7.8	117	56
Pilot GR-VV + Biochar 2	0.21	3.20	1.14	2.95	0.80	236	32	7.9	134	60
Pilot GR-GM + Biochar 1	0.19	3.08	1.04	3.85	1.14	172	45	1.7	109	64
Pilot GR-GM + Biochar 2	0.21	2.74	1.15	2.52	0.64	1388	61	8.1	106	74
Doris' field	0.20	3.28	0.92	2.77	0.76	583	41	8.1	135	64

Doris' field = quality of the cotton on the farmer's field next to our experiments

Appendix I

Appendix I – Macrorhizon soil water analyses

1ST SAMPLING – 13 MAY 2021										
Treatments	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	0	9997	9997	8.45	914	1525	17.4	1595	0.76	2.88
Control_2	0	6998	6998	8.33	938	2088	29.9	1718	1.66	1.18
Control_3	0	4999	4999	8.49	1094	1495	19.2	1912	5.04	0.26
Control_4										
DE Basalt_1									5.34	1.00
DE Basalt_2	0	4999	4999	8.52	727				4.90	2.58
DE Basalt_3	0	4999	4999	8.49	784				5.78	1.27
DE Basalt_4										
NO olivine_1	0	6998	6998	8.59	1127	2083	24.6	2121		
NO olivine_2	0	7998	7998	8.55	1071	1666	14.1	1765	0.47	0.54
NO olivine_3										
NO olivine_4	0	8498	8498	8.42	1100	1166	24.6	2076	14.29	4.42
ES olivine_1	0	6998	6998	8.51	816	1943	28.1	1458	3.55	1.36
ES olivine_2	0	5998	5998	8.44	978	2169	35.3	1976	1.84	0.49
ES olivine_3	0	5998	5998	8.46	767				14.97	6.98
ES olivine_4										
IT olivine_1	0	4999	4999	8.49	916				2.93	1.69
IT olivine_2	0	4999	4999	8.38	772	1908	19.2	1449	1.98	1.96
IT olivine_3	0	4999	4999	8.47	729	1373	24.6	1246	0.61	1.45
IT olivine_4	0	5998	5998	8.54	894	1771	19.2	1577	1.01	2.20
GR olivine GM_1										
GR olivine GM_2										
GR olivine GM_3	0	6998	6998	8.66	1035				3.15	0.85
GR olivine GM_4	0	7998	7998	8.30	1224	2247	40.4	2186	14.63	1.10
GR olivine VV_1	0	4999	4999	8.21	778	2245	45.8		2.38	0.85
GR olivine VV_2	0	7998	7998	8.77	1016				1.75	4.60
GR olivine VV_3	0	5998	5998	8.33	761	2356	77.8	1450	2.46	1.05
GR olivine VV_4	0	5998	5998	8.35	951	1924	26.4	1763	1.04	1.93
GR-VV + biochar_1	0	6498	6498	8.46	716				1.91	
GR-VV + biochar_2	0	6998	6998	8.47	1152				7.84	1.04
GR-VV + biochar_3										
GR-VV + biochar_4	0	6998	6998	8.17	1135	2814	61.9	2092	30.50	0.29
Pilot Control	0	3999	3999	8.25	1247	2280	152.2	2138	10	1.01
Pilot Biochar	0	4999	4999	8.29	1024	2036	54.7	1658	4.35	
Pilot GR olivine GM	0	4499	4499	8.09	859	1933	391.2	1275	10.41	0.29
Pilot GR olivine VV	0	7998	7998	8.35	1188	2280	76.0	1959	9.55	2.62
Pilot GR-VV + Biochar	0	4999	4999	7.79	1705	3532	426.7	2836	83.90	
Pilot GR-GM + Biochar	0	4999	4999	8.32	1094	2497	247.6	1823	22.97	

2ND SAMPLING – 11 JUNE 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	60	0	7998	7998	8.28	1032	1665	19.2	1846	6.99	4.80
Control_2	50	0	6498	6498	8.42	1050	2012	26.4	1997	15.22	6.81
Control_3	40	0	4999	4999	8.20	1327	2081	24.6	2387	8.35	1.72
Control_4	25	0	7998	7998	8.22	1152	2010	33.5	1802	4.21	6.14
DE Basalt_1											
DE Basalt_2											
DE Basalt_3											
DE Basalt_4											
NO olivine_1	30	0	7498	7498	8.34	1095	1723	22.8	1959	2.83	1.50
NO olivine_2	15	0	6998	6998	8.65	1187					2.53
NO olivine_3	5				8.43					12.45	0.96
NO olivine_4	30	0	6998	6998	8.38	1088	1348	22.8	2096	5.32	3.52
ES olivine_1	50	0	6998	6998	8.54	1101	2085	28.1	1967	2.79	3.72
ES olivine_2	40	0	6998	6998	8.34	1062	2033	22.8	2195	7.69	4.12
ES olivine_3	70	0	6998	6998	8.21	1046	1814	14.1	1997	2.25	3.26
ES olivine_4											
IT olivine_1	10	0	4999	4999	8.51	1022				8.87	4.02
IT olivine_2	45	0	7498	7498	8.21	938	2007	19.2	1757	22.73	8.29
IT olivine_3	32	0	7998	7998	8.44	989	1870	21.0	1889	10.30	3.36
IT olivine_4	75	0	8998	8998	8.20	1016	2015	17.4	1855	5.10	1.15
GR olivine GM_1	5	0	6998	6998	8.47	1132				3.32	6.62
GR olivine GM_2	10	0	4999	4999	8.16	731				15.10	5.64
GR olivine GM_3	20	0	6998	6998	8.40	1041	1825	26.4	2064	2.92	4.08
GR olivine GM_4	25	0	9997	9997	8.25	1132	1768	22.8	1968	22.03	1.72
GR olivine VV_1	60	0	6498	6498	8.51	1085	2369	29.9	2198	8.70	5.48
GR olivine VV_2	15	0	5998	5998	8.31	930		28.1		27.49	11.28
GR olivine VV_3	14	0	5998	5998	8.46	1070		44.0		90.17	20.71
GR olivine VV_4	30	0	6998	6998	8.54	1066	1817	38.9	2096	25.75	3.61
GR-VV + biochar_1	5	0	7498	7498	8.62	1013				44.05	34.12
GR-VV + biochar_2	20	0	9997	9997	8.53	1329		35.3		3.32	2.47
GR-VV + biochar_3	10	0	4999	4999	7.99	1043				75.87	4.39
GR-VV + biochar_4	45	0	5998	5998	8.12	1601	2886	38.9	3308	52.96	8.67
Pilot Control	50	0	5998	5998	8.05	1565	2460	19.2	2831	17.50	0.60
Pilot Biochar	80	0	6998	6998	8.05	1228	2120	19.2	2014	24.57	4.45
Pilot GR olivine GM	60	0	6998	6998	8.06	1438	2632	45.8	2434	53.32	3.85
Pilot GR olivine VV	75	0	9997	9997	8.54	1295	2093	15.9	2376	20.09	5.24
Pilot GR-VV + Biochar	55	0	4999	4999	7.79	2650	4355	118.4	5013	332.51	3.82
Pilot GR-GM + Biochar	80	0	6998	6998	7.99	1647	2931	42.2	2842	80.47	5.96

3RD SAMPLING – 28 JUNE 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	25	0	4999	4999	8.33	2129	2681	9.5	1630	0.28	2.40
Control_2	90	0	5998	5998	8.22	2290	6451	88.8	3604	0.44	2.79
Control_3	30	0	3999	3999	8.16	1876	5816	24.8		28.58	7.26
Control_4	50	0	4499	4499	7.89	2220	6165	104.4	3599	0.55	2.59
DE Basalt_1	15	0	4999	4999		1109				11.57	5.39
DE Basalt_2											
DE Basalt_3											
DE Basalt_4	25	0	3999	3999	7.92	1626	5094	46.8	2552	11.84	7.51
NO olivine_1	30	0	4999	4999	7.86	1417	7273	208.0	5027		6.48
NO olivine_2	10	0	4999	4999		1252				1.86	4.12
NO olivine_3	30	0	4999	4999	8.27	1624	5085	51.4	2719	3.55	5.76
NO olivine_4	25	0	6998	6998	8.30	1376	3502	33.8	1742	7.31	4.75
ES olivine_1	80	0	4499	4499	8.16	1621	4862	42.5		0.95	4.53
ES olivine_2	80	0	4999	4999	7.94	1417	4094	38.1		9.18	1.32
ES olivine_3	100	0	7498	7498	8.16	1354	3885	46.2		0.02	3.49
ES olivine_4	60	0	4499	4499	7.74	2060	6235	58.1	3010	0.40	3.29
IT olivine_1	40	0	3999	3999	7.93	1425	4715	31.5	2492	0.59	7.08
IT olivine_2	40	0	4999	4999	8.09	1835	5488	91.1	2455	33.48	7.25
IT olivine_3											
IT olivine_4	70	0	6498	6498	8.15	1246	4212	20.5	1995	0.44	7.42
GR olivine GM_1	60	0	6498	6498	8.04	1720	5193	53.5	2668	1.50	3.72
GR olivine GM_2	30	0	4499	4499	7.84	2260	7109	75.7	6320	3.40	4.09
GR olivine GM_3	90	0	3999	3999	7.88	1633	5227	60.1	1811	5.47	5.58
GR olivine GM_4											
GR olivine VV_1	25	0	4999	4999	8.33	1497	5174	24.8	2350	8.13	8.98
GR olivine VV_2	70	0	5998	5998	7.97	1436	4503	20.5	1776	5.71	4.19
GR olivine VV_3	30	0	4999	4999	8.13	2110	6721	75.7	3670	2.10	4.07
GR olivine VV_4	60	0	4499	4499	7.93	1476	4777	58.1	1676	2.18	4.65
GR-VV + biochar_1	30	0	4499	4499	8.15	1319	4000	24.8	1840	35.01	8.55
GR-VV + biochar_2											
GR-VV + biochar_3	8									31.72	3.83
GR-VV + biochar_4	50	0	4999	4999	8.15	1407	3867	44.8	1911	28.43	4.73
Pilot Control	150	0	4499	4499	7.78	1884	5586	42.5	1836	19.06	6.93
Pilot Biochar	100	0	7498	7498	7.98	2020	6122	38.1	2126	18.11	5.55
Pilot GR olivine GM	100	0	3999	3999	7.89	1841	5332	64.5	2874	14.14	7.37
Pilot GR olivine VV	130	0	3999	3999	7.85	1561	5033	77.8	2379	9.95	3.28
Pilot GR-VV + Biochar	120	0	6998	6998	7.90	1967	6429	80.1	3587	80.14	2.45
Pilot GR-GM + Biochar	120	0	4999	4999	7.91	1762	5631	40.4	3041	39.52	5.43

4TH SAMPLING – 5 JULY 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	10	0	6498	6498		1320	6540	37.1			1.60
Control_2	80	0	1999	1999	8.10	1169	5316	15.9	1762		2.22
Control_3	72	1000	2999	4999	8.30	1297	5227	31.7	2245	44.90	5.16
Control_4	75	0	2999	2999	8.20	1237	4747	17.4	2136	6.28	3.07
DE Basalt_1	22	0	3499	3499	8.10	1187			2392	0.07	3.34
DE Basalt_2											
DE Basalt_3	11	1250	2499	4999	8.00	1084	5288	44.0		2.26	1.29
DE Basalt_4	22	1500	1999	4999	8.30	1391	5954	42.2	2304		2.88
NO olivine_1	20	1000	1000	2999	8.30	1441			2453		3.62
NO olivine_2	22	0	4999	4999	8.20	1041	4912	29.9		0.61	3.79
NO olivine_3	45	0	4999	4999	8.10	1373	4490	21.0	2114		2.25
NO olivine_4	30	0	3499	3499	8.20	1265	4972	29.9	2377	1.62	3.04
ES olivine_1	100	0	3499	3499	8.10	1244	4519	24.6	2015		2.88
ES olivine_2	110	0	4499	4499	8.20	1170	4246	10.5	2013	5.55	1.84
ES olivine_3	50	1000			8.40	1180	5362	33.5	2070		3.12
ES olivine_4	45	1000	3499	5499	8.30	1402	4712	19.2			
IT olivine_1	30	0	3999	3999	8.20	1278	4454	42.2	2449		1.87
IT olivine_2	70	0	3499	3499	8.20	1234			2062	4.31	2.98
IT olivine_3											
IT olivine_4	75	0	3999	3999	8.20	1333	4242	24.6	2412	3.73	4.76
GR olivine GM_1	40	0	4999	4999	8.20	1323	4189	47.6	2004	2.89	4.07
GR olivine GM_2	30	0	3999	3999	8.20	1297	4052	31.7	2003	2.47	3.10
GR olivine GM_3	70	0	2999	2999	8.20	1228	4421	29.9	2137	1.03	3.24
GR olivine GM_4	20	0	4999	4999	8.40	1315	5702	22.8	2159		2.42
GR olivine VV_1	20	0	3999	3999	8.30	1221	4155	19.2	1928		3.23
GR olivine VV_2	100	0	4999	4999	8.10	1159	4997	44.0	1581	22.48	5.20
GR olivine VV_3	20	0	2999	2999	8.20	1434	4529	29.9	1615		7.60
GR olivine VV_4	50	0	2999	2999	8.20	1273	4213	14.1	1382		2.00
GR-VV + biochar_1	15	0	3999	3999	8.30	1912			1266	7.50	2.09
GR-VV + biochar_2	15	0	3999	3999	7.90	1971				9.23	3.45
GR-VV + biochar_3	15	0	2999	2999	8.10	1220	4597	29.9		5.76	4.38
GR-VV + biochar_4	70	0	3999	3999	8.20	1365	3051	40.4	1536	7.50	1.85
Pilot Control	160	0	4499	4499	7.80	1658	4060	28.1	885	16.39	3.20
Pilot Biochar	100	0	4999	4999	7.70	2220	8880	79.6	1070	14.46	2.22
Pilot GR olivine GM	135	0	3999	3999	7.90	2080	5510	56.5	2579	11.42	6.06
Pilot GR olivine VV	115	0	3999	3999	7.80	1512	6900	47.6	1185	24.13	1.20
Pilot GR-VV + Biochar	100	0	3499	3499	7.80	1606	6225	33.5	1761	81.68	2.32
Pilot GR-GM + Biochar	45	0	3999	3999	8.10	1524	6540	37.1	1589	61.20	4.31

5TH SAMPLING – 12 JULY 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1											
Control_2	100	0	4799	4799	8.16	1115	2136	27.1	1875	5.72	3.28
Control_3	60	0	5599	5599	8.07	1370	2887	38.1	2522	26.23	6.66
Control_4	80	0	5399	5399	8.19	1068	2227	27.1	1800	8.58	3.40
DE Basalt_1	10	1000	4999	6998						7.34	4.06
DE Basalt_2	20	0	4499	4499	8.32	1047	2344	77.8	8016	17.49	2.45
DE Basalt_3	15	0	2999	2999	7.94	960				6.75	1.21
DE Basalt_4	60	0	5599	5599	8.10	1048	2191	33.8	1802	4.44	3.20
NO olivine_1	3									9.58	5.15
NO olivine_2	10	1000	3999	5999						8.68	3.82
NO olivine_3	40	0	4499	4499	8.12	1020	1896	22.5	1645	6.68	2.90
NO olivine_4	35	0	3999	3999	8.19	975	2000	40.4	1906	9.62	4.22
ES olivine_1	100	0	5399	5399	8.12	947				10.15	4.05
ES olivine_2	110	0	5798	5798	8.10	1160	2394	29.2	2160	13.69	3.41
ES olivine_3	65	0	8298	8298	8.37	1210	2234	16.1	2329	10.48	5.24
ES olivine_4	30	1000	4999	6998	8.36	1206	2217	24.8	1856	6.27	3.42
IT olivine_1	80	0	5798	5798	8.18	1100	1856	18.2	1956	3.68	2.29
IT olivine_2	35	0	5499	5499	8.24	1000	2267	75.7	1875	16.39	9.02
IT olivine_3	10	0	4999	4999	8.30	1098				4.99	5.40
IT olivine_4	40	1000	3999	5999	8.44	1112	2327	16.1	2161	6.30	3.96
GR olivine GM_1	50	0	4999	4999	8.30	1200	2719	51.4	2081	6.23	6.17
GR olivine GM_2	25	0	4999	4999	8.28	1080	1810	35.8	1502	10.27	4.49
GR olivine GM_3	80	0	4599	4599	8.23	1040	1982	24.8	1814	12.52	4.64
GR olivine GM_4	15	1000	4999	6998	8.38	1160	2115	22.5	1852	9.37	5.35
GR olivine VV_1	10						2369	22.5	2001	12.52	5.37
GR olivine VV_2	100	0	5998	5998	8.20	1052	3016	22.5	3099	41.36	23.40
GR olivine VV_3	30	0	4999	4999	8.30	1020	1981	40.4	1622	10.17	31.15
GR olivine VV_4	20	0	2999	2999	8.20	1012		27.1	1669	21.35	3.86
GR-VV + biochar_1	10	1000	4999	6998						12.31	3.81
GR-VV + biochar_2	10	1000	3999	5999						16.42	3.64
GR-VV + biochar_3	3									19.55	2.32
GR-VV + biochar_4	30	0	5998	5998	8.25	1188	2181	33.8	1810	29.91	2.49
Pilot Control	160	0	4999	4999	8.00	1143	853	111.0	702	19.57	3.69
Pilot Biochar	100	0	5798	5798	8.20	990	1496	31.5	1734	5.61	1.32
Pilot GR olivine GM	140	0	5599	5599	8.17	1002	1506	24.8	1646	10.72	5.79
Pilot GR olivine VV	140	0	4999	4999	8.16	936	2134	42.5	1639	20.61	4.86
Pilot GR-VV + Biochar	160	0	4999	4999	8.05	980	2105	35.8	1675	28.10	1.75
Pilot GR-GM + Biochar	90	0	5599	5599	8.14	1120	2038	35.8	1869	40.77	18.87

6TH SAMPLING – 14 JULY 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1											
Control_2	120	0	6598	6598	8.00	1174	2092	24.8	1933	4.25	3.30
Control_3											
Control_4	30	0	4999	4999	8.17	1272	2360	27.1	1965	6.35	3.36
DE Basalt_1	15	2000	3999	7998		1281				3.60	3.18
DE Basalt_2											
DE Basalt_3											
DE Basalt_4	40	0	4999	4999	8.18	1180	1950	27.1	1669	2.51	2.49
NO olivine_1											
NO olivine_2	20	2000	3999	7998		1106	1723	18.2	1803	1.12	5.46
NO olivine_3	15	1000	6998	8998		1360				1.85	4.00
NO olivine_4	15	2000	5998	9998		1288				7.96	2.54
ES olivine_1	80	0	6798	6798	8.16	1193	1687	29.2	1381	1.73	2.12
ES olivine_2	60	0	5798	5798	8.05	1129	1811	22.5	1701	1.69	1.95
ES olivine_3	80	0	8598	8598	8.11	1479	2178	20.5	2360	1.73	4.30
ES olivine_4	13	1000	5998	7998	8.11	1324				1.73	4.02
IT olivine_1	80	0	5998	5998	8.04	1124	2077	24.8	2030	2.06	4.47
IT olivine_2	25	1000	4999	6998		1171	2175	20.5	1919	4.09	3.98
IT olivine_3	10									2.02	3.17
IT olivine_4	60	0	6798	6798	8.05	1348	2423	22.5	2174	2.06	3.64
GR olivine GM_1	30	0	5998	5998	8.28	1294	2146	58.1	1931	5.67	3.32
GR olivine GM_2	20	1000	4999	6998	8.36	1271	2165	31.5	1908	7.36	4.89
GR olivine GM_3	80	0	5599	5599	8.15	1118	2011	22.5	1949	8.76	2.40
GR olivine GM_4	60	0	6998	6998	8.08	1420	2574	27.1	2123	14.65	4.19
GR olivine VV_1	40	0	4999	4999	8.13	1162	2539	29.2	2029	2.55	5.18
GR olivine VV_2	100	0	6198	6198	8.07	1148	1978	27.1	1895	2.91	1.93
GR olivine VV_3	25	1000	4999	6998	8.35	1197	2084	40.4	1851	0.30	1.75
GR olivine VV_4											
GR-VV + biochar_1											
GR-VV + biochar_2	14	1000	5998	7998		1283				14.92	3.53
GR-VV + biochar_3											
GR-VV + biochar_4	25	1000	6998	8998		1290	2362	33.8	2080	9.20	1.88
Pilot Control	160	0	6398	6398	7.95	1188	2215	24.8	1905	7.88	2.40
Pilot Biochar	80	0	5399	5399	8.18	1088	1854	29.2	1720	3.24	1.11
Pilot GR olivine GM	120	0	6598	6598	8.14	1198	2009	29.2	1731	4.98	0.51
Pilot GR olivine VV	120	0	6798	6798	7.97	1208	2194	35.8	1826	11.36	3.81
Pilot GR-VV + Biochar	80	0	6598	6598	8.12	1852	2357	38.1	1950	48.84	1.91
Pilot GR-GM + Biochar	50	0	6598	6598	8.14	1350				55.90	7.45

7TH SAMPLING – 29 JULY 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1											
Control_2	100	0	7398	7398	8.00	1302	1252	17.9	1589	5.13	1.84
Control_3											
Control_4	15	0	7498	7498			2623	24.0	3475	1.93	2.24
DE Basalt_1											
DE Basalt_2	10	0	3999	3999			2005	15.9	2760	12.24	2.01
DE Basalt_3											
DE Basalt_4	40	0	5998	5998	8.08	1429	1910	38.1	1954	6.34	2.36
NO olivine_1											
NO olivine_2											
NO olivine_3											
NO olivine_4	20	0	5998	5998		1841	2445	22.0	3904	64.19	2.42
ES olivine_1	60	0	6398	6398	8.05	1302	2667	25.8	3731	5.92	1.77
ES olivine_2	40	0	4999	4999	8.22	1475	1412	13.8	1660	9.99	2.20
ES olivine_3	25	0	6998	6998	8.20	1475	2450	13.8	3905	3.93	2.13
ES olivine_4	20	2000	3999	7998	8.34	1442	2016	20.0	2166	4.51	4.20
IT olivine_1	32	0	5998	5998	8.18	1240	1878	17.9	2246	6.10	2.19
IT olivine_2	15	0	6998	6998						7.21	2.39
IT olivine_3											
IT olivine_4											
GR olivine GM_1							2211	29.9	2608	17.30	3.86
GR olivine GM_2											
GR olivine GM_3	40	0	3999	3999	8.16	1358	2311	20.0	2689	11.57	2.17
GR olivine GM_4	15	0	4999	4999			2178	0.0	2167	17.68	4.34
GR olivine VV_1											
GR olivine VV_2	15	0	4999	4999						10.83	2.49
GR olivine VV_3	35	0	5998	5998	8.12	1230	1680	32.0	1848	12.58	2.71
GR olivine VV_4											
GR-VV + biochar_1							1893	34.0	1890	32.58	2.09
GR-VV + biochar_2											
GR-VV + biochar_3											
GR-VV + biochar_4	35	0	5998	5998	8.14	1187	1395	32.0	1645	12.81	1.90
Pilot Control	90	0	5998	5998	8.10	1334	1510	24.0	1887	7.30	2.44
Pilot Biochar	35	0	3999	3999	8.00	1444	1912	34.0	2431	7.56	3.38
Pilot GR olivine GM	30	0	5998	5998	8.25	1307	1629	25.8	1792	15.43	1.44
Pilot GR olivine VV	110	0	5998	5998	8.00	1231	1727	27.9	1673	24.50	1.69
Pilot GR-VV + Biochar	80	0	6798	6798	8.13	1399	1972	42.2	1911	76.75	1.60
Pilot GR-GM + Biochar	50	0	6998	6998	8.12	1342	1834	38.1	1837	49.89	2.76

8TH SAMPLING – 6 AUGUST 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1											
Control_2	80	0	4999	4999	7.74	1478				11.57	2.27
Control_3	13	0	3999	3999	7.93	1756				63.31	3.76
Control_4	60	0	5798	5798	7.92	1370				80.68	27.63
DE Basalt_1											
DE Basalt_2	15	0	2999	2999	8.22	1546				14.89	4.98
DE Basalt_3	4									12.92	1.92
DE Basalt_4	15	0	4999	4999	8.21	1267				10.91	4.23
NO olivine_1	10	0	3999	3999						8.77	3.24
NO olivine_2	15	0	2999	2999	8.26	1165				7.28	5.92
NO olivine_3											
NO olivine_4	25	0	2999	2999	8.12	1674				63.44	9.84
ES olivine_1	30	0	2999	2999	8.12	1506				18.60	5.44
ES olivine_2	20	0	4999	4999	8.22	1469				8.69	3.07
ES olivine_3	20	0	5998	5998	8.20	1531				7.87	2.51
ES olivine_4	15	2000	3999	7998	8.30	1160				10.25	5.35
IT olivine_1	60	0	4999	4999	7.89	1270				5.95	2.84
IT olivine_2	10	2000	3999	7998	8.38	1271				24.09	11.47
IT olivine_3											
IT olivine_4	20	0	6998	6998	8.12	1600				5.87	3.43
GR olivine GM_1	15	0	6998	6998	8.17	1474				16.08	2.99
GR olivine GM_2	20	0	4999	4999	8.13	1678				22.24	5.55
GR olivine GM_3	40	0	4999	4999	8.07	1493				20.65	7.22
GR olivine GM_4											
GR olivine VV_1											
GR olivine VV_2	80	0	6398	6398	7.98	1409				9.55	5.62
GR olivine VV_3	30	0	5998	5998	8.14	1468				10.60	5.03
GR olivine VV_4											
GR-VV + biochar_1											
GR-VV + biochar_2											
GR-VV + biochar_3											
GR-VV + biochar_4	30	0	4999	4999	8.17	1574				28.54	4.61
Pilot Control	90	0	6198	6198	8.00	1301				10.06	2.29
Pilot Biochar	30	0	5998	5998	8.16	1545				7.48	3.01
Pilot GR olivine GM	50	0	5998	5998	8.05	1311				13.93	1.55
Pilot GR olivine VV	60	0	5599	5599	8.00	1341				9.35	1.45
Pilot GR-VV + Biochar	90	0	5599	5599	8.03	1375				52.54	1.53
Pilot GR-GM + Biochar	60	0	5399	5399	8.06	1388				42.46	1.36

9TH SAMPLING – 12 AUGUST 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	80	0	5399	5399	7.91	1398	2271	21.0	2375	5.13	2.38
Control_2											
Control_3											
Control_4											
DE Basalt_1	30	0	5499	5499	7.89	1632	2426	12.0	3042	15.08	2.81
DE Basalt_2											
DE Basalt_3											
DE Basalt_4											
NO olivine_1											
NO olivine_2	10				8.12	1616				10.06	4.16
NO olivine_3	10				8.22	1859				8.15	2.50
NO olivine_4	50	0	4999	4999	8.02	1386	2146	21.0	2117	7.01	3.53
ES olivine_1	40	0	5499	5499	8.10	1364	2106	14.1	2417	8.30	2.70
ES olivine_2	50	0	5998	5998	8.09	1535	2294	9.7	2662	5.48	3.24
ES olivine_3	15				8.27	1351				6.87	5.36
ES olivine_4	20				8.19	1371				4.59	3.74
IT olivine_1											
IT olivine_2	10				8.19	1570				4.83	3.96
IT olivine_3	15				8.14	1494				5.50	3.39
IT olivine_4											
GR olivine GM_1	20				8.26	1376	2203	29.9	2087	7.29	3.57
GR olivine GM_2	25	0	5998	5998	8.22	1430	2142	18.7	2487	6.80	2.75
GR olivine GM_3	10				8.31	1374				54.34	3.92
GR olivine GM_4	10				8.44	1295				10.95	8.82
GR olivine VV_1	50	0	6998	6998	8.17	1491	2289	14.1	2699	8.48	3.93
GR olivine VV_2											
GR olivine VV_3											
GR olivine VV_4											
GR-VV + biochar_1											
GR-VV + biochar_2											
GR-VV + biochar_3											
GR-VV + biochar_4	50	0	5499	5499	8.20	1308	1802	16.4	2100	17.44	2.25
Pilot Control	25	2000	6998	10998	8.30	1664	2108	18.7	3008	22.40	2.11
Pilot Biochar	40	1500	5499	8498	8.32	1461	2103	18.7	1804	27.37	4.82
Pilot GR olivine GM	50	0	5998	5998	8.17	1233	2127	21.0	1804	21.44	2.63
Pilot GR olivine VV	25	1000	6498	8498	8.30	1580	2523	32.0	2528	113.23	3.60
Pilot GR-VV + Biochar	10				8.24	1425				44.72	3.06
Pilot GR-GM + Biochar		0	5399	5399							

10TH SAMPLING – 19 AUGUST 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	5									10.17	3.06
Control_2	60	0	1999	1999	7.94	1433	2478		2653	7.54	2.71
Control_3											
Control_4	15	0	3999	3999	8.28	1518				8.55	3.57
DE Basalt_1	30	0	4999	4999	8.11	1660	2363		2886	10.17	2.18
DE Basalt_2											
DE Basalt_3											
DE Basalt_4	10									4.20	3.09
NO olivine_1	10	3000	1999	7999	8.32	1166				6.34	3.07
NO olivine_2											
NO olivine_3											
NO olivine_4	15	0	4999	4999	8.25	1677				18.18	4.74
ES olivine_1	60	0	4999	4999	8.09	1448	2358		2455	5.22	3.15
ES olivine_2	80	0	5998	5998	7.94	1308	1962		2124	19.14	2.49
ES olivine_3	50	0	4999	4999	8.05	1624	2419		2941	5.92	4.60
ES olivine_4	25	0	1999	1999	8.18	1412	2313		2252	5.04	3.95
IT olivine_1	50	0	3999	3999	8.16	1210	1932		2104	4.24	2.68
IT olivine_2	20	3000	3999	9998	8.35	1430	2220		2186	5.29	3.93
IT olivine_3											
IT olivine_4	50	0	5998	5998	8.13	1378	2205		2172	8.13	3.67
GR olivine GM_1	5				8.34	1428				11.16	3.08
GR olivine GM_2	20	3000	3999	9998	8.32	1277	2106		1923	5.68	2.63
GR olivine GM_3											
GR olivine GM_4	20	0	1000	1000	8.28	907	1439		1257	29.40	3.02
GR olivine VV_1											
GR olivine VV_2	80	0	6398	6398	8.04	1378	2082		2291	4.62	1.78
GR olivine VV_3	25	0	5998	5998	8.23	1382	2234		2312	6.62	3.66
GR olivine VV_4	30	0	3999	3999	8.25	1323	1951		2045	5.18	3.67
GR-VV + biochar_1											
GR-VV + biochar_2	10	3000	4999	10998	8.37	1408				30.65	2.98
GR-VV + biochar_3											
GR-VV + biochar_4	40	0	4999	4999	8.09	1558	2060		2325	29.60	3.20
Pilot Control	100	0	5199	5199	8.02	1308	1844		2017	12.28	2.29
Pilot Biochar	5				8.46	1395				8.69	3.75
Pilot GR olivine GM	40	0	3999	3999	8.17	1309	1956		1985	14.22	2.06
Pilot GR olivine VV	100	0	4399	4399	8.03	1155	1873		1671	21.12	5.58
Pilot GR-VV + Biochar	110	0	4999	4999	8.04	1374	2094		1988	52.04	5.49
Pilot GR-GM + Biochar	40	0	3999	3999	8.14	1233	2062		1852	34.05	5.13

11TH SAMPLING – 25 AUGUST 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1											
Control_2	30	0	1999	1999	8.23	1405	3004	14.3	3127	5.58	3.69
Control_3											
Control_4	25	2000	4999	8998	8.46	1415	2561	12.3	2442	6.17	4.21
DE Basalt_1	25	0	2999	2999	8.29	1524	2313	2.3	2898	7.48	1.60
DE Basalt_2											
DE Basalt_3	10	2000	2999	6999		1054				6.09	7.03
DE Basalt_4	10	2000	2999	6999		1160				6.46	3.82
NO olivine_1	10	2000	2999	6999		1183				22.10	8.90
NO olivine_2	10	3000	3999	9998		1452				4.52	1.54
NO olivine_3	8	3000	2999	8998		1642				5.80	4.29
NO olivine_4	15	0	4999	4999	8.26	1642	2035		2810	12.23	2.23
ES olivine_1	60	0	5798	5798	8.29	1250	2142	12.3	2027	7.92	5.68
ES olivine_2	50	0	2999	2999	8.25	1190	1905	6.4	2022	5.76	2.43
ES olivine_3	20	0	3999	3999	8.38	1595	2831	6.4	3197	6.02	3.68
ES olivine_4	20	2000	2999	6999	8.43	1363	2129	8.4	1996	3.49	3.62
IT olivine_1	60	800	5199	6798	8.30	1161	1856		1963	8.69	5.43
IT olivine_2	25	3000	2999	8998	8.43	1438	2219		2117	5.40	4.14
IT olivine_3	20	3000	2999	8998	8.43	1811	3186	8.4	2946	3.60	3.83
IT olivine_4	60	800	5798	7398	8.33	1320	2168		2088	2.91	3.70
GR olivine GM_1	10	2000	3999	7998		1349	2112		1959	10.00	2.48
GR olivine GM_2	25	0	3999	3999	8.20	1322	2115	16.4	1949	7.59	3.31
GR olivine GM_3											
GR olivine GM_4	40	0	2999	2999	8.26	1307	2055	12.3	1781	20.33	2.91
GR olivine VV_1											
GR olivine VV_2	50	2000	4999	8998	8.31	1299	1977	6.4	2195	3.79	2.06
GR olivine VV_3	30	1000	3999	5999	8.32	1296	2105	10.2	2012	4.67	3.59
GR olivine VV_4	15	0	4999	4999	8.25	1329	1956	8.4	1930	5.22	4.10
GR-VV + biochar_1	10	0	2999	2999		1011				18.48	4.22
GR-VV + biochar_2	25	2000	4999	8998	8.33	1307	2185	18.2	1866	16.81	2.63
GR-VV + biochar_3											
GR-VV + biochar_4	60	0	5199	5199	8.26	1418	2044		2290	25.24	2.69
Pilot Control	95	0	4599	4599	8.19	1153	1610	4.3	1697	9.42	2.70
Pilot Biochar	25	0	4999	4999	8.21	1684	1615	2.3	2999	15.25	1.73
Pilot GR olivine GM	60	0	6198	6198	8.30	1448	2104		2283	17.93	2.09
Pilot GR olivine VV	95	0	4999	4999	8.21	1170	2084	14.3	1736	14.67	1.61
Pilot GR-VV + Biochar	100	0	5399	5399	8.23	1262	2354	8.4	1736	7.41	1.90
Pilot GR-GM + Biochar	30	2000	4999	8998	8.33	1193	2005	16.4	2084		3.39

12TH SAMPLING – 31 AUGUST 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_1	6									14.67	4.93
Control_2	90	0	7118	7118	8.06	1357	2256	18.7	2492	7.41	14.59
Control_3	5									40.60	3.00
Control_4	50	0	4999	4999	8.20	1341	1887	20.7	1784	7.26	2.99
DE Basalt_1	50	0	6998	6998	8.22	1516	1857	12.3	2418	8.32	16.19
DE Basalt_2											
DE Basalt_3	5									18.01	6.45
DE Basalt_4	25	0	6498	6498	8.08	1219				5.25	2.73
NO olivine_1	10									5.91	3.65
NO olivine_2											
NO olivine_3	45	0	6498	6498	8.29	1418	2027	16.6	2076	4.78	2.63
NO olivine_4	30	1000	6998	8998	8.57	1732	2311	12.3	3309	10.00	2.42
ES olivine_1	400	0	8298	8298	8.18	1310	1451	18.7	1471	7.01	2.78
ES olivine_2	70	0	3999	3999	8.23	1149	1953	14.3	2210	6.02	2.13
ES olivine_3	45	0	6498	6498	8.12	1698	2492	12.3	3319	5.73	2.64
ES olivine_4	25	1500	5998	8998	8.34	1471	2328	16.6	2296	6.39	3.81
IT olivine_1	60	2000	5499	9498	8.44	1133	2185	14.3	2309	2.25	2.14
IT olivine_2	60	0	5499	5499	8.25	1306	1928	16.6	1894	3.71	3.79
IT olivine_3	25	2000	5499	9498	8.40	1840	2935	16.6	3056	4.79	3.30
IT olivine_4	110	0	7998	7998	8.30	1369	2109	14.3	2248	7.88	3.30
GR olivine GM_1	22				8.31	1337	2010	62.2	1898	11.88	2.11
GR olivine GM_2	27	1000	5998	7998	8.32	1370	2069	24.8	2015	5.60	2.18
GR olivine GM_3											
GR olivine GM_4											
GR olivine VV_1	4									7.27	3.45
GR olivine VV_2	70	0	6898	6898	8.18	1214	2299	16.6	2642	7.43	1.36
GR olivine VV_3	40	1500	5499	8498	8.34	1345	2134	24.8	2209	3.35	2.94
GR olivine VV_4	27	1000	6498	8498	8.39	1359	1875	16.6	1993	9.22	3.41
GR-VV + biochar_1											
GR-VV + biochar_2	15	1500	6498	9498	8.36	1350	2018	26.9	1824	15.38	114.88
GR-VV + biochar_3											
GR-VV + biochar_4	60	0	7698	7698	8.20	1473	1870	14.3	2264	24.91	2.42
Pilot Control	25	0	3999	3999	8.23	1354	1487	16.6	2125	11.75	2.16
Pilot Biochar	30	0	7998	7998	8.26	1667	1899	12.3	3291	13.83	1.86
Pilot GR olivine GM	18					1297	1780	14.3	1987	22.15	2.08
Pilot GR olivine VV	110	0	7698	7698	8.12	1297	2307	18.7	2243	10.13	1.42
Pilot GR-VV + Biochar	55	0	5998	5998	8.06	1433	2226	18.7	2297	47.40	1.70
Pilot GR-GM + Biochar	30	0	6998	6998	8.14	1206	1936	26.9	1790	10.71	1.53

Appendix J

Appendix J – Lysimeter soil water analyses

1ST SAMPLING – 22 JULY 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_4	mL	1000	2999	6998	8.19	291	436	37.9	134	8.23	2.01
DE Basalt_1	20						219	79.1	165	9.99	3.52
IT olivine_2	40	1000	1000	2999	8.10	288	493	26.4	123	7.54	0.93
GR olivine GM_3	500	100	4299	8698	7.88	1161	1517	43.7	189	11.86	2.12
GR-VV + biochar_4	150	200	1800	3799	7.92	1768	2639	22.3	3613	280.74	1.99
Pilot Control	130	200	4399	8998	8.00	786	1038	32.0	989	51.25	1.00
Pilot Biochar	20	2000	1000	3999			314	53.5	217	17.15	0.73
Pilot GR olivine GM	50	1000	4999	10997	8.18	940	1076	26.4	1092	29.11	3.60
Pilot GR olivine VV	25				8.09	263	317	24.3	59		
Pilot GR-VV + Biochar	30	2000	1999	5999	8.13	611	749	168.8	402	20.44	1.49
Pilot GR-GM + Biochar	120	200	5199	10597	7.86	2790	5079	174.7	6154	69.08	0.99
2ND SAMPLING – 21 SEPTEMBER 2021											
Treatments	**Volume mL**	**CO_3^{2-} µmol/L**	**HCO_3^- µmol/L**	**CA µmol/L**	**pH**	**EC**	**Ca^{2+} µmol/L**	**K^+ µmol/L**	**Mg^{2+} µmol/L**	**Ni µg/L**	**Cr µg/L**
Control_4	150	400	1800	3999	7.98	1873				14.67	1.99
ES olivine_1	150	400	1900	4199	8.13	1670				8.60	1.27
GR olivine GM_3	350	400	3299	6998	8.20	1252				8.01	1.85
Pilot Control	450	400	4799	10106	7.92	2230				34.19	2.82
Pilot Biochar	190	300	4699	9892	7.92	2140				20.22	1.90
Pilot GR olivine GM	14	600	4599	9694	8.07	1459				20.54	3.04
Pilot GR olivine VV	105	700	5299	11169	8.13	2160				74.71	1.20
Pilot GR-VV + Biochar	225	500	5499	11582	7.99	3330				67.70	1.14
Pilot GR-GM + Biochar	85	800	10397	21894	8.31	1322				148.92	0.31

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