KTIF Final Report

Rock On Soils Final Report

1. PROJECT TITLE/APPLICANT

1.1.Title

Basic silicate rock by-product: a new agricultural input that captures CO_2 also known as 'Rock On Soils'

1.2.Overview of your company

SOPA was incorporated as a member co-operative in 1988 and since then has grown to a membership association of more than 300 organic businesses throughout the UK. More than 80% of SOPA members are farmers, mostly based in Scotland, but there are also food processors and merchants throughout the UK.

SOPA owns the only Scottish-based organic standards for production as well as processing, approved in the UK by Defra.

SOPA operates a dedicated Membership service for advice and support for its members. This support covers a wealth of expertise from market intelligence, communications, membership discounts, access to funding and policy.

Our purpose is to work on behalf of our members, to support and grow the environmental and financial sustainability of their businesses. Some of the initiatives we offer to our members include a discounted sampling service for soil, forage and manures, as well as diverse things like access to skilled public relations professionals. We also help them access funding for organic conversion and maintenance through our specialist knowledge of the AECS funding stream offered by Scottish Government. SOPA Member Services offer mentoring and one-to-one support for converting farmers.

Because we work so closely with our members, we know their businesses very well. Where they seek out trade connections and supply chain we signpost them to networks and routes to build business relationships. A lot of our work is helping our members achieve the rigorous organic standards required by law.

By relying on natural systems to support production such as the use of legumes for biological nitrogen fixation, Scotland's organic farmers by their every day actions reduce the reliance on chemical inputs. As our members, and indeed the wider agricultural sector become more attuned to environmental protection and climate change mitigation, SOPA recognises the role that organic farmers have to play in striving to meet Scottish Government Net Zero targets.

It is in this context hat SOPA has valued the opportunities presented in this Rock on Soils project. It is a rare opportunity for farmers to have direct access to scientists, and vice versa, and the interaction in the project has been welcome. The instances of information and knowledge sharing on things like soil science cost-benefit financial returns and business pressures, has been valued by all parties.

2. EXECUTIVE SUMMARY

Rock On Soils was a nine-month farm innovation project. A collaboration between scientists and farmers, the aim was to explore the use of a basic silicate rock as a method of sequestering carbon into agricultural soils by providing farmers with the information they need to assess the value of using the product not only to capture carbon, but also to potentially improve soil and plant health and performance.

Rotmell Farm in Perthshire had applied 20T/ha of crushed basic silicate rock (dolerite) to a pasture field in 2017, leaving an area untreated as a control. This offered a unique opportunity to use it as a test site. There were three key objectives:

- To monitor the impacts of applying the product on soils, plants and carbon storage
- To form a small pilot group of farmers to contribute their thoughts and experiences on the potential use of the product on their farms
- To develop a mobile App to calculate the CO_2 sequestration potential on farm

The most significant change seen on the trial site has been in soil microbiology. The monitoring shows that the area that received crushed basic silicate rock has a more balanced and higher value microbial biodiversity; there is a more beneficial microbiome present. This effect is evident three years after treatment suggesting that the benefit is being maintained well after treatment. Essentially we are seeing a more biologically sustainable soil.

In particular, there are more microbial species in the basic silicate rock treated area that undertake the following functions;

- Sequestering carbon
- Mobilising nitrogen
- Mobilising phosphorous and potassium
- Biologically controlling pathogenic bacteria and nematodes

And lower levels of pathogenic microbes which cause;

- Black point
- Ergot
- Fusarium crown rot

The project shows that there are wider benefits of the crushed silicate rock beyond just carbon sequestration. The changes to the soil microbiome we have seen tick many more boxes than just tackling climate change and include restoration of ecosystem health, protecting biodiversity and natural capital.

However, these benefits are difficult to financially value and will vary between farms. In this case black point, ergot and fusarium crown rot are not necessarily seen as disease issues for pasture, but they are for cereals. The farmer pilot group all identified improved soil health as a potential driver of their interest in the product, but see the current cost of applying the product at 20T/ha as a barrier to use at the moment. There is a need to start to assign values to such an ecosystem service benefit.

Further work needs to look at different application rates, on different soils, on different crops at greater depths and follow the changes over a wider timeframe than was possible within this project. This project should be viewed as a work in progress.

3. PROJECT DESCRIPTION

Rock On Soils was a nine-month farm innovation project exploring the use of crushed basic silicate rock as a soil input to both sequester carbon and improve soil and plant health and performance. A collaboration between scientists and farmers, the project was looking to build on existing research findings which have shown promise in the use of crushed basic silicate rock, a by-product of quarrying, to capture and store carbon in urban soils.

Our aim was to put the theory into practice and gain a clearer understanding of the potential benefits of using crushed silicate rock at the farm scale. Basing this on robust, impartial evidence to provide farmers with the information needed to fully assess the value of the use of basic silicate rock as a potential investment in soil carbon sequestration.

Basic silicate rocks, such as dolerite and basalt are volcanic in origin and found across Scotland (see Map in Appendix 1). As these rocks weather naturally, they form calcium or magnesium carbonate, capturing CO_2 as part of the process. Being mineral rather than biological in origin, the carbon is stored as inorganic rather than organic carbon. Inorganic carbon is much more stable than organic carbon, but forms more slowly. It is possible to speed up, or enhance the rate of weathering by using crushed rock. Quarry fines, a quarry by-product less than 4mm in aggregate size, are suitable.

The minerals released on weathering, such as calcium, magnesium, sodium, potassium and zinc potentially have value within the agricultural system too. Plants and soil microorganisms add to the weathering process by accessing key minerals they need for production. The rock can therefore also provide slow, biologically controlled release of minerals, potentially offering additional benefits such as the supply of a broad range of nutrients, an increase in soil pH and the formation of new soil leading to an improvement in soil structure. This is of particular interest to organic farmers who rely on natural processes to improve soil mineralogy, rather than man-made petroleum-based fertiliser inputs.

Rotmell Farm in Perthshire had applied 20T/ha of crushed basic silicate rock (dolerite) to a pasture field in 2017, leaving an area untreated as a control. This offered a unique opportunity to assess the impact of the application on plant and soil performance over time. The project developed three key objectives; firstly to monitor the impacts of applying crushed silicate rock on soil and plant nutrient content, carbon sequestration and storage capacity of the soil at Rotmell Farm. Secondly, to form a small pilot group of farmers to raise awareness of the product, follow the project journey and contribute their thoughts and experiences on the potential use of the product for their own farming systems. The farmer group would also feed in to the third objective - to design and develop a mobile phone App to calculate the CO_2 sequestration potential on farm.

4. FINANCE

4.1. Sum awarded

£68,246

5. PROJECT AIMS/OBJECTIVES

The aim of the project was to explore the adoption of the use of a basic silicate rock as a method of sequestering carbon into agricultural soils by providing farmers with the information they need to assess the value of the product not only to capture carbon, but also to potentially improve soil and plant health and performance.

The project set to achieve these aims with the following objectives

1. Monitoring any on the ground changes in GHG emissions and soil and plant quality at Rotmell Farm. These included;
    - changes in plant nutrient content and productivity
    - changes in soil nutrient content (mineralogy, nutrient availability & pH) and microbiology (population differences of bacteria, fungi, protozoa, nematodes)
    - changes in soil CO_2 emissions and soil inorganic carbon levels
    - changes in soil structure - density, percolation, particle size distribution and bearing capacity
2. Forming a small group of farmers to join a pilot group to raise awareness of the product, gain their views, build on Rotmell Farm's practical experiences of using the product and widening the focus beyond one farm. This included;
    - supplying the pilot farmers with a small amount of rock product to test
    - running three workshops to introduce the product, to disseminate the initial results from Rotmell and finally to identify their thoughts, concerns, challenges and any potential limitations of using the product on farm
3. Developing a simple mobile phone App that that will calculate the amount of carbon farmers can potentially capture and store on a field basis when applying the rock

6. PROJECT OUTCOMES

6.1. How were aims/objectives achieved?

Objective 1: Monitoring on the ground changes at Rotmell Farm

Comparing plots from the field which received an application of 20 t/ha of crushed basic silicate rock in 2017 with an untreated control area, a variety of field samples and analysis were undertaken between July and October 2020. There were no other field inputs.

Different analyses were undertaken to evaluate the performance and health of the plant, soil and biology. This information then fed in to identify potential benefits and/or negative effects of the silicate rock on the agricultural system.

a) Package 1 included analyses of soil, root and plant chemistry. It was designed to identify the transfer of chemical elements from the crushed rock to the plant. This looked at the soil, the soil-water interphase, the roots and the upper plant system. These included both plant nutrients and potentially toxic elements. Root biomass and shoot productivity were also measured.
b) Package 2 included analyses on soil micro and macro-organisms. It was designed to assess their abundance and advanced DNA analysis was used to identify their ecological function.

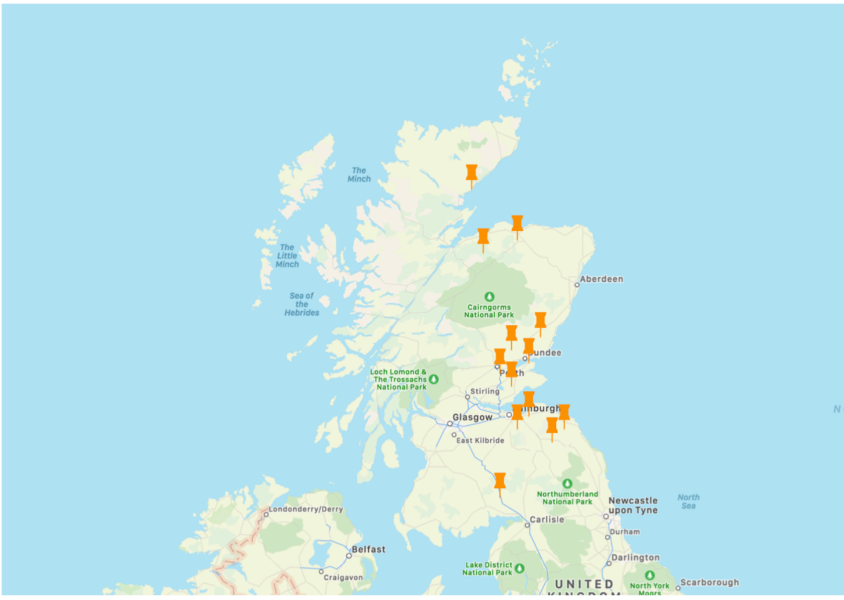
c) Package 3 included soil physical tests. This was designed to understand any changes of the physical properties of soil due to the rock application and any potential influence of these physical factors on plant performance.
d) Package 4 included analyses of air, water and soil to measure the capacity of the system to store and/or release the greenhouse gas carbon dioxide (CO_2). The reason for this is that inorganic carbon exists as the gas CO_2, in liquid as dissolved inorganic carbon, and in solid form as a mineral.

The data was then analysed to identify any differences between the area that had received the silicate rock and untreated control area.

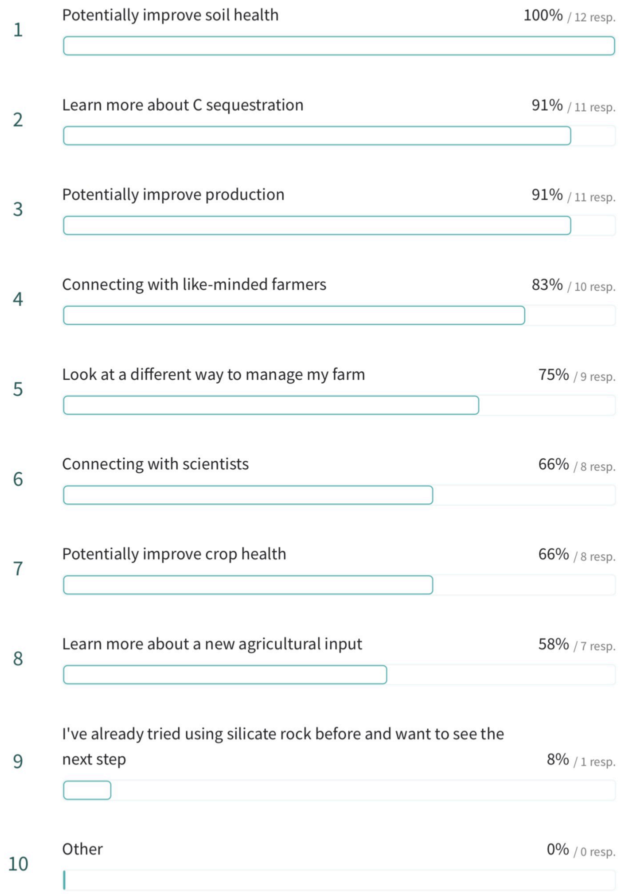
Information on the analysis, including the laboratory and methods used is presented Annex 3.

Objective 2: Forming a pilot farmer group

Thirteen farmers joined the pilot group. They were located across Scotland (see map below) and reflected a range of farm enterprises - arable, cattle, sheep, deer, field vegetables, hens and pigs. Just over 40% were registered organic, and only one of the farmers had prior experience using crushed silicate rock on vegetable crops.



When surveyed at the start of the project about their reasons to be involved in the project, all of the group were interested in the potential of crushed silicate rock to improve soil health, 91% wanted to learn more about C-sequestration and the potential to improve production. They were also keen on innovation with 73% interested in looking at different ways to manage their farms, and working collaboratively with other like-minded farmers and scientists.

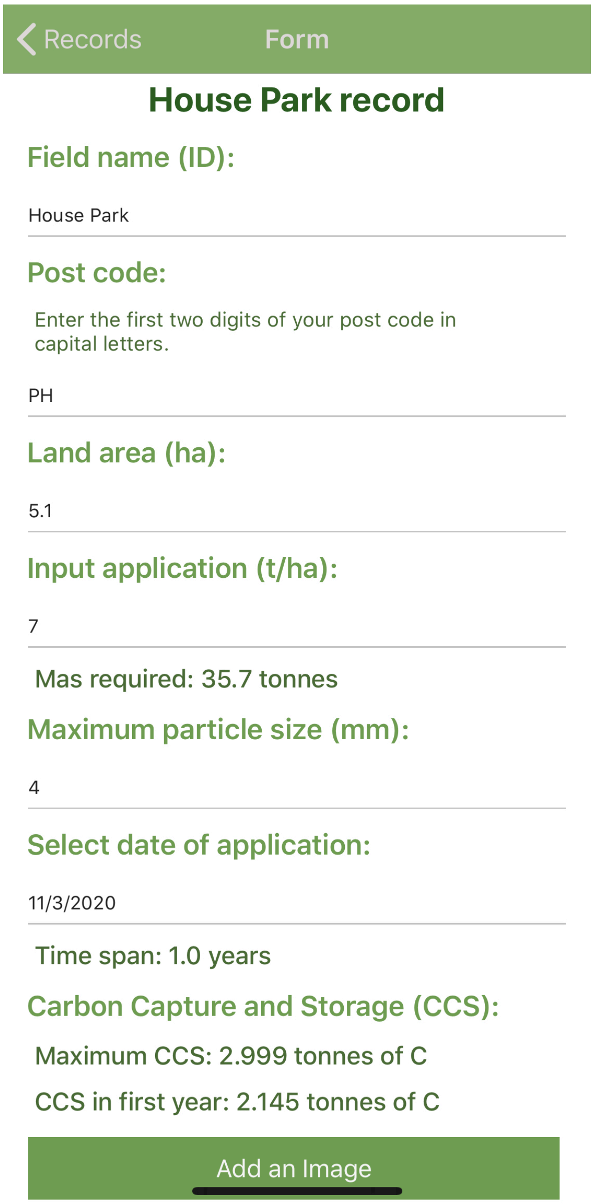


Objective 3: Developing an App to calculate C-sequestration

The app was designed alongside the farmer pilot group to provide a tool for predicting CO_2 sequestration capacity of applying crushed basic silicate rocks on the land. It also provides information on the project and links to further sources of information on climate smart farming, such as the Farm Carbon Toolkit and Farming for a Better Climate.

The software used to develop the app was the open-source software *NativeScript* (https://nativescript.org/). The software was selected from a range of alternatives, based on suitability for development of open-source apps compatible with iPhone and Android phones and tablets, and on ease of use for training purposes.

The Carbon Capture and Storage (CCS) calculator uses a mathematical model developed within the App code The user needs to enter information on the tonnage of rock applied, the date and area of application. The first two digits of postcode are entered to give an indication of average rainfall. The results show the maximum carbon captured alongside the amount captured in the first year.



The App can also access the phone's camera and can be saved alongside the calculation in a 'records' section.

In the second phase of the app development, the app prototype was distributed among the pilot group of farmers in the second online workshops. The app capabilities and functionalities were presented to the pilot group of farmers and questionnaires were distributed to obtain feedback on relevant aspects. This also allowed the app development team to test app performance across different devices and identify sources of error, difficulties in upload or variations in appearance across multiple devices and operating systems. The farmers' feedback was collected in questionnaires that followed the second online workshop, which were used to implement changes.

Further information on the App can be found in Annex 4

6.2. Milestones

Key Output	Milestone	Achieved
Monitoring on the ground changes on Rotmell Farm	Complete sampling and analysis of results	All planned monitoring and analysis completed
	• plant nutrients & productivity	Completed 12 March 21
	• soil nutrients & microbiology	Completed 12 March 22
	• soil CO_2 & inorganic carbon	Completed 18 Feb 21
	• soil structure	Completed 1 March 21
Farmer Pilot Group	Set up pilot group with at least 10 farmers	13 farmers joined group
	Send pilot farmers bag of product to apply to test site	Sent September 2020
	Deliver Workshop 1 - Introduction of product	Delivered 11 August 20
	Deliver Workshop 2 - Dissemination of provisional results and launch App	Delivered 17 December 20
	Deliver Workshop 3 - Introduction to product	Delivered 2 March 21
Develop App to calculate carbon sequestration	Complete App development	Completed 12 March 21

7. LESSONS LEARNED

7.1. Issues/Challenges

Probably the biggest challenge has been the short project timescales, this was more due to the project gaining approval towards the end of the SRDP, rather than an intended timescale. On-the-ground monitoring data has only been collected from part of a production season (July until October) and three years after a single application of the crushed silicate rock. Consequently the information collected is only a snapshot rather than a follow-through from the point of field application. We appreciate that any agricultural field is a complex biogeochemical system. The team looked at a comprehensive range of features, but we may have missed some of the more immediate changes and are yet to see any potential longer term effects.

The sampling campaign has worked around normal farming activities, but one measurement of above ground plant production was affected by grazing of the site.

The pilot farmers were also sent some crushed silicate rock product to try out on a small trial plot on their own farms. The wet and cold winter weather has hampered any meaningful on-farm observations (such as water infiltration and earthworm counts) within the project timeframe.

The project also coincided with the COVID-19 pandemic. Although the team managed to undertake all works within Scottish Government guidelines, there have been delays in getting results from the laboratories as they have not been staffed at full capacity and some facilities were not fully open until later in the project. In January, BBC Radio 4 were also been keen to record an episode for their “39 Ways to Save the Planet” series but current COVID restrictions have prevented travel by the production team.

The COVID restrictions have also meant that all meetings for both the delivery team and the farmer pilot group have been online. Although this has hasn’t affected outcomes, building relationships online, particularly within a short timeframe is more difficult. Not being able to meet on farm as planned, that lack of social connection plus tricky rural broadband connections has made group engagement less spontaneous and more challenging than if we had on farm meetings.

There were some challenges with getting the App functioning for all the farmer pilot group. Some of the farmers had difficulty in downloading either the original or updated versions, despite best efforts. The issue seemed to be with downloading QR codes. Once they encountered difficulty it was harder for them to engage as they felt the issue was with their lack of technical ability or capacity.

7.2. Impacts

The full impacts of this project won’t be expected to be seen within its short timescale. However, the results give a strong indication of potential longer term environmental, economic and social benefits from the application of crushed basic silicate rock onto agricultural land.

The most significant change seen on the trial site has been in soil microbiology. The results show that the treated area has a more balanced and higher value biodiversity; in other words, there is a more beneficial microbiome present. This effect is still evident three years after application of the rock suggesting that the benefit is being maintained well after treatment. Essentially we are seeing a more biologically sustainable soil, capable of cycling nutrients, capturing carbon and resisting crop pathogens. In addition, we didn’t see any negative effects of applying the product.

At the moment it’s difficult to fully value these benefits without undertaking more work to quantify these on a range of farm types. For example, crop pathogens are rarely seen as an issue in pasture-based systems (as per the trial site), but improved resistance to crop pathogens would potentially bring more value to arable or horticultural systems and reduce reliance on synthetic inputs.

In terms of social benefits, all the farmers within the pilot group were interested in the product if it could potentially improve soil health as well as capture and store carbon. They care about their soil, its health and functionality and their social responsibility. They are actively seeking ways to farm productively whilst reducing reliance on synthetic inputs and contributing to Net Zero Targets. They have enjoyed being part of a group of like minded farmers looking for innovative solutions. They have particularly appreciated the rigour and impartiality that the science team have brought to assessing a new input, noting that it’s rare in the agricultural sector.

8. COMMUNICATION & ENGAGEMENT

8.1. Detail throughout the project's lifetime

A key strength of the project and its delivery was the engagement between the scientists and the pilot farmer group. Three workshops were held throughout the project and allowed valuable sharing of knowledge, thoughts, experiences and perspectives.

The dissemination of the project findings to the wider agricultural community was planned once the monitoring work was concluded. COVID delays has meant that final results from labs are later than planned, so wider dissemination of the key findings will likely have most impact beyond this report date.

Twitter, a podcast and webinar were identified as the main communication methods for this particular project.

Communication Method	Reach
Three virtual workshops for the pilot farmers were held throughout the project	13 farmers in pilot group
Twitter account created for @RockOnSoils	256 followers 1781 visits 48,247 impressions
Facebook page established October 2020	
Press release announcing project launch - 4 Aug 20 Coverage in Scottish Farmer, The Courier, Scottish Field, Agriland EIP-Agri and Agrigate Global. Articles also hosted on JHI and Macaulay Development Trust websites	Reach is estimated at over 34,000
SOPA Newsletter article - 11 Sep 20 & 15 Oct 20	484 and 362 recipients
Video introducing the project launched Oct 2020 https://www.youtube.com/watch?v=6NLTkb63me0	150 views
Webinar run jointly with Farm carbon Toolkit featuring Rotmell as Livestock Soil Farmer of the Year 2020 and showcasing the project https://www.youtube.com/watch?v=g0iKVnU2-3s	110 attendees 810 views
Podcast speaking with host and pilot farmer about importance of soils and carbon https://www.spreaker.com/user/bespoken_uk/rock-on-soils-complete?utm_medium=widget&utm_source=user%3A11791693&utm_term=	Launched 8 Mar 21 - 500 listens in first week.
Press release announcing key project findings	Release date Mar 20 Anticipated reach 34,000
Wikipedia entry - for more technical information on basic silicate rock mineralogy, elemental chemical composition, occurrence in the UK and potential environmental benefits - (content in Appendix 6)	Page completed and under publication review by Wikipedia

8.2. FAS Engagement

FAS was engaged via social media and a summary of the findings has been provided to upload to their website.

8.3. EIP-AGRI Engagement

The project was registered on EIP-Agri Website https://ec.europa.eu/eip/agriculture/en/find-connect/projects/basic-silicate-rock-product-new-agricultural-input and a final report with key findings will also be sent to them. They were also been tagged in tweets. A final report will also be shared.

8.4. Other Engagement

Host farmer Alex Brewster from Rotmell was announced as Farm Carbon Toolkit's 2020 Soil Farmer of the Year and hosted a virtual farm tour in October which provided the opportunity to showcase the project as part of that event. The event had 110 attendees. The video recording of the event has been viewed 810 times.

The project has also joined the Fields4Ever (https://fields4ever.biomemakers.com/) European initiative. This provided free soil microbial DNA analysis giving a valuable insight into the function the microbes we found play in supporting soil and crop health and production. The soil microbial DNA from Rotmell Farm build into a worldwide database, improving understanding of how soil microbiomes function.

Project news and updates were shared via the SOPA organic newsletter with a reach of c.800.

9. KEY FINDINGS & RECOMMENDATIONS

9.1. Key Findings

The following summarises the key findings in meeting the project objectives.

Objective 1: Monitoring on the ground changes at Rotmell Farm

It's important to note that the monitoring undertaken at Rotmell is three years following the single application and rate of the rock product and due to timescales of the project only included part of a growing season. The monitoring is only a snapshot of the impacts of the product which is being used in a complex biogeochemical system. (Full data is in Appendix 3)

Soil microbial changes

The most significant change seen on the trial site has been in soil microbiology. The monitoring shows that the area that received crushed basic silicate rock has a more balanced and higher value microbial biodiversity; in other words, there is a more beneficial microbiome present. This effect is evident three years after treatment suggesting that the benefit is being maintained well after treatment. Essentially we are seeing a more biologically sustainable soil.

In particular there are more microbial species in the basic silicate rock treated area that undertake the following functions;

- Sequestering carbon
- Mobilising nitrogen
- Mobilising phosphorous and potassium
- Biologically controlling pathogenic bacteria and nematodes

And lower levels of pathogenic microbes which cause;

- Black point
- Ergot
- Fusarium crown rot

There were, however, less microbes that predate on pathogenic fungi, and higher levels of anthracnose and powdery mildew in the treated versus untreated areas. It's important to note though, that presence of these pathogens doesn't necessarily lead to disease.

Soil nutrient and structure changes

There doesn't appear to be any negative effect of applying basic silicate rock.

Basic silicate rocks contain a mix of elements including some heavy metals such as titanium, vanadium, lithium and strontium albeit in small quantities. Some of these can be toxic to plants and animals, however there didn't appear to be any increases of these heavy metals in the soil or plant analysis.

The monitoring also showed that particles of the applied rock were found down to 10cm, which was the maximum depth tested. There is therefore no need for farmers to actively incorporate the product into the soil. Surface application even on an existing perennial crop will result in the product finding its way into the soil.

Compared with the soil at Rotmell Farm, the rock had a larger particle size distribution and a different chemical composition. There is therefore potential for the applied rock to change soil structure and chemical composition.

No differences in soil pH between the treated and untreated areas were seen.

Soil CO_2 and inorganic carbon changes

The monitoring didn't show any difference in the amount of CO_2 being respired by plant roots and microbes back to the atmosphere from the soil.

Basic silicate rocks sequester carbon into an inorganic form. We didn't find any differences in soil inorganic carbon levels at the depth investigated (10cm). A test of field drainage water also showed no difference. We are confident that the formation of inorganic carbon happens. Not finding it may be down to three possibilities;

- The inorganic carbon has formed and been removed via groundwater before the project began
- The application rate of 20T/ha is too low to see any marked differences
- The inorganic carbon has moved below the sampling depth of 10cm

Objective 2: Forming a pilot farmer group

The pilot farmer group provided a valuable contribution to the project. They brought a wider perspective to the project delivery team, moved the focus beyond a single farm and gave valuable insight into potential barriers to the wider uptake of using crushed silicate rock as a method of sequestering soil carbon.

The farmer group had a wide range of soil organic carbon levels on their own farms and all are interested in making changes to reduce emissions and sequester more carbon. The highest level of soil organic carbon was on a livestock farm with 4.5%, the lowest was on an arable field at 1.3%. The average was 2.77%. The farmers are already making changes, through organic certification, tree planting, cover cropping, minimum or zero tilling, applying compost and improving grazing management. All these measures involve protecting or sequestering organic, rather than inorganic carbon.

The monitoring work on Rotmell revealed minor or no difference in direct production measures that can easily be given a financial value to identity any potential cost saving or yield benefit. The most significant change, a more biologically sustainable soil is difficult to financially value as it is indirect and will vary from farm to farm; the potential benefits of using the product are a gain in ecosystem support services.

The key consideration for the group was the cost:benefit of using the product. Costs for applying crush silicate rock will vary according to distance from the quarry, but for Rotmell farm the costs were similar to those of spreading lime at approximately £32/tonne. However, the application rate assessed in the project was 20T/ha giving a total cost of £640/ha. For the farmers in the group this cost was seen as a prohibitively high, particularly when compared with amendments such as lime, which is giving them production and soil health benefits.

The mobile phone App developed under Objective 3 calculates the total amount of carbon that can be sequestered by basic silicate rock. One tonne of product can sequester 0.08tonnes of carbon. Although we don't yet have a formalised carbon agricultural trading scheme, a suggested trading value of £25/tonne won't meet product application costs.

However, the farmers weren't saying "no" to using the product, just not at that cost without further information on the potential co-benefits. They also felt that they are likely to get financial support for other emerging policy measures that will support carbon sequestration - such as cover cropping and tree planting - which could relegate the use of basic silicate rock unless it too is supported.

Another issue highlighted by the farmers is a lack of clarity on what the scope of their farm carbon sequestration potential is. The results from the farmer soil analysis shows a wide variation in organic carbon levels, but for those at higher levels, is there much scope for increase? Measuring soil organic carbon is notoriously challenging, with much variation even within fields. One of the pilot farmers said he had been measuring soil organic matter for 20 years and sees variations between years, but no real increase over that timescale. However, it's important to note that basic silicate rock sequesters carbon into the inorganic rather than organic form, and there is currently no evidence that sequestering both organic and inorganic are incompatible. The farmers want to learn more about soil carbon.

Objective 3: Developing the App

The App provides a useful tool to allow farmers to calculate the amount of inorganic carbon they potentially capture and store on a field basis when applying the rock.

Although some farmers found difficulty in downloading the App on their phones, those who did manage found it easy to use and value being able to put a figure on the carbon capture potential of individual fields and save that data. Of great value is having the ability to demonstrate a contribution to Net Zero.

For those who struggled to download it, feedback was that a web rather than App based calculator would be useful. Particularly as recording field inputs tends to be done in the office rather than on the move.

9.2. Recommendations

Based on the key findings and the pilot farmer input, we have identified the following recommendations

- Further work needs to be undertaken on different farm types to see if we get a similar soil microbial benefit, particularly in farming systems that would benefit most such as arable.
- This work should feed into valuing the indirect benefits that improvements to ecosystems services can bring, such as reduced pathogen risk and better nutrient cycling.
- This project has only shown a brief snapshot of the effects of applying basic silicate rock. It is highly likely we have missed some effects, whilst others are yet to be seen. Further monitoring is needed to fill these gaps and track the effects from the point of application and beyond three years.
- We need to look at what effect we get at different application rates
- We need to look for inorganic carbon at greater than 10cm depth and in more detail in groundwater.
- We need to build on current understanding and think about how we can get the most from this product. Examples include, does applying it with manure or compost lead to enhanced benefits? Is there an additive effective when used with other soil health measures such as minimum tillage?
- Feedback from the farmer group suggests that the cost of crushed silicate rock is a barrier to its use. Policy support is likely needed to help overcome this issue notably by ensuring that support for other climate change incentives such as cover cropping or tree planting doesn’t cause additional market failure
- We need to understand the full emissions cost of applying the product. Distance from the quarry and method of application may negate some of the sequestration benefits.
- The farmer pilot group welcomed the validation the science team brought. Future projects looking at new innovations should consider this collaborative model.

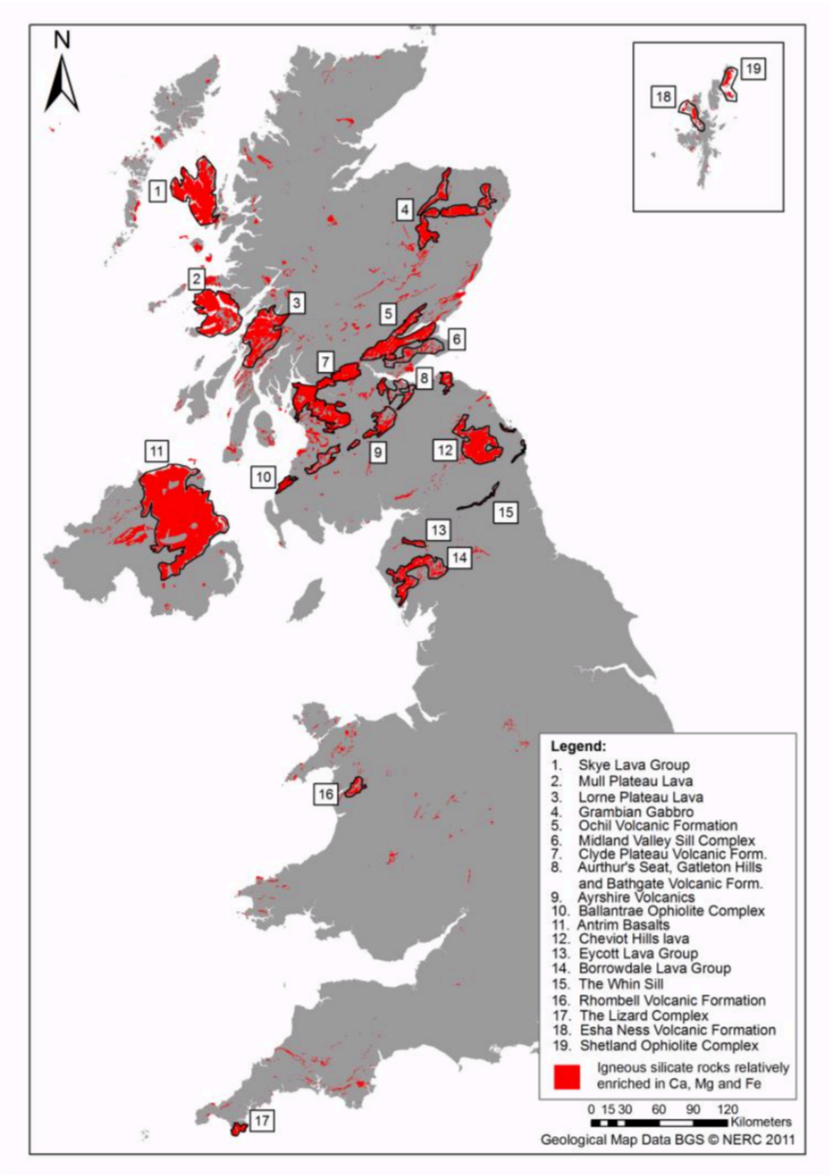
10. CONCLUSION

Although we have perhaps missed and are yet to see some of the benefits of using crushed basic silicate rock, the changes we have seen are important and suggest wider benefits of the product beyond just carbon sequestration. The beneficial changes we have seen to the soil microbiome tick many more boxes than just tackling climate change. Restoring ecosystem health and protecting Scotland's biodiversity and natural capital can also be included. It is clear that this natural product has potential and we need to do more work to fully understand, realise and fully value this potential. This project should be viewed as a work in progress, and as is often the case we find that new knowledge raises more questions than answers, so we would welcome further work in this area.

There is a real need for action and not just talk when it comes to tackling climate change and this model of bringing together farmers and scientists has shown a lot can be achieved within a very short timescale. Progress is being made. Farmers are not short of potential solutions, ideas and questions they need answered. The science team can provide answers with rigour and impartiality; a validation to help identify dead ends and open pathways ahead. We need more projects like this to help achieve our urgent climate change targets.

ANNEXES

1. **Map of Suitable Basic Silicate Rock** From Renforth (2012)



Renforth, P 2012. The potential of enhanced weathering in the UK. International Journal of Greenhouse Gas Control, Volume 10, 229-243

2. Nomenclature

Basic silicate rocks include dolerite and basalts

Acronyms

CCS	Carbon Capture and Storage
LOD	Loss on Dehydration
LOI	Loss on Ignition
EC	Electrical conductivity
TIC	Total Inorganic Carbon
DIC	Dissolved Inorganic Carbon
PSD	Particle Size Distribution

Units

t	tonne (10^6 g)
kg	kilogram (10^3 g)
g	gram
mg	milligram (10^{-3} g)
µg	microgram (10^{-6} g)
m	metre
cm	centimetre (10^{-2} m)
m^2	square metre
ha	hectare (10^4 m^2)
L	litre
s	second
µS	micro-Siemens
%	percentage (x0.01)

Chemical element list

Al	Aluminium
Fe	Iron
Ca	Calcium
Na	Sodium
P	Phosphorous
S	Sulphur
K	Potassium
Mn	Manganese
Mg	Magnesium
O	Oxygen
C	Carbon
H	Hydrogen
CO_2	Carbon dioxide

2. Experimental design

Rotmell farm fields

Two grazing fields with similar history were identified (Figure 1). Both fields were last ploughed in 2010 and sown in 2012 with grass and red clover seed mixtures. In 2013 the fields received a farmyard manure application of 25 t/ha as organic fertiliser. One of these two fields has not received any further application since, here onwards the "Control" field. The other field received an application of 20 t/ha of crushed dolerite in 2017 as an innovative organic agricultural fertiliser, here onwards the "Dolerite" field. In 2018 and 2019 both fields were grazed during the April to October period approximately once per month for two to three days, and during the November to March period once for the same length of time.

The studied fields are two continuous fields of Rotmell farm shown in Figure 1. A ditch collecting water from the underground field drains runs parallel to the bottom of these fields (blue arrow in the figure), eventually discharging into the Tay river.

Schematic view

Figure 2 shows the location of the experimental units located at the Control and Dolerite fields of Rotmell farm. The figure also shows the topography of the area and show hills to the right of the image and that he two fields have a similar terrain slope dipping eastwards towards the Tay water course.

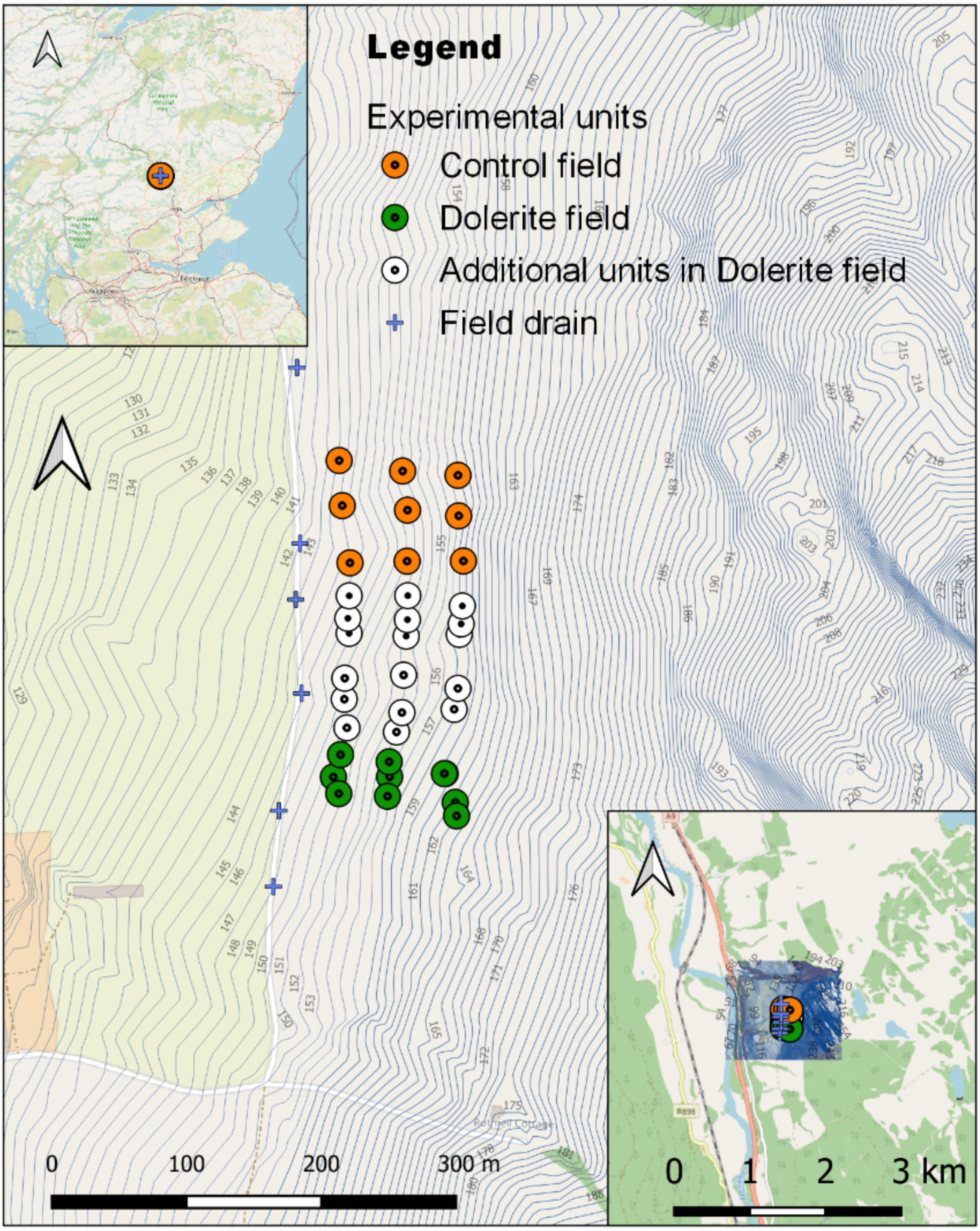


Figure 2 Schematic view of fields at Rotmell Farm and location of areas for analysis in field BD and D. BD stands for Basalt quarry fines mixed with composted manure (or Dung).

Sampling areas

Each experimental unit consisted of an area of approximately 5 m^2. In each experimental unit there was a ring (top left) to measure soil-atmosphere carbon dioxide fluxes. Soil cores were obtained from the area surrounding the blue square in the picture, which was used to delimit the area of plant sampling, of approximately 1 m^2. Soil physical tests were also conducted in the area surrounding the blue square.

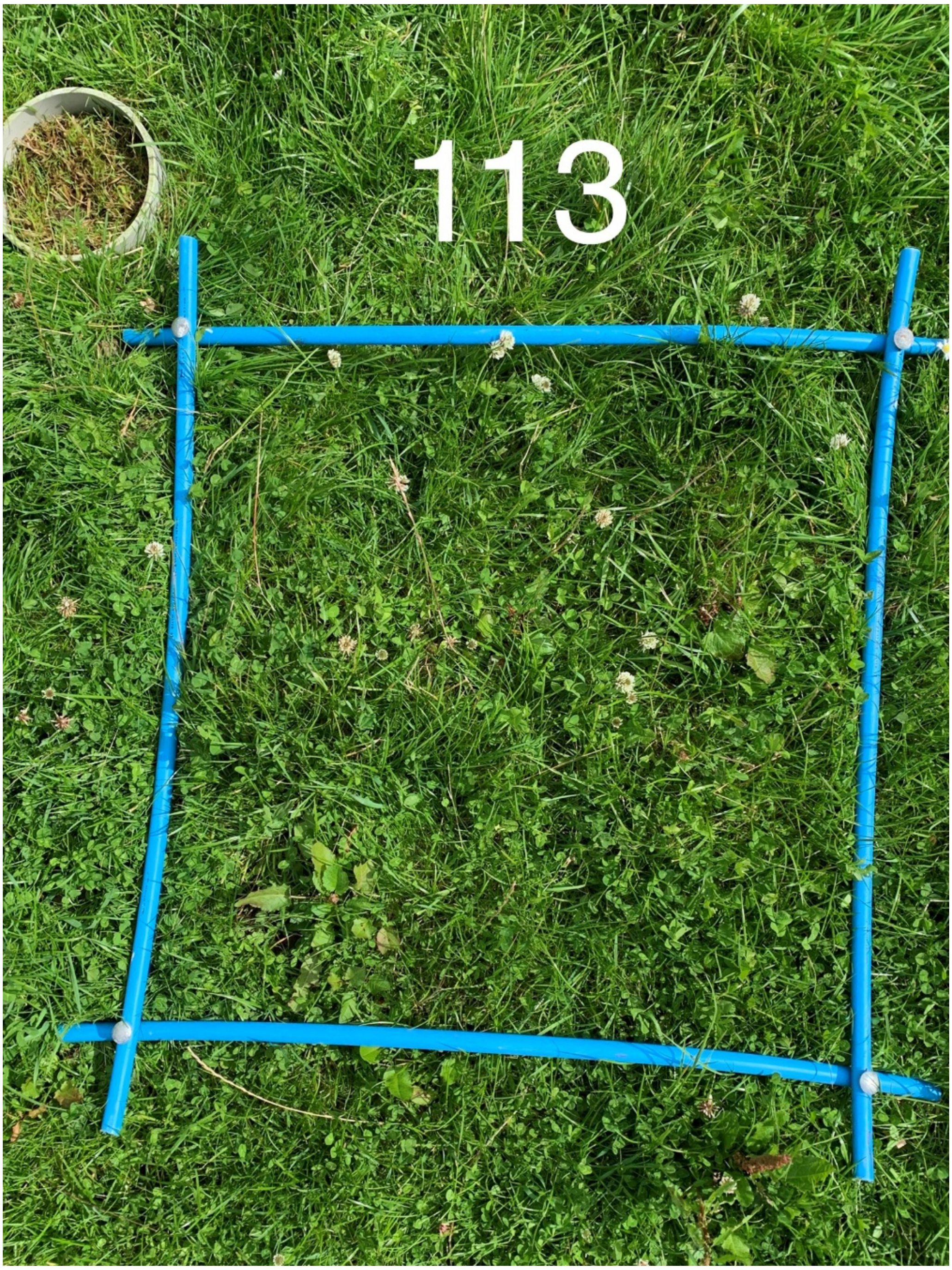


Figure 3 View of experimental unit. The figure identifies the location for CO_2 measurements (ring on the top left of the picture), the location for plant productivity sampling (inner area of the blue square), the location of the soil cores sampling (corners of the blue square), and the location of the soil physical tests (around the blue square).

Samples

Examples of the type of samples obtained at each experimental unit are shown below. Soil cores were typically of 10 cm diameter and 10 cm depth. Several soil cores were obtained in each experimental unit. Plant samples were collected both in bulk and for separate species. Soil-atmosphere air measurements were conducted in situ with the soil chamber system shown in Figure 4.3.

Figure 4 Soil (1), plant (2), air (3) and water (4) samples.

Field drains

Water samples were obtained at the field drains collecting water from the Control and Dolerite fields. Figure 5 shows an example of one of these field drains where water samples were obtained.

Figure 5 Field drain.

3. Analysis results

3.1. Analysis package 1: soil, plant and water chemistry

Soil mineralogy

The common list of minerals conforming soils and rocks were determined by the X-Ray Diffraction technique.

Three samples were analysed:

- the fresh rock sourced from the quarry,
- a sample of soil of the treated field obtained from mixing material from the nine experimental units of the Dolerite field and;
- another sample of soil obtained through the same procedure from the Control field.

Results presented in Figure 6 show that the soil of the Control and Dolerite fields are very similar and no major changes in the minerals contained in them is seen. The data indicates the soil at Rotmell is mostly composed of quartz and plagioclase. The rock contains minerals that are at low to nil levels in the soil. Plagioclase and pyroxene are the important minerals in the rock as they are rich in calcium and magnesium and induce inorganic carbon sequestration upon weathering. The data highlights the potential of the amendment to induce changes in the local soil mineralogy.

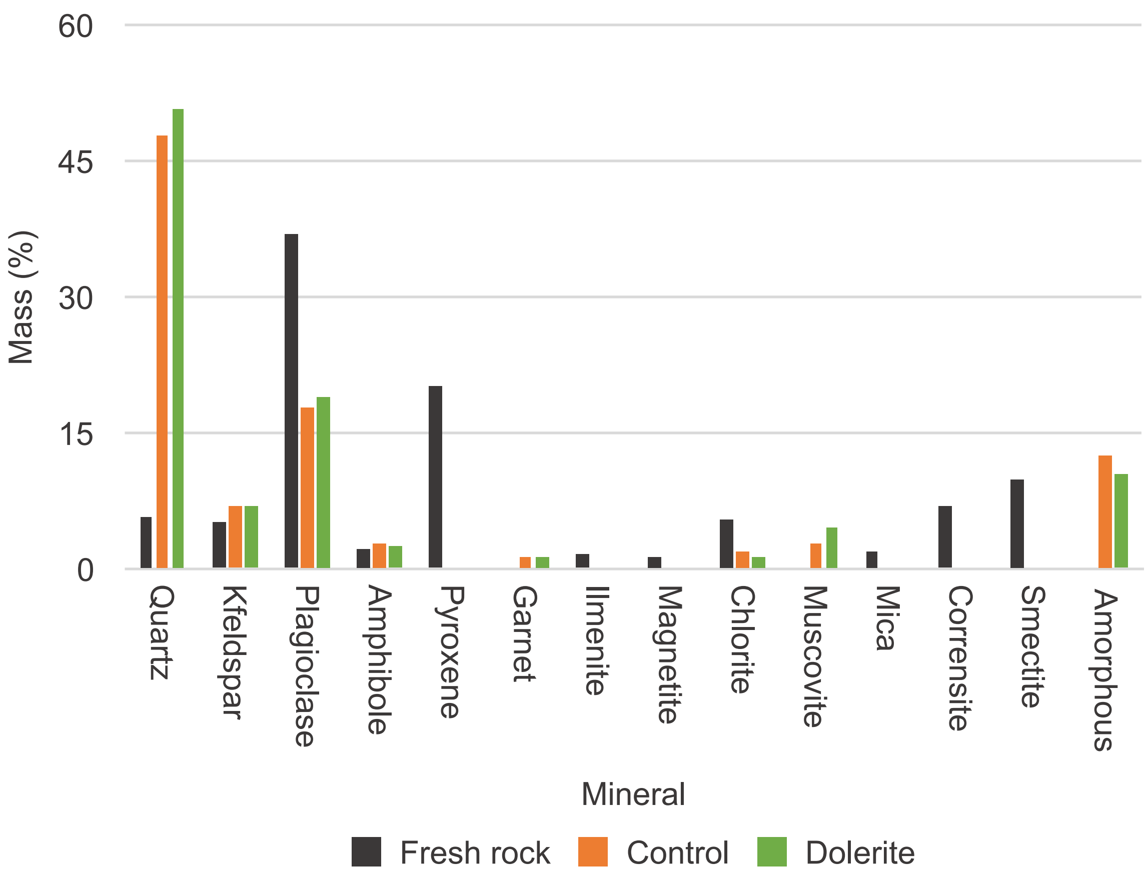


Figure 6 Minerals present in the fresh rock, and of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average of 9 sampling locations in each field.

Soil chemical composition: Major elements

The chemical composition of the major, or more abundant elements contained in the of soils and rock was analysed by the X-Ray Fluorescence technique. LOD and LOI are loss on dehydration and ignition respectively.

Three samples were analysed:

- fresh rock sourced from the quarry,
- a sample of soil of the treated field obtained from mixing material from the nine experimental units of the Dolerite field and;
- another sample of soil obtained through the same procedure from the Control field.

Results presented in Figure 7 show the soil from both the Control and the Dolerite fields have practically the same chemical composition. In addition, the rock is more abundant in aluminium, calcium, magnesium, sodium and titanium but lower in silica. Overall, these results show that the chemical composition of the added material differs from that of the soil, meaning there is potential for changing the soil chemical composition.

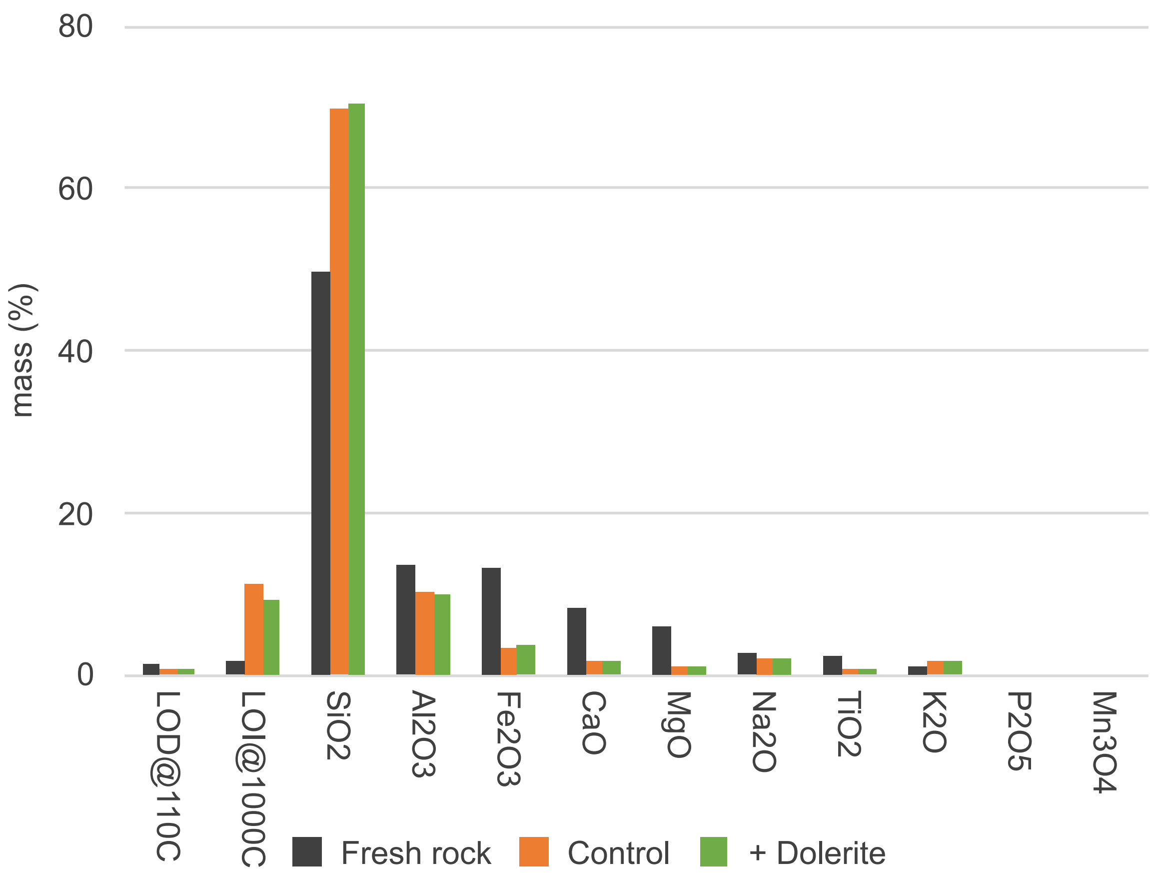


Figure 7 Chemical composition of major chemical element oxides in fresh rock, and of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average of 9 sampling locations in each field.

Soil chemical composition: Trace elements

The chemical composition of soils and rock were determined by the ICP-OES/MS technique. This technique was used to determine the chemical elements present in the rock in smaller amounts, escaping the limits of detection of the X-Ray Fluorescence technique.

In total, 21 samples were analysed:

- 3 samples of the fresh rock sourced from the quarry,
- 9 soil samples obtained from the experimental units of the Dolerite field and;
- 9 soil samples obtained from the experimental units of the Control field.

Results presented in Figure 8 indicate both the Control and the Dolerite fields have practically the same chemical composition of trace elements, and that the rock contains higher concentration of barium, cobalt, copper, nickel, strontium, zinc, boron and vanadium. Overall, these results show that the chemical composition of the added material differs from that of the soil, meaning there is potential for changing the soil chemical composition.

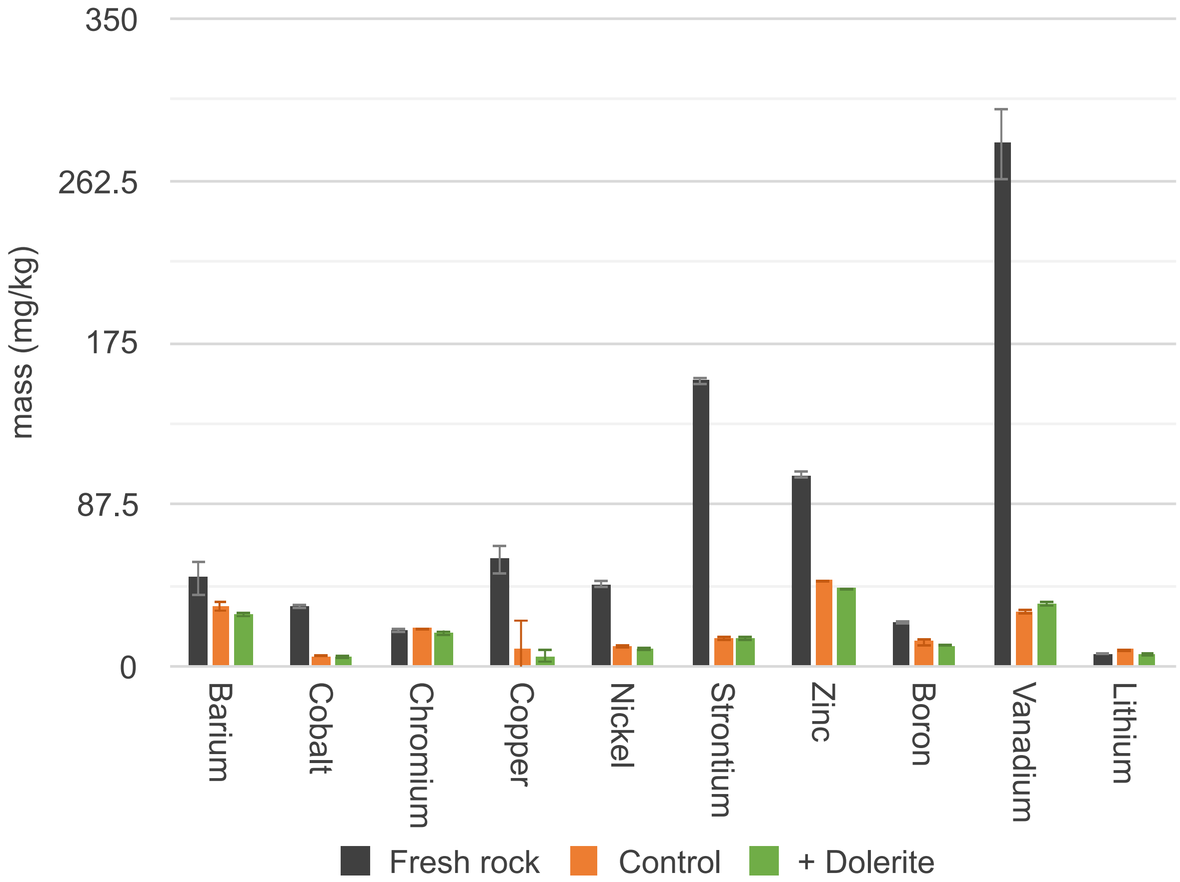


Figure 8 Chemical composition of trace chemical element in fresh rock, and of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average and standard deviation of 9 sampling locations in each field.

The soil-water interphase: available chemical elements

The soil extractable elements were determined by the ICP-OES/MS technique. This technique was used to determine the proportion of chemical elements present in the soil easily available to plants and microorganisms.

In total, 18 samples were analysed:
- 9 soil samples obtained from the experimental units of the Dolerite field and;
- 9 soil samples obtained from the experimental units of the Control field.

Results presented in Figure 9 show both soils from the Control and Dolerite fields have a very similar abundance of available major elements, and significative differences are not appreciated. Of the major elements, small differences are seen in sodium and sulphur content. Of the elements present in minor abundance, differences are observed for chlorine, bromine, cadmium, chromium, nickel, aluminium and manganese. However, in both cases these differences are small to insignificant.

Other relevant trace elements such as cobalt, copper, zinc and boron do not differ significantly across the studied sites.

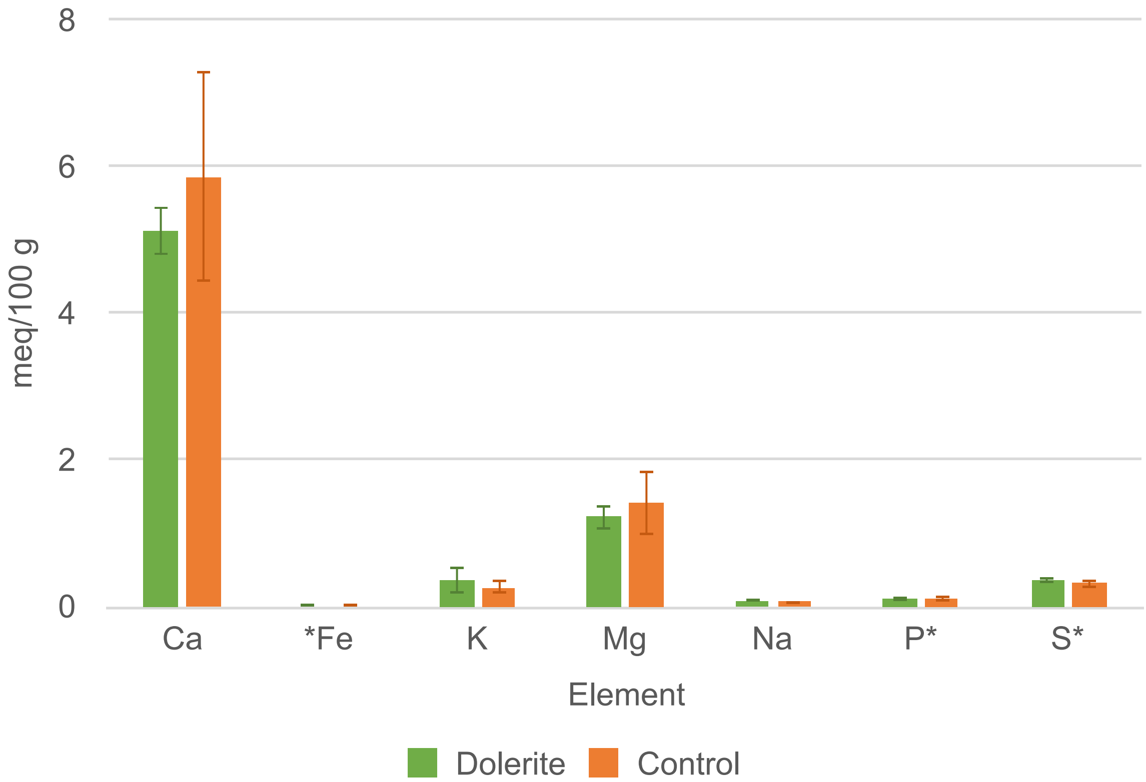


Figure 9 Soil extractable major elements of soil samples obtained from the Control and Dolerite field. The data presented is the average of 9 samples from each field.

The soil-water interphase: pH

The pH of the soil was determined using a pH meter at depths 0 to 5 cm and 5 to 10 cm. This was conducted in moist conditions at low liquid to solid ratio to simulate real conditions of the soil in the field. The pH was analysed in 0.01 M $CaCl_2$ and soil:solution ratio of 2.5.

In total 36 soil samples were analysed:
- 9 soil samples from the Control field from the 0-5 and 5-10 cm depths.
- 9 soil samples from the Dolerite field from the 0-5 and 5-10 cm depths.

Results in Figure 10 reveals soil pH of the Control and Dolerite fields was similar at both of studied depths, with average values ranging from 5.68 and 5.95. The Dolerite field showed a slight decrease in soil pH at 5-10 cm depth compared to the top 5 cm.

Overall, the results indicate no significant difference across the studied sites.

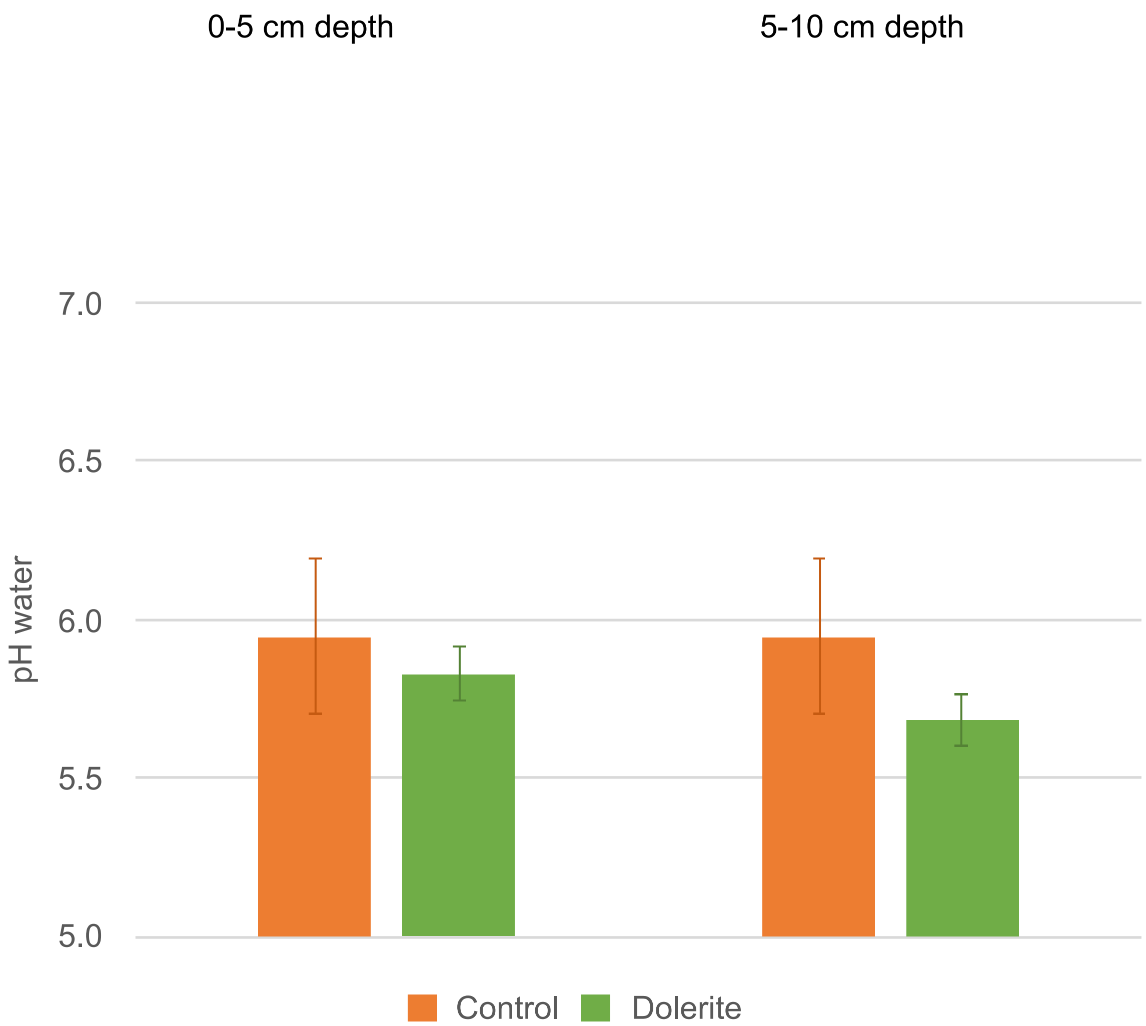


Figure 10 Soil pH of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average and standard deviation of 9 sampling locations in each field.

The soil-water interphase: Electrical conductivity

The Electrical Conductivity (EC) of the soil was determined using an EC meter. This was conducted in moist conditions at low liquid to solid ratio to simulate real conditions of the soil in the field. The EC was analysed at a soil:solution ratio of 2.

In total 36 soil samples were analysed:
- 9 soil samples from the Control field from the 0-5 and 5-10 cm depths.
- 9 soil samples from the Dolerite field from the 0-5 and 5-10 cm depths.

Results in Figure 10 indicate the EC of the Control and Dolerite fields was similar across the studied sites and at the two studied depths. The graph also indicates a marked increase in EC with depth, such that EC was significantly higher at 5-10 cm than at the top 5 cm. Higher variability across sites of the same field is also observed at 5 to 10 cm depth. The average EC ranged between 189 and 196 at 0-5 cm and 390 and 504 at 5 to 10 cm depth. In average, the Dolerite field shows higher EC values at 5 to 10 cm depth compared to the Control field. However, the high variability across sites at this depth indicates EC was not significantly higher in the Dolerite field than in the Control field. Further data analysis is required to elucidate changes attributable to the amendment.

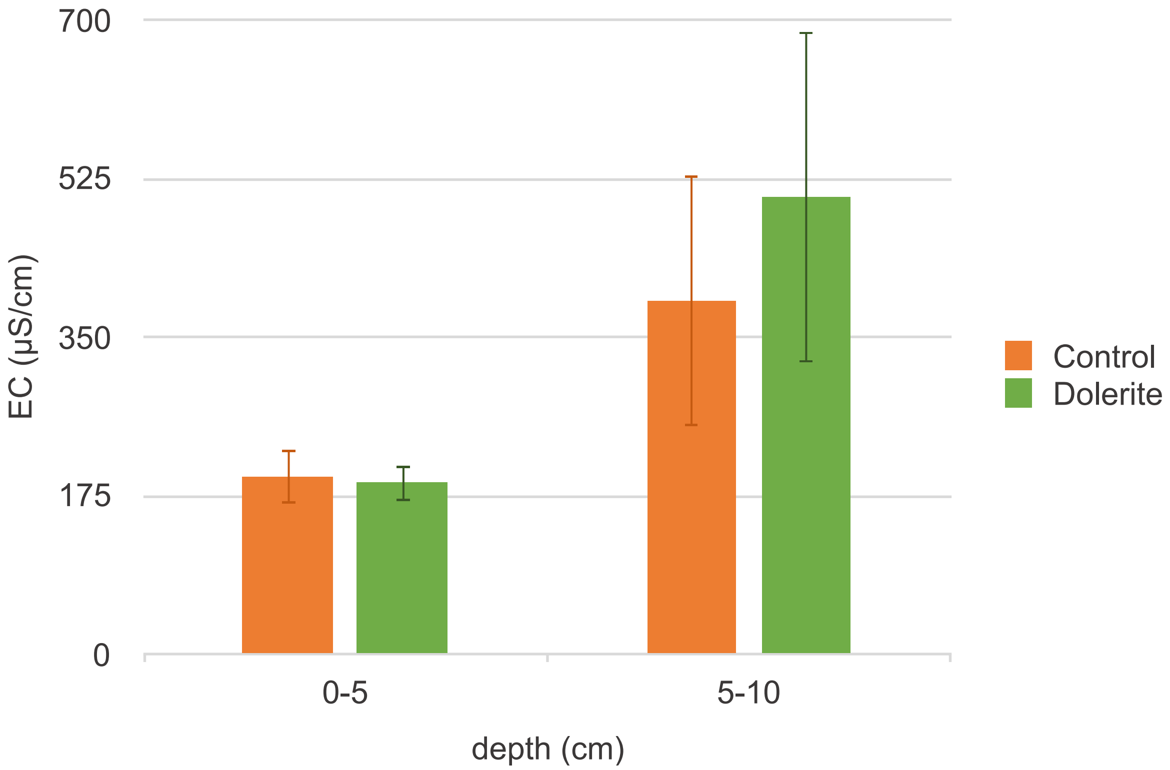


Figure 11 Soil Electrical Conductivity of Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

Plant and root chemical composition

The plant and root chemical composition were determined by the ICP-OES/MS technique. This technique was used to determine the concentration of relevant elements monitored in the soil, the soil-solution interphase, and the rock to determine transfer of these elements to the plant system. Additionally, plant and root carbon and nitrogen were determined.

The major elemental chemical composition of plant and root samples obtained from the Control and Dolerite fields is presented in Figure 12. The data reveals that both the plant upper system and the root system were of similar chemical composition for samples obtained from the Control and Dolerite fields with no major differences seen.

The elemental composition of the upper plant system revealed that of the major elements, nitrogen, carbon, calcium, iron, magnesium, and sulphur show slightly higher concentration in the upper plant system. However, these differences are small. For the minor elements, cobalt, chromium, nickel, and aluminium show lower values in the samples obtained from the Dolerite field, whereas strontium is found in a slightly higher concentration.

In the root system, sodium and sulphur showed slight difference across the two studied fields, with sodium concentration higher in the Dolerite field and sulphur higher in root samples from the Control field. However, these differences were small. Additionally, differences are observed in manganese and tin (Sn) (data not shown) with manganese is found in slightly higher proportion in roots from the Control field.

Other relevant trace elements such as cobalt, copper, zinc and boron do not differ significantly across the studied sites.

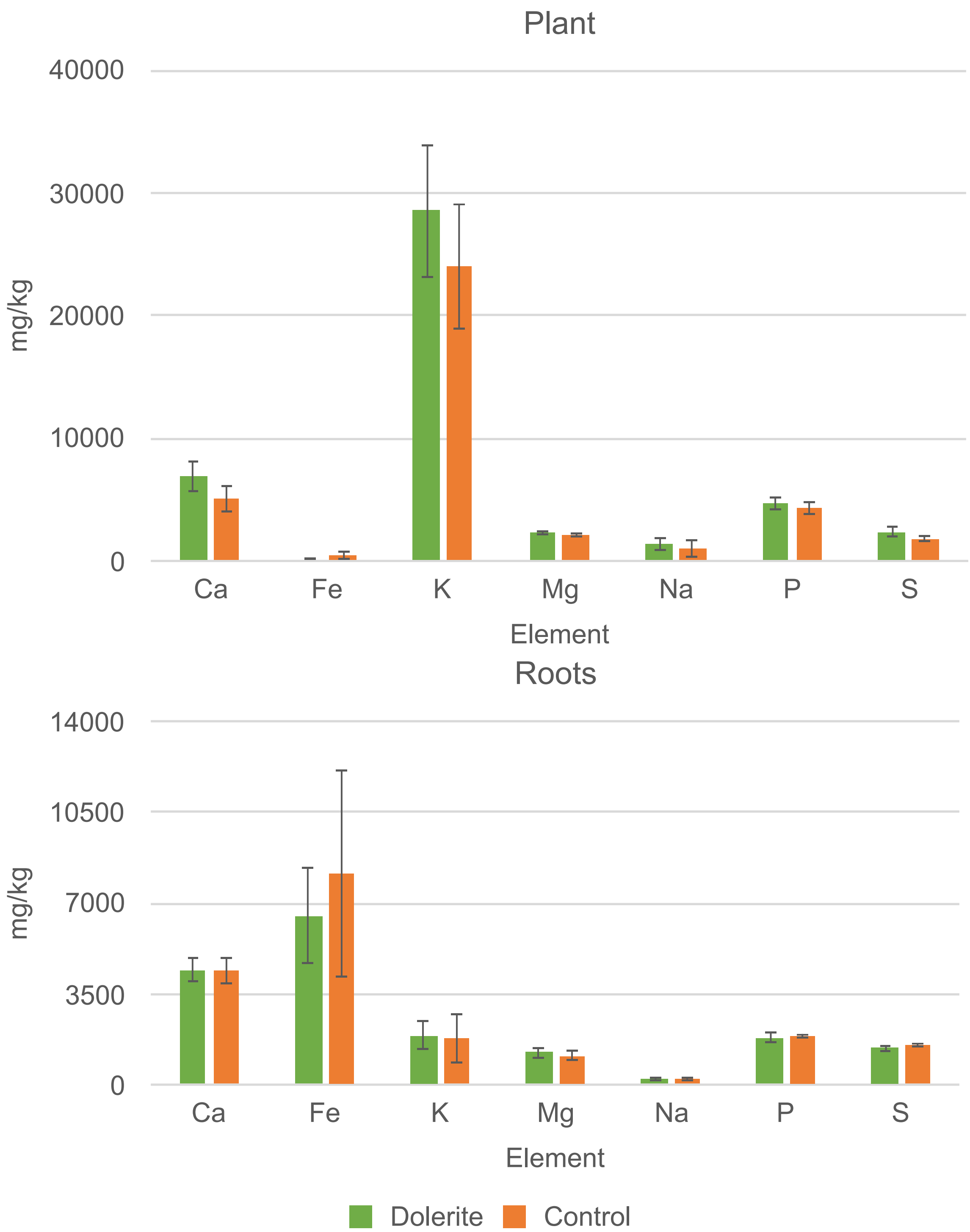


Figure 12 Plant (top) and root (bottom) major element chemical composition of plants obtained from the Control and Dolerite fields. Vertical and error bars indicate the average and standard deviation of nine samples obtained from each field.

Plant productivity

Plant productivity was determined by measuring the mass of plants per area at specific time points. Sampling at Rotmell farm was conducted at two time points, one in August and the other in September.

In total, 36 samples were collected:

- 18 plant samples from the Control field
- 18 plant samples from the Dolerite field.

The productivity measurement of the Control field of September was affected by a short grazing period. No conclusions can be drawn from the data presented in Figure 13.

Note: In further projects, productivity measurements should be conducted throughout the growing season.

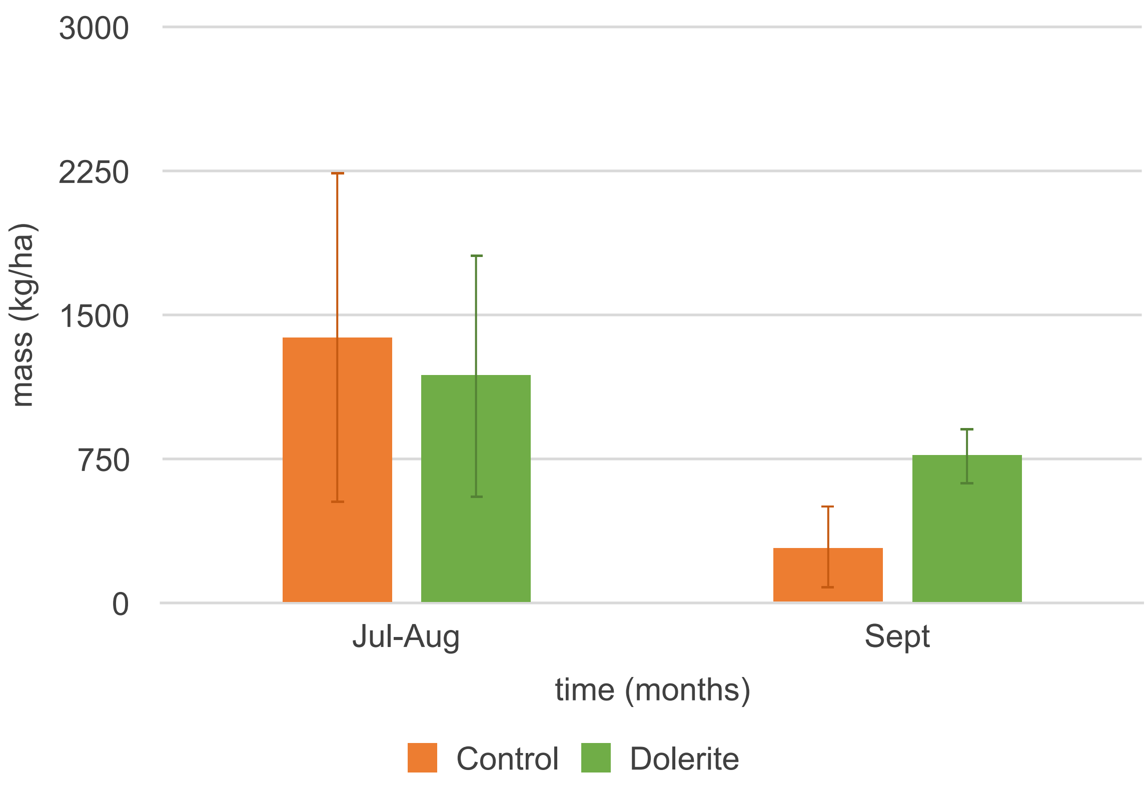


Figure 13 Plant productivity presented a the mass of kg per hectare conducted at two specific time points of the Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field. The September cut at the Control field locations was influenced by a short grazing period, thus it is not recommended its use to drive conclusions.

Root productivity

Root productivity was determined by measuring the mass of roots at specific depths. For this soil cores were cut in slices and washed thoroughly to obtain the root samples, which were then dried and weighed.

In total, 18 soil cores were processed:
- 9 from the Control field
- 9 from the Dolerite field

Root measurements were conducted at four depth intervals:
- 0 (surface) to 2.5 cm depth.
- 2.5 to 5 cm depth.
- 5 to 7.5 cm depth
- Greater than 7.5 (max 10 cm).

The data presented in Figure 14 indicates that the studied soil cores obtained from the Control and Dolerite fields had similar root mass content across sites and depth. The data indicates root mass accumulates at the top 5 cm depth and decreases significantly at 7.5 cm depth to reach near zero values at 10 cm.

No significant changes are seen between the Control and the Dolerite fields, although there is great variability across sites.

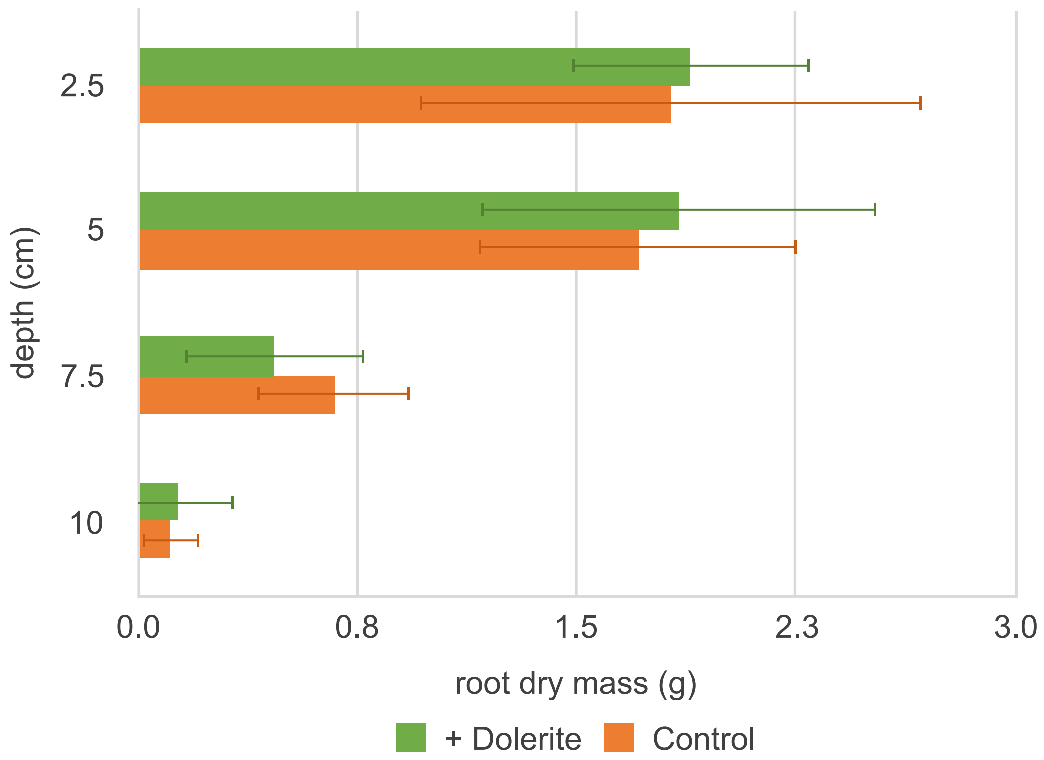


Figure 14 Root dry mass at certain depth ranges of Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

3.2. Analysis package 2: soil biology

Microorganisms: Microbes and Fungi

Biomass

The soil microbial biomass was determined on soil samples obtained from two depths.
In total 36 soil samples were analysed:

- 9 soil samples from the Control field from the top 10 and 10-30 cm depths.
- 9 soil samples from the Dolerite field from the 0-5 and 5-10 cm depths.

The data presented in Figure 15 shows that soil microbial biomass of the Control and Dolerite fields was similar. The data also shows a marked decrease of soil microbial biomass with depth, indicating soil microorganisms are more abundant at the top 10 cm.

Overall, there are apparent no changes in microbial biomass between the Control and Dolerite fields at the same depth.

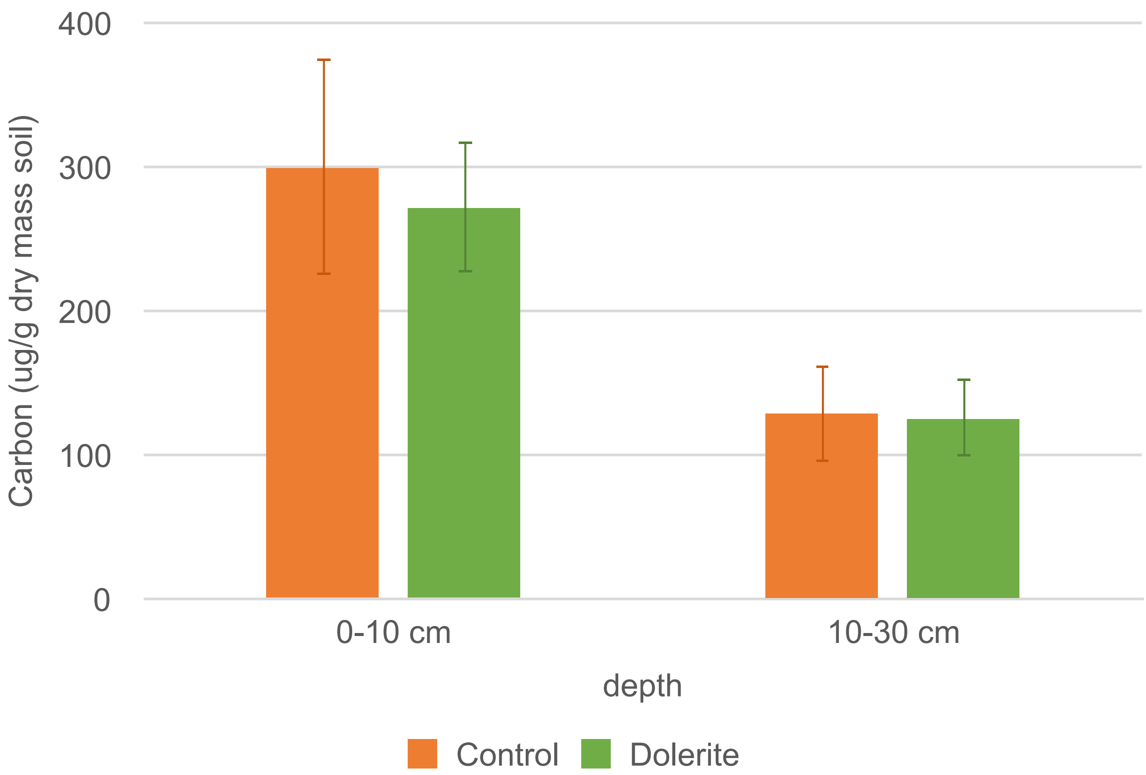


Figure 15 Biomass of soil bacteria expressed as micrograms of Carbon and normalised to the dry mass of soil of Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

DNA

Soil microbial DNA analysis of fungi and bacteria was conducted on soil samples obtained from the Dolerite and Control fields at two different depths: 0-10 cm and 10-30 cm. In total, 36 samples were analysed.

The data shows differences in the diversity of the microbial communities for both fields, indicating that the dolerite had an effect on microbial population of fungi and bacteria. In addition, the data shows marked differences in microbial communities across the studied depths for both fields. We effectively saw four microbial communities, differing by depth and by treatment. The differences at depth were probably attributable to the effect of depth rather than to the dolerite amendment. Overall, the biodiversity data indicates that dolerite has had a strong effect on bacteria and fungi populations across the studied sites which is observable three years after application.

Analysis of microbial diversity reveals that despite the microbial communities across the Dolerite and Control fields is different, the overall diversity of these communities, as well as their functionality and resilience was similar. Additionally, the data reveals that there was a lower biodiversity indexes on fungi on the Dolerite treatment. This suggest that the Dolerite treatment is influencing the fungal community, allowing a particular species to thrive and become more dominant. Drilling down further, the data further indicated that the Dolerite treatment has induced a more balanced and higher functional value microbial community than that found in the Control field.

Analysis on the potential for nutrient cycling and use from soil microorganisms, the data revealed that in both Control and Dolerite fields carbon sequestration through various metabolic pathways is occurring, but at a higher level in the Dolerite field. Similarly, for Nitrogen, Potassium and Phosphorous the data revealed a higher potential for mobilisation of these elements in the soil environment in the Dolerite compared to the Control field.

Analysis on the functions of the microbial communities identified revealed the Dolerite field microbial communities contained an increased abundance of species that help control diseases caused by bacteria and nematodes, but not fungi. This may indicate a higher resistance of soils treated with Dolerite against pathogenic organisms.

Analysis of pathogenic microbes present showed the Dolerite field had higher levels of anthracnose and powdery mildew, but lower levels of black point, ergot and fusarium crown rot.

Macro-organisms: Nematodes

Biomass

The abundance of nematodes in soil were determined on soil samples obtained from the Control and Dolerite fields.

In total 18 soil samples were analysed:

- 9 soil samples from the Control field from the top 10 and 10-30 cm depths.
- 9 soil samples from the Dolerite field from the 0-5 and 5-10 cm depths.

The data presented in Figure 16 indicates that the abundance of nematodes in soil of the Control and Dolerite fields was similar across the studied sites. There is a great variability in nematodes abundance within samples obtained from the same field. On average, a slightly higher abundance of nematodes is found at the Control field compared to the Dolerite field, however, changes between the two fields are not significant due to the great variability across the sampled sites. Maximums across the two fields are practically identical, but the Dolerite field shows significantly lower values at some of the studied sites compared to the Control site.

The abundance of nematodes in soil of the Control and Dolerite fields was similar

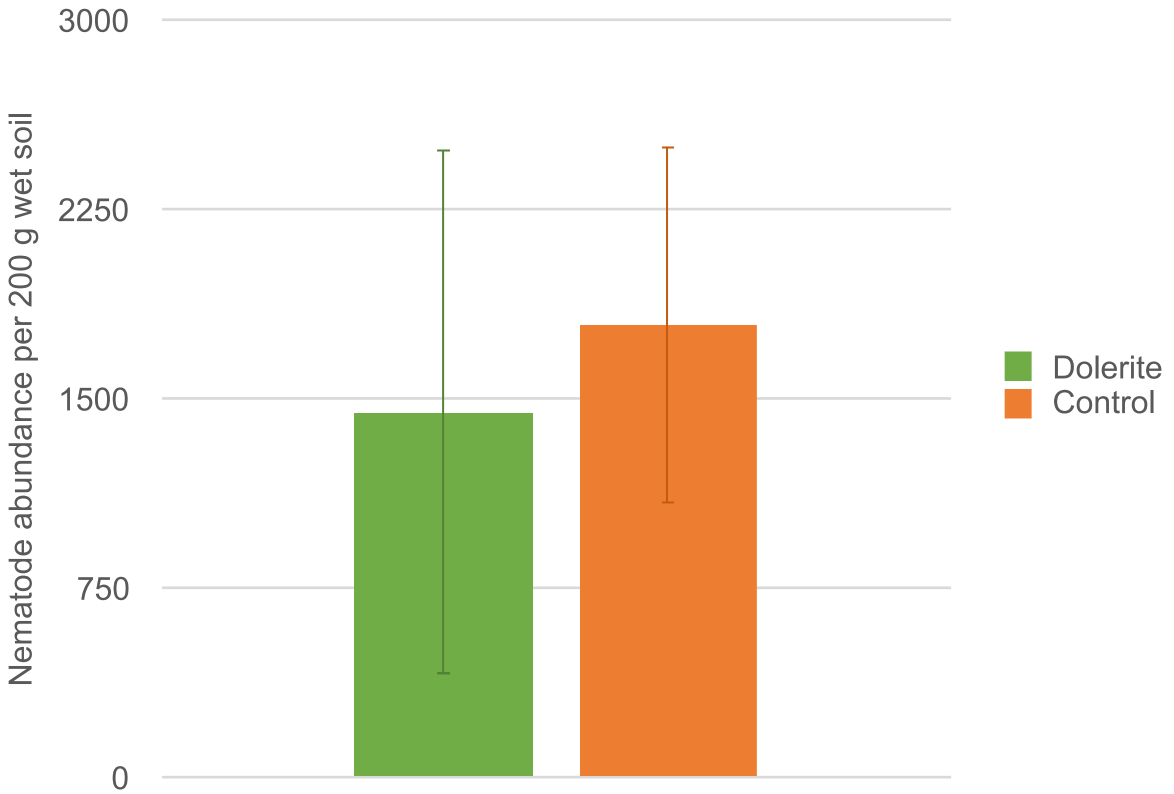


Figure 16 Nematode abundance in soil samples obtained from the Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

3.3.Analysis package 3: soil physics

Particle Size Distribution

The soil particle size distribution according to standard geotechnical procedures.

In total, 18 soil cores were processed:
- 9 from the Control field
- 9 from the Dolerite field

The data presented in Figure 17 shows the percentage of dry mass of soil fractions below <2 mm categorised in fractions of coarse sand (2 mm to 0.6 mm), medium sand (0.6-0.212 mm), fine sand (0.212-0.063 mm) and fines <0.063 mm, which are composed of silt and clay.

The data shows the particle size distribution of the Control and Dolerite fields was similar, although great variability is observed across samples of the same field. Particle size distribution of the crushed rock differs significantly from that of the soil. Particles of fresh rock larger than 2 mm were identified at all depths of the top 10 cm.

This highlights the potential of the material to produce changes in the particle size distribution of the top 10 cm.

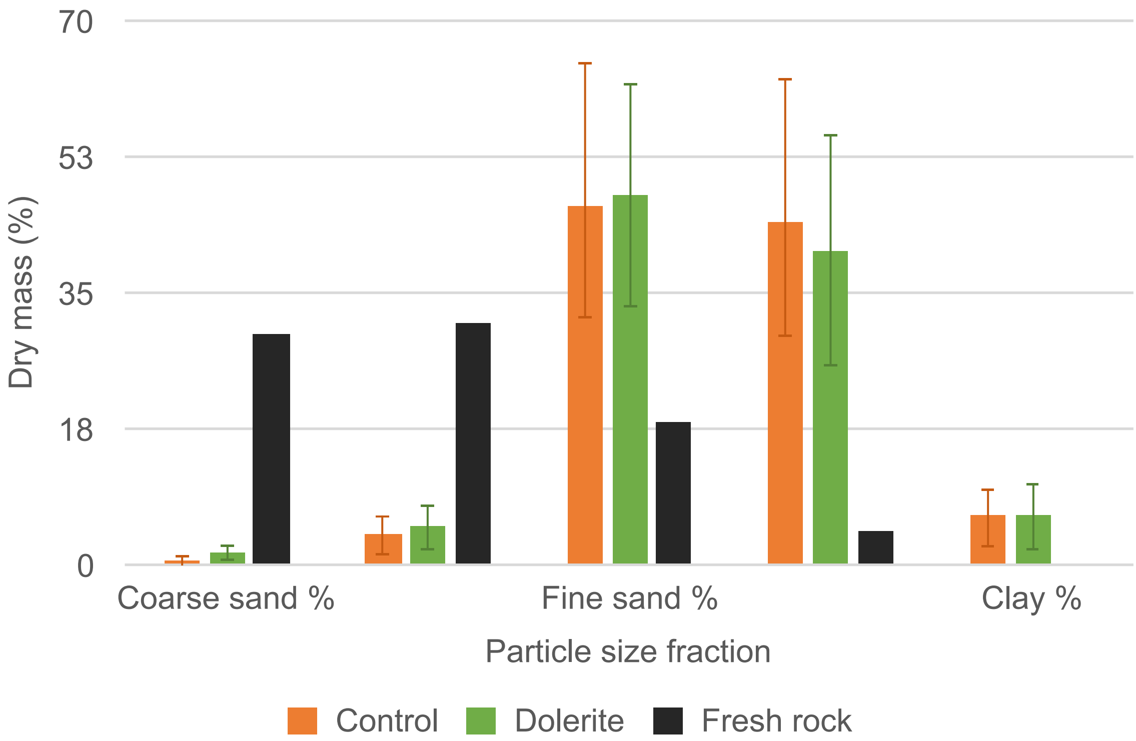


Figure 17 Soil granulometry of Control and Dolerite fields and the fresh rock.

Penetration resistance

The resistance of soil to penetration was determined in situ at the Control and Dolerite fields of Rotmell. In total, 54 in situ tests were conducted.

The data presented in Figure 18 shows the blow counts necessary to penetrate the cone to a specific depth up to 30 cm. The data shows the penetration resistance increases with depth, in accordance with higher compaction levels. Along the root zone (<10 cm depth) soils of both fields are significantly softer than at deeper depths. Soils of the Dolerite field show higher resistance around the 9-11 cm depth.

Overall, significant variability across the analysed sites within the same field is observed and no apparent changes attributable to the rock amendment are apparent.

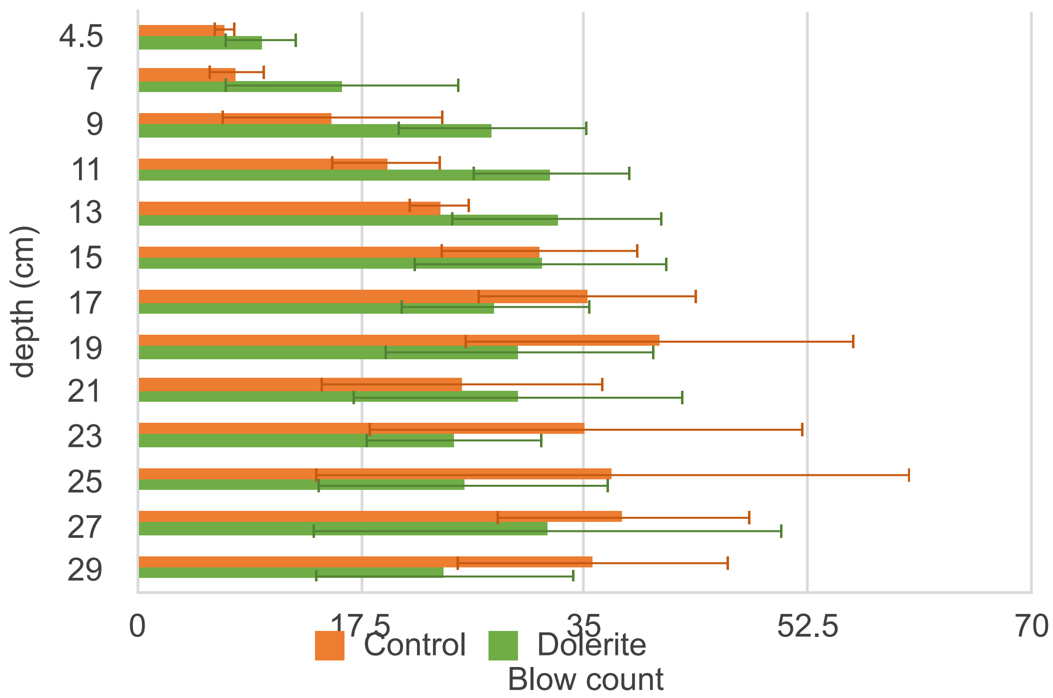


Figure 18 Soil penetration resistance presented as the number of blow counts required to penetrate to a certain depth of Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

Shear resistance

The soil resistance to shear was determined in situ at the Control and Dolerite fields of Rotmell. In total, 54 in situ tests were conducted.

The data presented in Figure 19 shows the soil resistance to an applied torque at specific depth up to 30 cm. The data shows the soil resistance increases with depth, in accordance with higher compaction levels. Along the root zone (<10 cm depth) and up to 15 cm depth, soils of both fields show similar resistance values. Soil from the Dolerite field show slightly higher resistance up to 7.5 cm; however, these differences are small.

Overall, no effect on shear resistance is apparent.

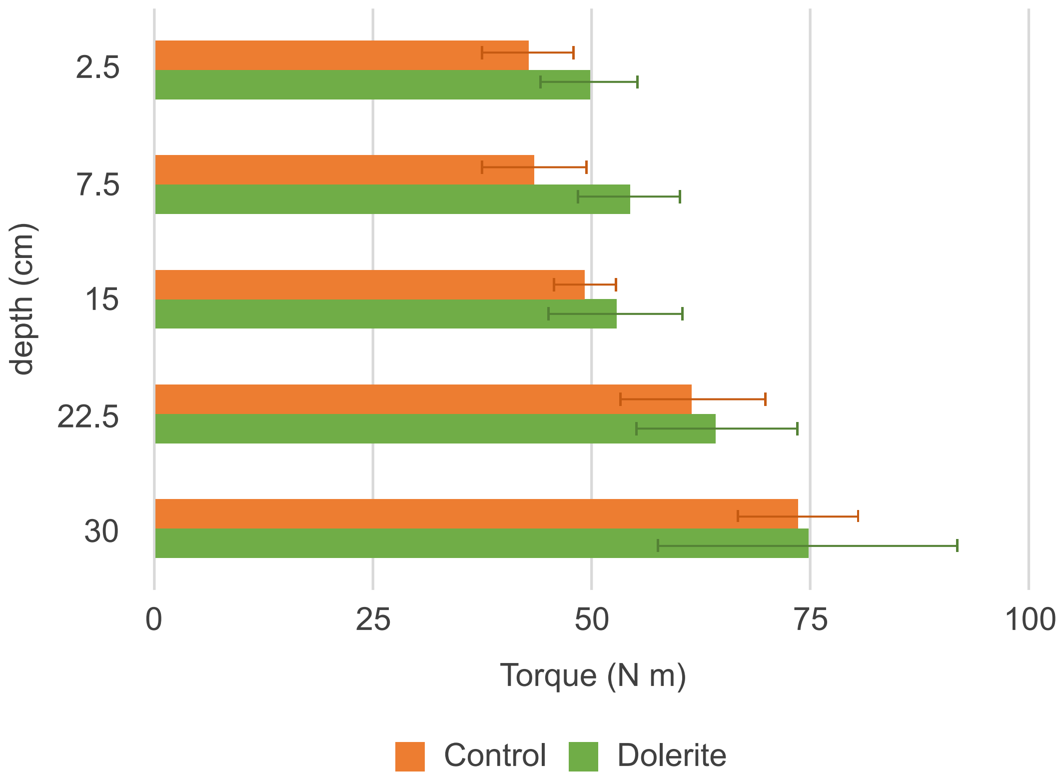


Figure 19 Soil resistance to shear expressed as the torque required to tear the soil at certain depths of the Control field and field treated with 20 t/ha of crushed Dolerite. Data presented is the average and standard deviation of 9 sampling locations in each field.

3.4.Analysis package 4: the inorganic carbon cycle

In soil as a mineral

The soil total inorganic carbon (TIC) in the form of the mineral calcite ($CaCO_3$) was determined by the Coulometer technique. The TIC content was determined in worm casts and at two soil depths, 5 and 10 cm. The worm casts were obtained from the soil surface.

The data presented in Figure 20 shows the TIC content in percentage of dry mass of found in worm casts and the soil top 10 cm. The data shows the TIC content of the Control and Dolerite fields was not apparently different. The graph shows the TIC content of worm casts from the surface and the top 5 cm were similar, and the TIC content decreases slightly with depth. However, these changes are not significant.

Note: Studies at greater depth should be conducted.

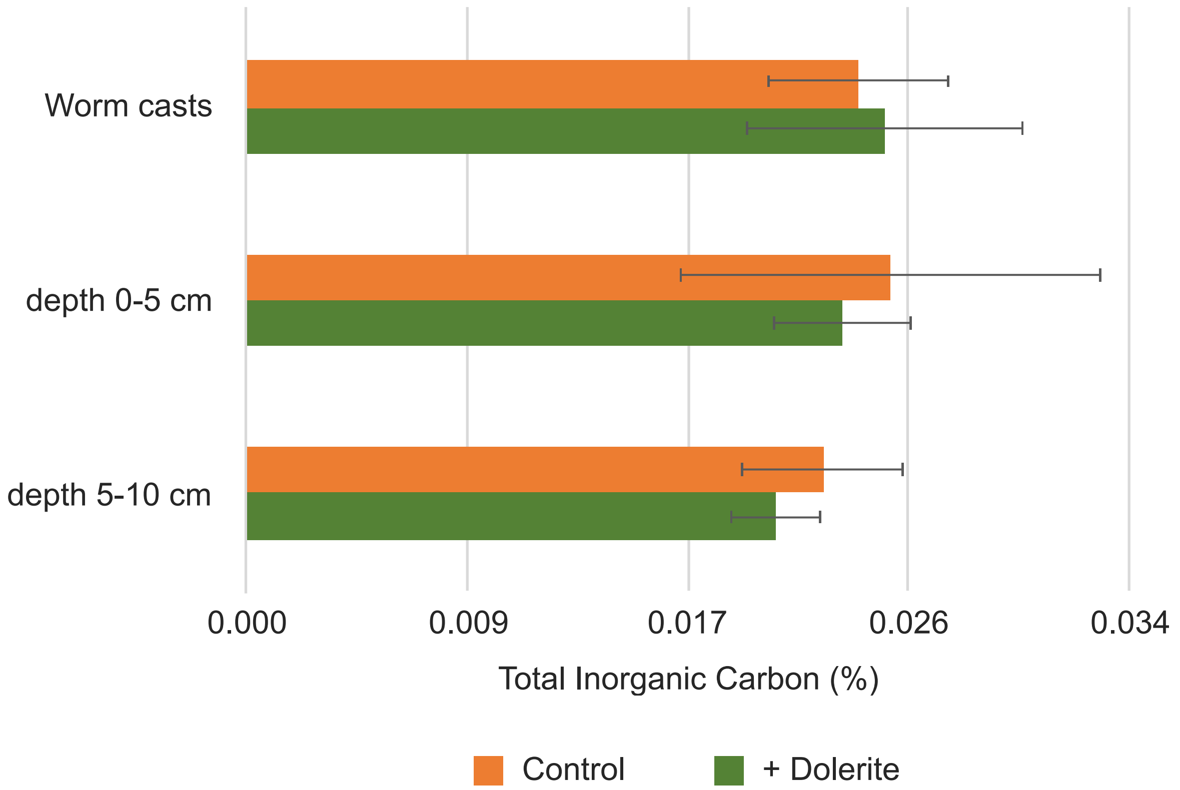


Figure 20 Total Inorganic Carbon (TIC) content in worm casts collected at the soil surface, and at soil depths 0-5 cm and 5-10 cm of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average and standard deviation of 9 sampling locations in each field.

In the soil-water interphase: alkalinity

The soil alkalinity was determined at depths 0 to 5 cm and 5 to 10 cm. This was conducted in moist conditions at low liquid to solid ratio to simulate real conditions of the soil in the field. The analysis was conducted at a soil:solution ratio of 2.5.

In total 36 soil samples were analysed:
- 9 soil samples from the Control field from the 0-5 and 5-10 cm depths.
- 9 soil samples from the Dolerite field from the 0-5 and 5-10 cm depths.

Results in Figure 21 reveal the alkalinity of soil samples of the Control and Dolerite fields was similar at both of studied depths, with average values ranging from 13 and 19 mg/L of equivalent dissolved CO_2. Slightly higher values are observed at the top 5 cm with respect to 5-10 cm depth.

Overall, the results indicate no significant difference across the studied sites.

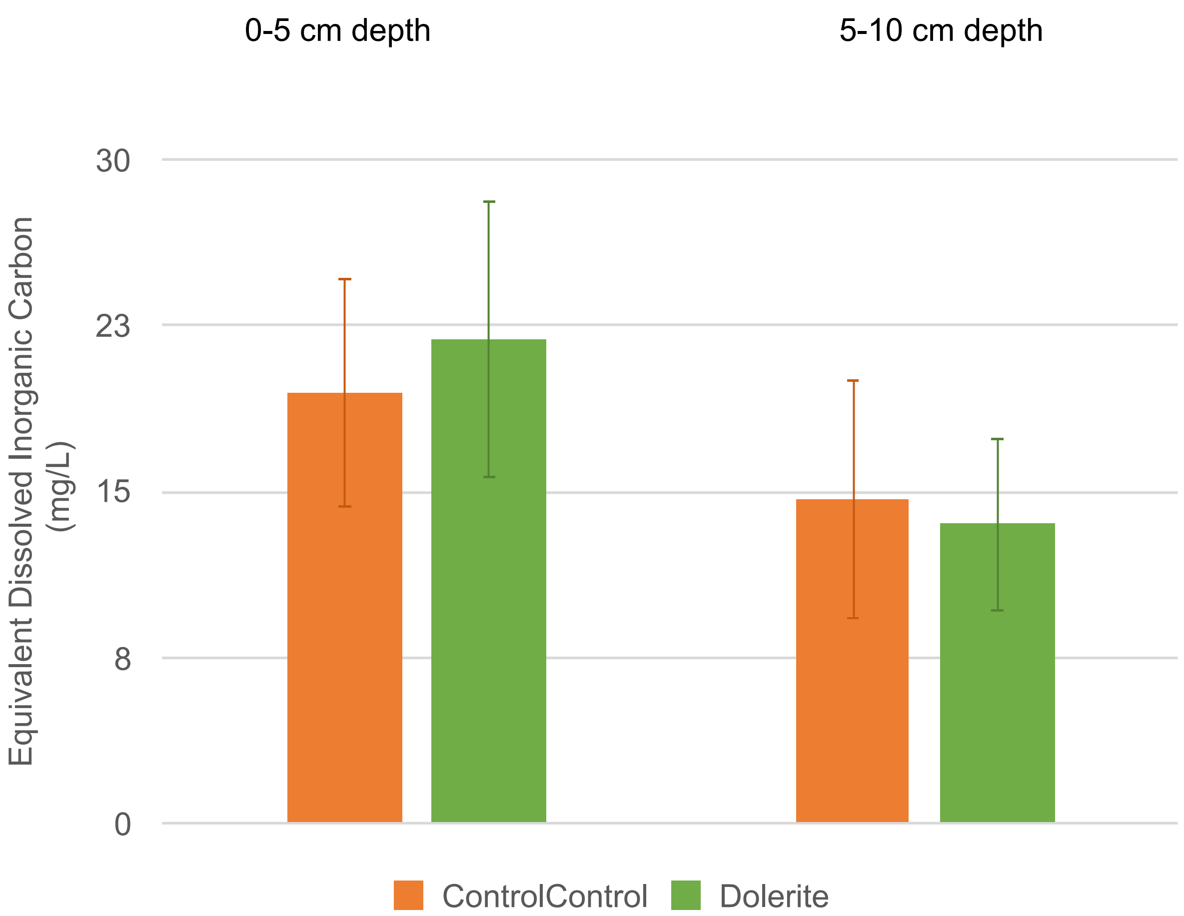


Figure 21 Soil solution alkalinity presented as dissolved CO_2 in water of the Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average and standard deviation of 9 sampling locations in each field.

In water runoff: field drains

The amount of inorganic carbon dissolved in water escaping the system through the field drains was determined in water samples obtained along the field drains indicated in Figure 2 from south (Dolerite field) to north (Control field).

Results in Figure 22 show the amount of inorganic carbon dissolved in water obtained from the field drains. The data reveals significant variability across the different field drains. The variability is observed both between field drains located at the Dolerite and Control fields, and within the field drains of each field. The data is not conclusive.

Note: Samples were obtained at one time point and therefore results are indicative. A more comprehensive sampling campaign should be conducted to draw conclusions. Further, a more comprehensive study of the local underground hydraulic system and the location of the field drains should be conducted.

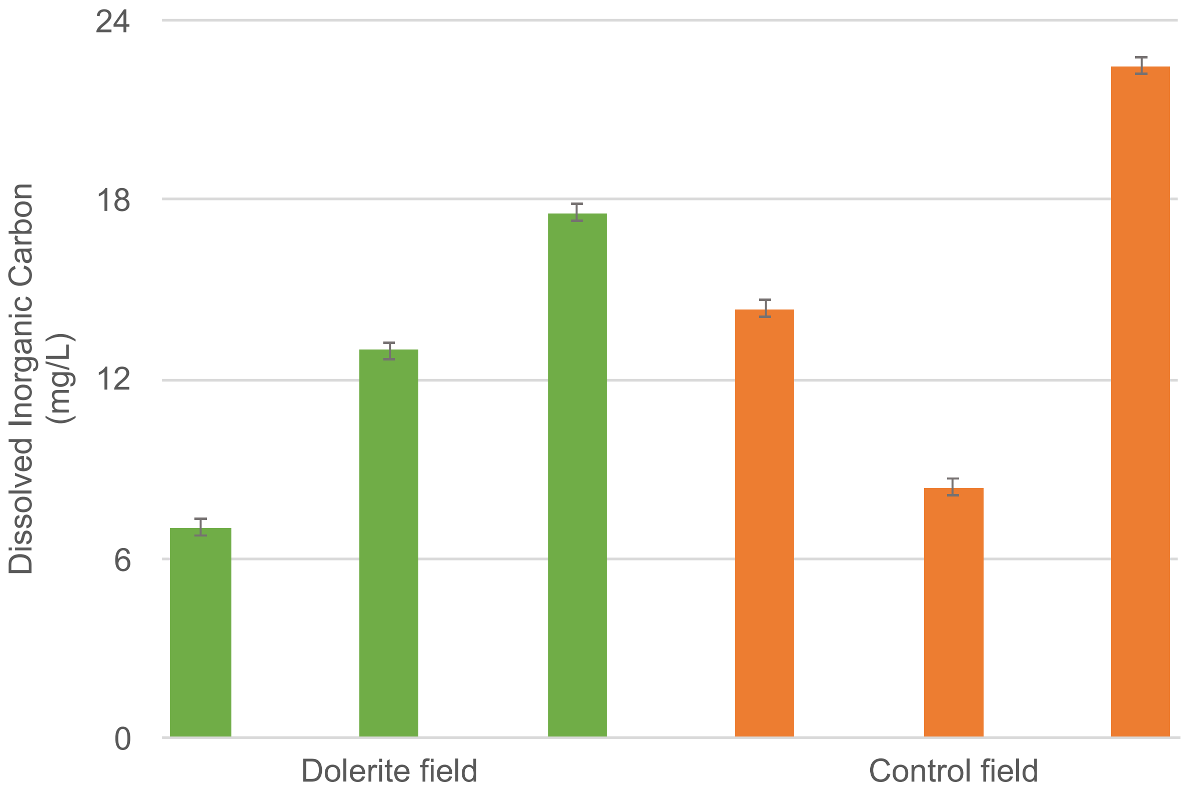


Figure 22 Dissolved inorganic carbon (DIC) content in water samples obtained from the field drains identified in Figure 2. The data presented in each vertical bar, from left to right, correspond to the six sampling locations identified in Figure 2 from south (bottom of figure) to north (top of figure)

In air as a gas:

The soil-atmosphere carbon dioxide fluxes were monitored over a five-month period comprising the mid-summer to autumn. The measure of soil respiration was conducted with a portable carbon dioxide analyser attached to a soil chamber system. Measurements were conducted mostly on a weekly basis.

The data in Figure 21 presents the soil respiration measured at specific time points across the Control and Dolerite fields. The positive fluxes indicate in all cases soil was emitting carbon dioxide. Note this measurement does not account for plant carbon dioxide uptake via photosynthesis. The data shows carbon dioxide emissions were significantly greater in summer and decreased steadily towards autumn. The graph also includes preliminary data from February which shows even lower values. This data is in accordance with annual seasonal fluctuations.

Differences in soil respiration between the Control and Dolerite fields are not apparent.

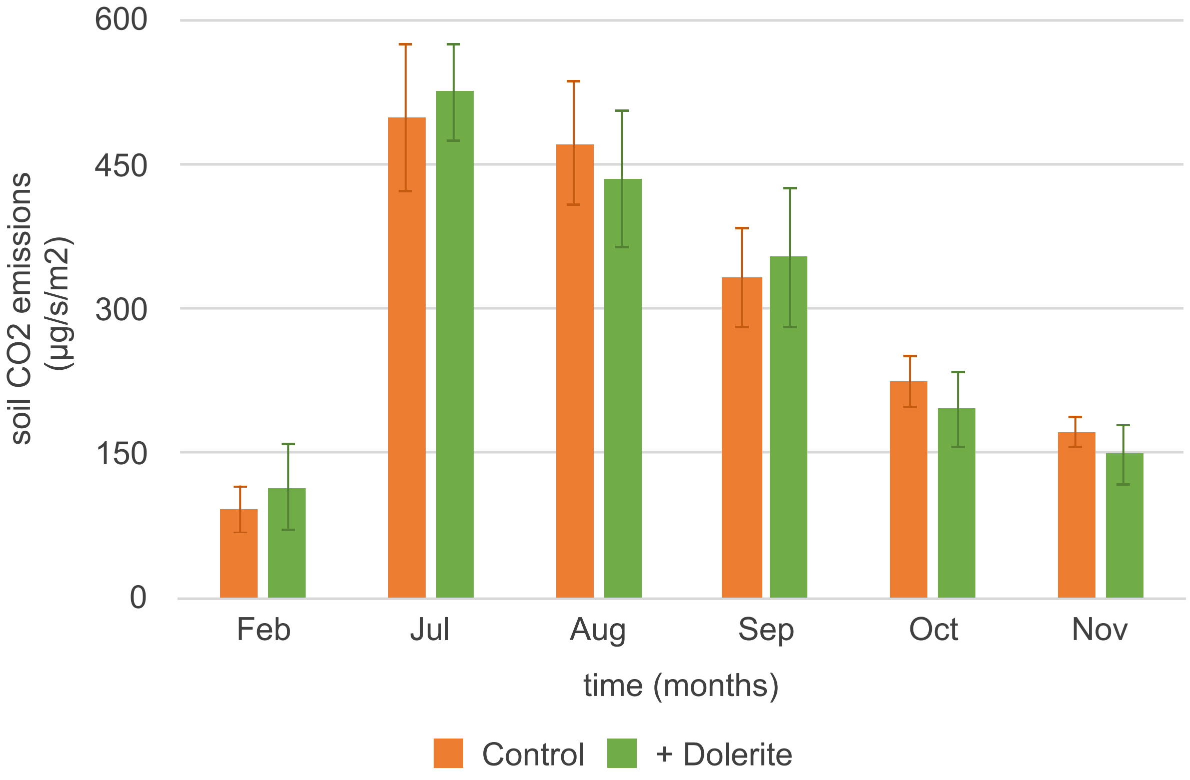


Figure 23 Soil CO_2 emissions presented as monthly average values of Control field and field treated with 20 t/ha of crushed Dolerite. The data presented is the average and standard deviation of 9 sampling locations in each field.

3.5.Detail of analysis

Table 1 List and detail of analyses (see below)

Package	Type of sample	Analysis detail	Laboratory	Technique
1	Soil	Soil mineralogy	James Hutton Institute	X-Ray Diffraction
1	Soil	Soil chemistry: coarse chemical elemental composition	James Hutton Institute	X-Ray Fluorescence
1	Soil	Digestion of soil samples for determination of chemical elements	James Hutton Institute	Aqua Regia Digestion
1	Soil	Soil chemistry: trace chemical elemental composition	James Hutton Institute	ICP-OES
1	Soil	Total Organic Carbon and Nitrogen in soil	James Hutton Institute	Elemental Analysis
1	Soil-water	pH of the soil-water solution	Abertay University	pH meter
1	Soil-water	Electrical conductivity of the soil-water solution	Abertay University	EC meter
1	Soil-water	Major extractable chemical elements of the soil-water interphase	James Hutton Institute	Ammonium acetate extraction
1	Soil-water	Determination of elements: Al As Ba B Ca Cr Cu Cd Fe Hf K Li Mg Mo Mn Na Ni P Pb Sr S Sb Se Si Sn Sr Ti V Zn Zr + In	James Hutton Institute	ICP-OES
1	Soil-water	Determination of elements: F, Br, Cl, NO3 and SO4 extracted in H2O	James Hutton Institute	Ion Chromatograph y
1	Soil-water	Extraction of Nitrogenous compounds	James Hutton Institute	1M KCl Extraction
1	Soil-water	Determination of soil nitrogenous compounds: TON, NH4 and NO2 (KCl matrix)	James Hutton Institute	Discrete analyser
1	Soil	Sample preparation: drying, sieving, grinding and milling.	Abertay University	Standard methods
1	Soil-water	Determination of Phosphate content (PO4) from Water extract	James Hutton Institute	Discrete analyser
1	Plant	Plant productivity: dry mass plant	Abertay University	Standard methods
1	Plant	Sample preparation: drying, sieving and milling.	James Hutton Institute	Standard methods
1	Plant	Total Organic Content and Nitrogen in plants	James Hutton Institute	Elemental Analyser
1	Plant	Digestion of plant samples	James Hutton Institute	Aqua Regia digestion

1	Plant	Determination of elements: Al As Ba B Ca Cr Cu Cd Fe Hf K Li Mg Mo Mn Na Ni P Pb Sr S Sb Se Si Sn Sr Ti V Zn Zr + In	James Hutton Institute	ICP-OES
1	Root	Root productivity: dry mass of roots	Abertay University	Standard methods
1	Root	Sample preparation: drying, sieving, grinding and milling.	Abertay University	Standard methods
1	Root	Total Organic Carbon and Nitrogen in roots	James Hutton Institute	Elemental Analyser
1	Root	Digestion of root samples for determination of chemical elements	James Hutton Institute	Aqua Regia digestion
1	Root	Determination of elements: Al As Ba B Ca Cr Cu Cd Fe Hf K Li Mg Mo Mn Na Ni P Pb Sr S Sb Se Si Sn Sr Ti V Zn Zr + In	James Hutton Institute	ICP-OES/MS
1	Plant	Plant leaves reflectance	NERC FSF Edinburgh University	Spectroscopy
2	Soil	Microbial abundance	Forschungszentrum Juelich	Biomass C and N
2	Soil	Microbial diversity (fungi, bacteria)	Fields4Ever	DNA sequencing
2	Soil	Nematodes abundance, diversity and functionality	James Hutton Institute Dundee	Abundance
3	Soil	Bulk density	Abertay University	Standard methods
3	Soil	Water infiltration (percolation)	Abertay University	Not conducted
3	Soil	In situ determination of soil shear resistance	Abertay University	Vane test
3	Soil	In situ determination of the dynamic penetration resistance	Abertay University	Dynamic Penetration
3	Soil	Particle size distribution I	Abertay University	Soil pre-treatment

3	Soil	Particle size distribution II	Abertay University	Sedimentation by hydrometer
4	Worm cast	TIC in mineral form as Carbonates	Edinburgh University	Coulometer
4	Worm cast	Carbonate stable isotopes	Forschungszentrum Juelich	EA-IRMS
4	Soil	TIC in the mineral form as Carbonates	Edinburgh University	Coulometer
4	Soil	Carbonate stable isotopes	Forschungszentrum Juelich	EA-IRMS
4	Soil-water	Alkalinity	Abertay University	Titrimetry
4	Water	Dissolved Inorganic Carbon	Edinburgh University	Coulometer
4	Soil	pH	Abertay University	pH meter
4	Air	Soil CO_2 fluxes	Field	Gas chamber NDIR LICOR 8100

4. Application Prototype

4.1.The app in screenshots

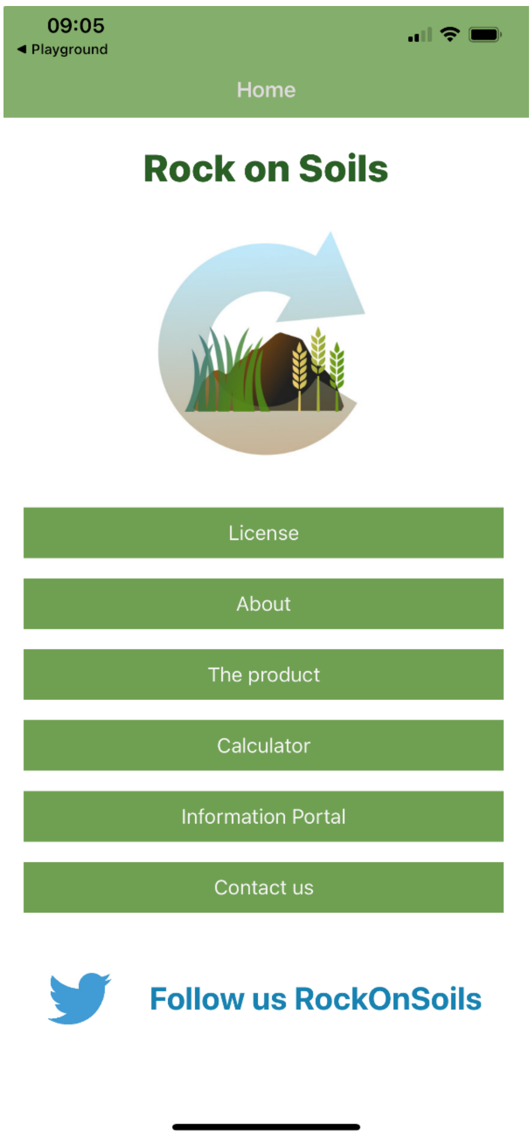
The home page

Summary functions:

- Present the app theme and the logo of the project
- Integrate all the different pages of the app and organised them as a list of buttons.
- Include a direct link to the project twitter account.

The license page

The license was developed by lawyers of Abertay University in accordance with the App characteristics, as provided by the app development team of Abertay and the James Hutton Institute. The full terms and conditions can be found in section 4.4.



Background information

The background information on the project and on crushed basic igneous silicate rock is provided in the About and the Product pages shown in Figure 22.

Summary information:

- The About page (Figure 22 left) informs the user on the project overarching goal, the institutions involved and the project funders.
- The Product page (Figure 22 right) provides basic background information on the product, including its constituent chemical elements, the weathering of the material, Carbon Capture and Storage (CCS) and the rock's CCS capacity.

Figure 25 The about page (left) and the product page (right).

External links

Links to external sources are included in the Home and the About pages. Figure 23 shows two examples.

Summary of links:

- The Home page includes a link to the twitter account (Figure 23 left). If the user's phone has the twitter app installed, this link allows the user to move to the twitter app where they are redirected to the project twitter account @RockOnSoils.
- The About page includes links to the partner organisations websites and a link to the project website on the European Commission EIP-AGRI website (Figure 23 right).

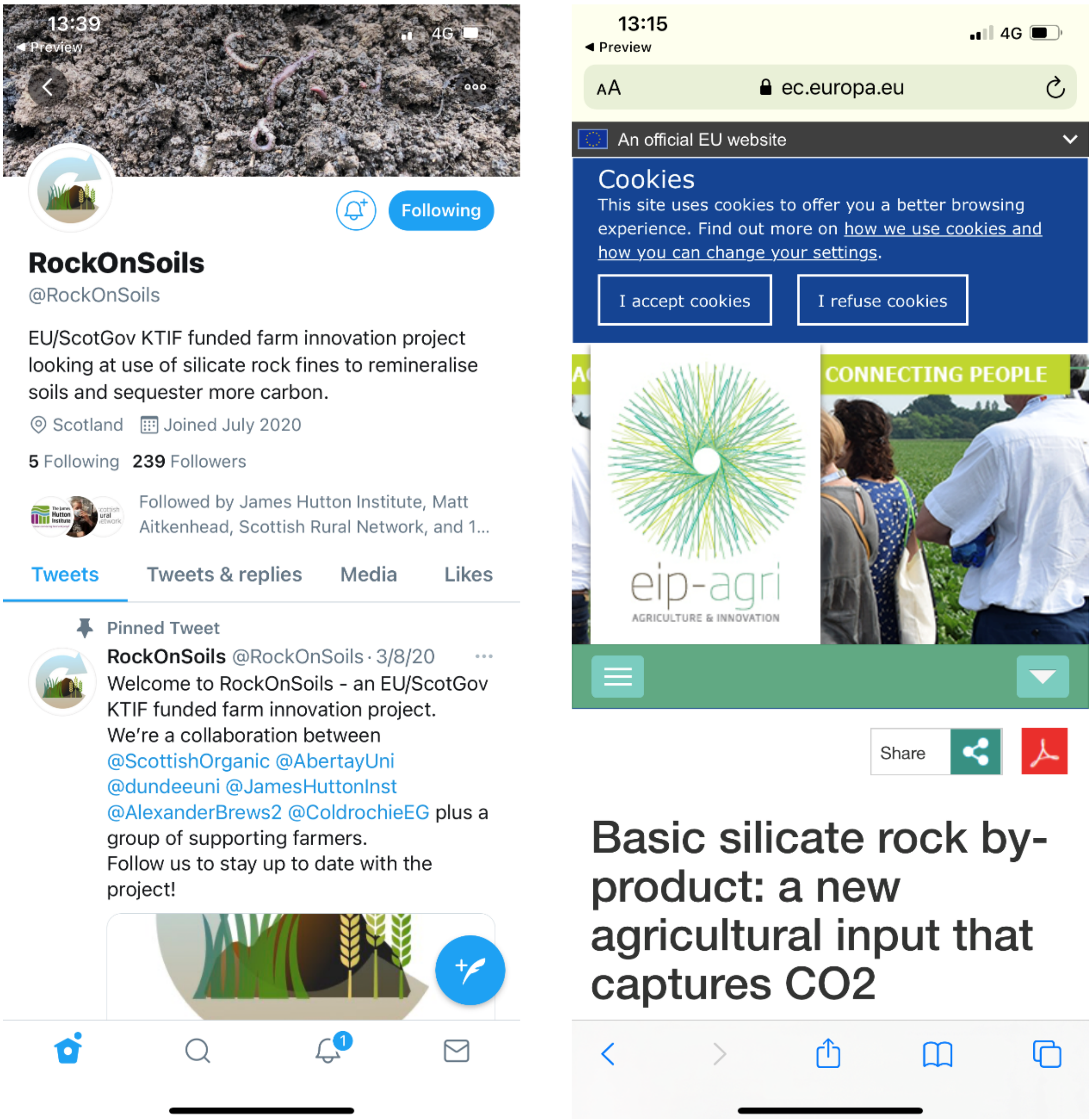


Figure 26 External links to twitter account (left) and to the projects' website on the EU EIP-Agri website (right).

The Carbon Captures & Storage (CCS) calculator

Summary functions:

- Display a form to allow the user to enter the relevant input parameters in an ordered manner. Data is entered via text boxes and scrolling lists.
- Integrate the input data to produce estimates of CCS annually and in total.
- Interact with the user responding to input data by displaying the output data instantaneously on the form. Examples of this interactive responsive mode are the title or the CCS calculations.
- Access to the phone's camera and GPS location.
- Store the input and resulting data in a list of records for later access by the user.
- Figure 24 shows an example of the form to fill in to add a record.

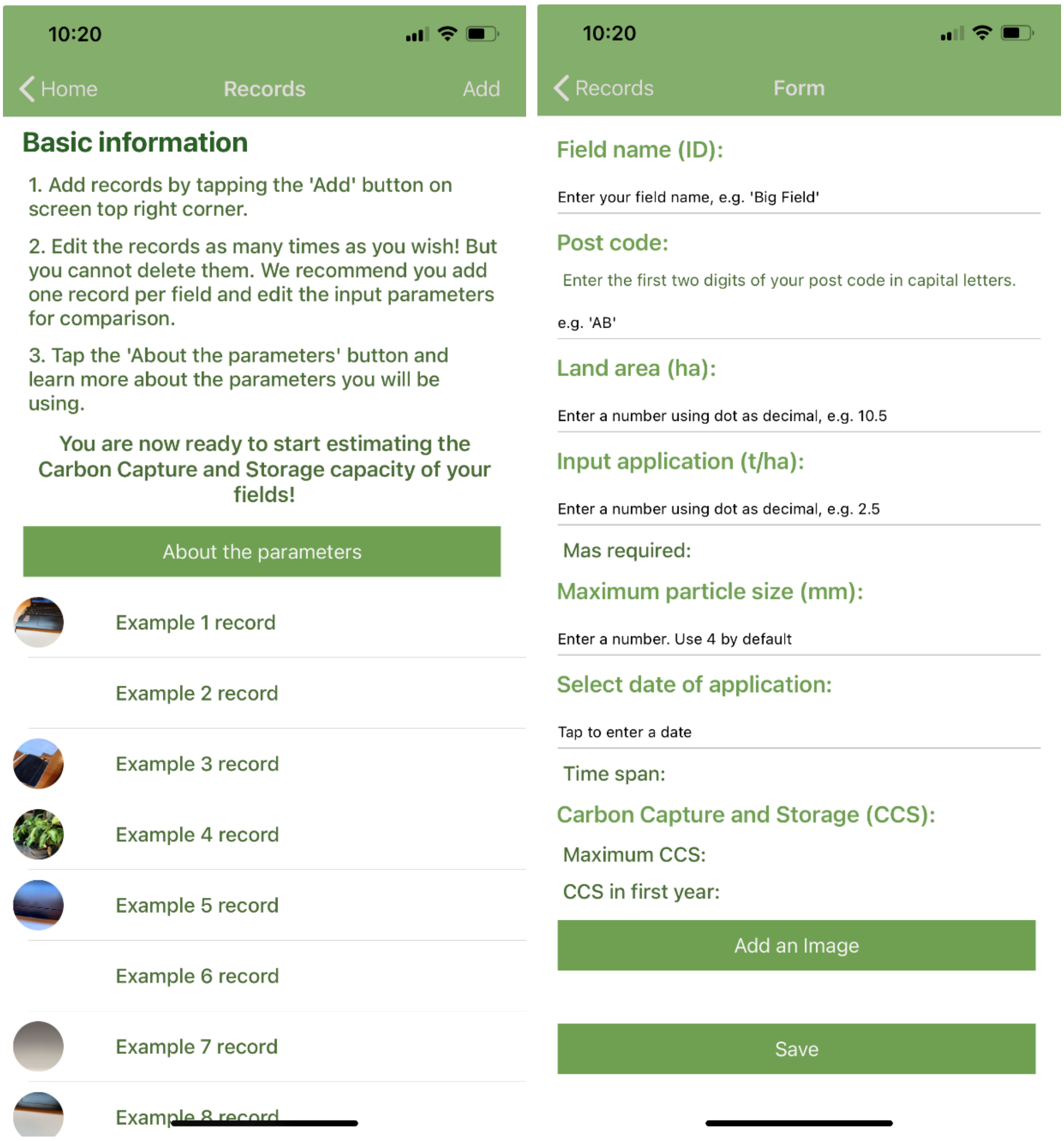


Figure 27 The Records page and the Calculator form.

The Information Portal

Summary functions:

- Compile relevant sources of information beyond the crushed basic igneous rock product and integrate them in a single page (Figure 25 left). These include sources of information of geology, soil, plants and fauna related the rural environment.
- Link national organisations, including societies, formation portals and public institutions portals with the app and access the information contained in their websites through external links embedded in the organisations' logos.
- Grant access to publicly available datasets included in the listed organisations through the navigation in the external links provided.

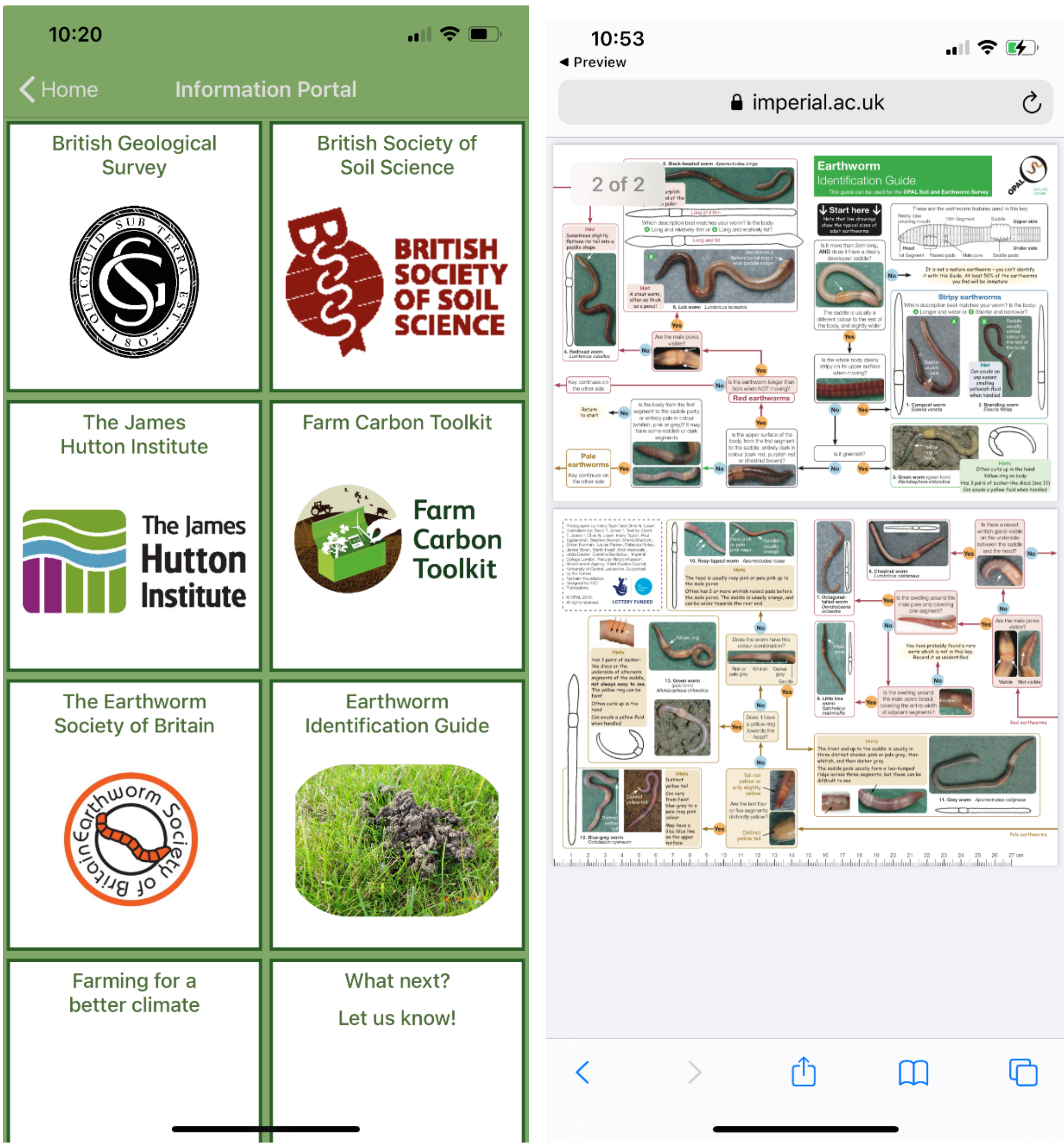


Figure 28 Information portal (left) and example of external link to the Earthworm Identification Guide (right).

4.2.The CCS mathematical model

The Carbon Capture and Storage (CCS) capacity of the dolerite amendment is estimated using the mathematical model implemented in the app as:

Equation 1

$$F = 0.05 + (0.002T + 0.00013R + 0.97e^{-0.15M})^2$$

Equation 2

$$CCS_1 = F \, x \, CCS_{max}$$

Equation 3

$$CCS_{max} = 0.084I \, x \, A$$

Where F is the fraction of the total carbon capture and storage capacity sequestered the first year, T is the annual mean temperature (in ºC), R is the annual mean rainfall (in mm), M is the maximum particle size of the applied material (in mm), CCS_1 is the Carbon Capture and Storage capacity of the first year following application (in tonnes). CCS_{max} is the maximum Carbon Capture and Storage capacity of the applied amendment when all the material has reacted (in tonnes), I is the input application rate (in tonnes per hectare) and A is the area of land where the material is applied (in hectares).

The environmental parameters annual mean rainfall and temperature are estimated form the first two digits of the user postcode (e.g. “AB”).

4.3.Organisations listed in the Information Portal

The organisations listed in Table 2 were contacted to request a logo and permission to use a link to the respective websites. The list of organisations included in the App Information Portal was defined by the app development team in conjunction with the project manager and project lead.

Table 2 List of organisations included in the App Information Portal.

Organisation name	Embedded web link in logotype
The British Geological Survey	https://www.bgs.ac.uk/
The British Society of Soil Science	https://soils.org.uk/
The James Hutton Institute	https://www.hutton.ac.uk/learning/soilshutton
The Farm Carbon Toolkit	https://www.farmcarbontoolkit.org.uk/
The Earthworm Society of Britain	https://www.earthwormsoc.org.uk/identification
The Earthworm Identification Guide	https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/opal/SOIL-4pp-chart.pdf
Farming for better Climate programme	https://www.farmingforabetterclimate.org

4.4.App license

PLEASE READ THESE LICENCE TERMS CAREFULLY

BY USING THIS APP YOU AGREE TO THESE TERMS WHICH WILL BIND YOU.

IF YOU DO NOT AGREE TO THESE TERMS, DO NOT USE THIS APP.

WHO WE ARE AND WHAT THIS AGREEMENT DOES

We Abertay University of Kydd Building, Bell Street, Dundee license you to use:

- RockOnSoils mobile application software (**App**) and any updates or supplements to it.
- The service you connect to via the App and the content we provide to you through it (**Service**).

as permitted in these terms.

YOUR PRIVACY

We will not collect any personal data through your use of the App and the Services.

Please be aware that internet transmissions are never completely private or secure and that any message or information you send using the App or any Service may be read or intercepted by others, even if there is a special notice that a particular transmission is encrypted.

HOW TO TELL US ABOUT PROBLEMS

If you want to learn more about the App or the Service or have any problems using them please contact us by email c.comadran-casas@abertay.ac.uk.

HOW YOU MAY USE THE APP, INCLUDING HOW MANY DEVICES YOU MAY USE IT ON

In return for your agreeing to comply with these terms you may:

- download or stream a copy of the App and view, use and display the App and the Service on such devices for your personal purposes only.
- use any Documentation to support your permitted use of the App and the Service.

YOU MUST BE 18 TO ACCEPT THESE TERMS AND BUY THE APP

You must be 18 or over to accept these terms and buy the App.

YOU MAY NOT TRANSFER THE APP TO SOMEONE ELSE

We are giving you personally the right to use the App and the Service. You may not otherwise transfer the App or the Service to someone else, whether for money, for anything else or for free. If you sell any device on which the App is installed, you must remove the App from it.

CHANGES TO THESE TERMS

We may need to change these terms to reflect changes in law or best practice or to deal with additional features which we introduce. We will give you at least 30 days notice of any change with details of the change or notifying you of a change when you next start the App.

If you do not accept the notified changes you will not be permitted to continue to use the App and the Service.

IF SOMEONE ELSE OWNS THE PHONE OR DEVICE YOU ARE USING

If you download or stream the App onto any phone or other device not owned by you, you must have the owner's permission to do so. You will be responsible for complying with these terms, whether or not you own the phone or other device.

WE MAY COLLECT TECHNICAL DATA ABOUT YOUR DEVICE

You agree that in installing the app we will have access to limited technical data during the installation process. Following installation we will delete all technical data.

WE ARE NOT RESPONSIBLE FOR OTHER WEBSITES YOU LINK TO

The App or any Service may contain links to other independent websites which are not provided by us. Such independent sites are not under our control, and we are not responsible for and have not checked and approved their content or their privacy policies (if any).

You will need to make your own independent judgement about whether to use any such independent sites, including whether to buy any products or services offered by them.

LICENCE RESTRICTIONS

You agree that you will:

- not rent, lease, sub-license, loan, provide, or otherwise make available, the App or the Services in any form, in whole or in part to any person without prior written consent from us;
- not copy the App, Documentation or Services, except as part of the normal use of the App or where it is necessary for the purpose of back-up or operational security;
- not translate, merge, adapt, vary, alter or modify, the whole or any part of the App, Documentation or Services nor permit the App or the Services or any part of them to be combined with, or become incorporated in, any other programs, except as necessary to use the App and the Services on devices as permitted in these terms;
- not disassemble, de-compile, reverse engineer or create derivative works based on the whole or any part of the App or the Services nor attempt to do any such things, except to the extent that (by virtue of sections 50B and 296A of the Copyright, Designs and Patents Act 1988) such actions cannot be prohibited because they are necessary to decompile the App to obtain the information necessary to create an independent program that can be operated with the App or with another program (**Permitted Objective**), and provided that the information obtained by you during such activities:
    - is not disclosed or communicated without the Licensor's prior written consent to any third party to whom it is not necessary to disclose or communicate it in order to achieve the Permitted Objective; and
    - is not used to create any software that is substantially similar in its expression to the App;
    - is kept secure; and
    - is used only for the Permitted Objective;
- comply with all applicable technology control or export laws and regulations that apply to the technology used or supported by the App or any Service.

ACCEPTABLE USE RESTRICTIONS

You must:

- not use the App or any Service in any unlawful manner, for any unlawful purpose, or in any manner inconsistent with these terms, or act fraudulently or maliciously, for example, by hacking into or inserting malicious code, such as viruses, or harmful data, into the App, any Service or any operating system;

- not infringe our intellectual property rights or those of any third party in relation to your use of the App or any Service, including by the submission of any material (to the extent that such use is not licensed by these terms);
- not transmit any material that is defamatory, offensive or otherwise objectionable in relation to your use of the App or any Service;
- not use the App or any Service in a way that could damage, disable, overburden, impair or compromise our systems or security or interfere with other users; and
- not collect or harvest any information or data from any Service or our systems or attempt to decipher any transmissions to or from the servers running any Service.

INTELLECTUAL PROPERTY RIGHTS

All intellectual property rights in the App, the Documentation and the Services throughout the world belong to us (or our licensors) and the rights in the App and the Services are licensed (not sold) to you. You have no intellectual property rights in, or to, the App, the Documentation or the Services other than the right to use them in accordance with these terms.

OUR RESPONSIBILITY FOR LOSS OR DAMAGE SUFFERED BY YOU

You acknowledge that this App is provided without charge by a charitable organisation and agree that the following limitations on liability are reasonable.

We are responsible to you for foreseeable loss and damage caused by us. If we fail to comply with these terms, we are responsible for loss or damage you suffer that is a foreseeable result of our breaking these terms or our failing to use reasonable care and skill, but we are not responsible for any loss or damage that is not foreseeable. Loss or damage is foreseeable if either it is obvious that it will happen or if, at the time you accepted these terms, both we and you knew it might happen.

We do not exclude or limit in any way our liability to you where it would be unlawful to do so. This includes liability for death or personal injury caused by our negligence or the negligence of our employees, agents or subcontractors or for fraud or fraudulent misrepresentation.

When we are liable for damage to your property. We will not be liable for damage that you could have avoided by following our advice to apply an update offered to you free of charge or for damage that was caused by you failing to correctly follow installation instructions or to have in place the minimum system requirements advised by us.

We are not liable for business losses. The App is for domestic and private use in the UK only. If you use the App for any commercial, business or resale purpose we will have no liability to you for any loss of profit, loss of business, business interruption, or loss of business opportunity.

Our losses to you are capped. You agree that our total aggregate liability to you in relation to these licence terms shall not exceed £100.

Limitations to the App and the Services. The App and the Services are provided for general information purposes only. They do not offer advice on which you should rely. You must obtain professional or specialist advice before taking, or refraining from, any action on the basis of information obtained from the App or the Service. Although we make reasonable efforts to update the information provided by the App and the Service, we make no representations, warranties or guarantees, whether express or implied, that such information is accurate, complete or up to date.

Please back-up content and data used with the App. We recommend that you back up any content and data used in connection with the App, to protect yourself in case of problems with the App or the Service.

Check that the App and the Services are suitable for you. The App and the Services have not been developed to meet your individual requirements.

We are not responsible for events outside our control. If our provision of the Services or support for the App or the Services is delayed by an event outside our control then we will contact you as soon as possible to let you know and we will take steps to minimise the effect of the delay. Provided we do this we will not be liable for delays caused by the event but if there is a risk of substantial delay you may contact us to end your contract with us and receive a refund for any Services you have paid for but not received.

WE MAY END YOUR RIGHTS TO USE THE APP AND THE SERVICES IF YOU BREAK THESE TERMS

We may end your rights to use the App and Services at any time by contacting you if you have broken these terms in a serious way. If what you have done can be put right we will give you a reasonable opportunity to do so.

If we end your rights to use the App and Services:

- You must stop all activities authorised by these terms, including your use of the App and any Services.
- You must delete or remove the App from all devices in your possession and immediately destroy all copies of the App which you have and confirm to us that you have done this.
- We may remotely access your devices and remove the App from them and cease providing you with access to the Services.

WE MAY TRANSFER THIS AGREEMENT TO SOMEONE ELSE

We may transfer our rights and obligations under these terms to another organisation. We will always tell you in writing if this happens and we will ensure that the transfer will not affect your rights under the contract.

YOU NEED OUR CONSENT TO TRANSFER YOUR RIGHTS TO SOMEONE ELSE

You may only transfer your rights or your obligations under these terms to another person if we agree in writing.

If a court finds part of this contract illegal, the rest will continue in force

Each of the paragraphs of these terms operates separately. If any court or relevant authority decides that any of them are unlawful, the remaining paragraphs will remain in full force and effect.

Even if we delay in enforcing this contract, we can still enforce it later

Even if we delay in enforcing this contract, we can still enforce it later. If we do not insist immediately that you do anything you are required to do under these terms, or if we delay in taking steps against you in respect of your breaking this contract, that will not mean that you do not have to do those things and it will not prevent us taking steps against you at a later date.

Which laws apply to this contract and where you may bring legal proceedings

These terms are governed by Scots law and you can bring legal proceedings in respect of the products in the Scottish courts. If you live in England you can bring legal proceedings in respect of the products in either the Scottish or the English courts. If you live in Northern Ireland you can bring legal proceedings in respect of the products in either the Northern Irish or the Scottish courts.

5. Questionnaires

5.1. Questionnaires

Questionnaire 1 - 2nd online workshop

1. Do all the screens show fully in your phone?
2. Does the App crash anywhere?
3. Are the navigational tap buttons clear and easy to use
4. Are the font and image sizes adequate?
5. Do you like the colour scheme? What would be your preferred colour?
6. On the 'calculator' page do you find the ‘input parameters' page useful? What, if anything, would you change?
7. When using the 'calculator', is it easy to access the data input page and once there, is it clear and easy to use? What, if anything would you like to change?
8. Is 'the product' page useful? Is there anything you'd like to see added or removed from there?
9. Do you find the 'education portal' page useful? Is there any information or link NOT currently there that you'd like to see? Would you remove any of the links?
10. Is there any other function or information that you'd like the App to provide?
11. Out of 10, how would you rate the usefulness of the App to your decision making on potentially using crushed silicate rock

Questionnaire 2 - 3rd online workshop

1. In the home page, does the twitter link (icon) work?
2. In the about page, does the “Learn more” button take you to the project website of the European Commission?
3. In the about page, within the sections “Who is involved” and “The funders”, do the links of the tappable icons work?
    4. Note: the Rotmell farm icon does not have any link embedded, therefore nothing should happen when tapped.
5. When using the 'calculator', is it easy to access the data input page and once there, is it clear and easy to use?
6. Does the license screen display well?
7. Have you explored any of the links of the Information Portal? If so, have you encountered any problem?
8. On the calculator form, do you encounter any problem with the calculations? E.g. NaN values, negative values, app crash…?
9. On the calculator form, are all the parameters stored when you revisit a saved record?
10. Out of 10, how would you rate the usefulness of the App to your decision making on potentially using crushed silicate rock?

5.2.Answers

The data obtained from the respondent's answers is presented in Figure 29. Questions 1 to 9 of Questionnaire 1 above were split into 11 question categories shown in the legend (e.g., "Pages display well", "Buttons function well", etc.). Possible answers to these questions were grouped into the following categories: 'No', 'Not really', 'Okay', and 'Yes', and are shown in the horizontal axis. Additionally, the horizontal axis includes the response rate to each of the 11 question categories; and the rate of open responses generated by each question. Open responses are additional comments the respondent included in their answers that were beyond the defined answers, i.e. "Yes", "No", etc, which were analysed separately. The vertical axis informs on the recurrence in percentage.

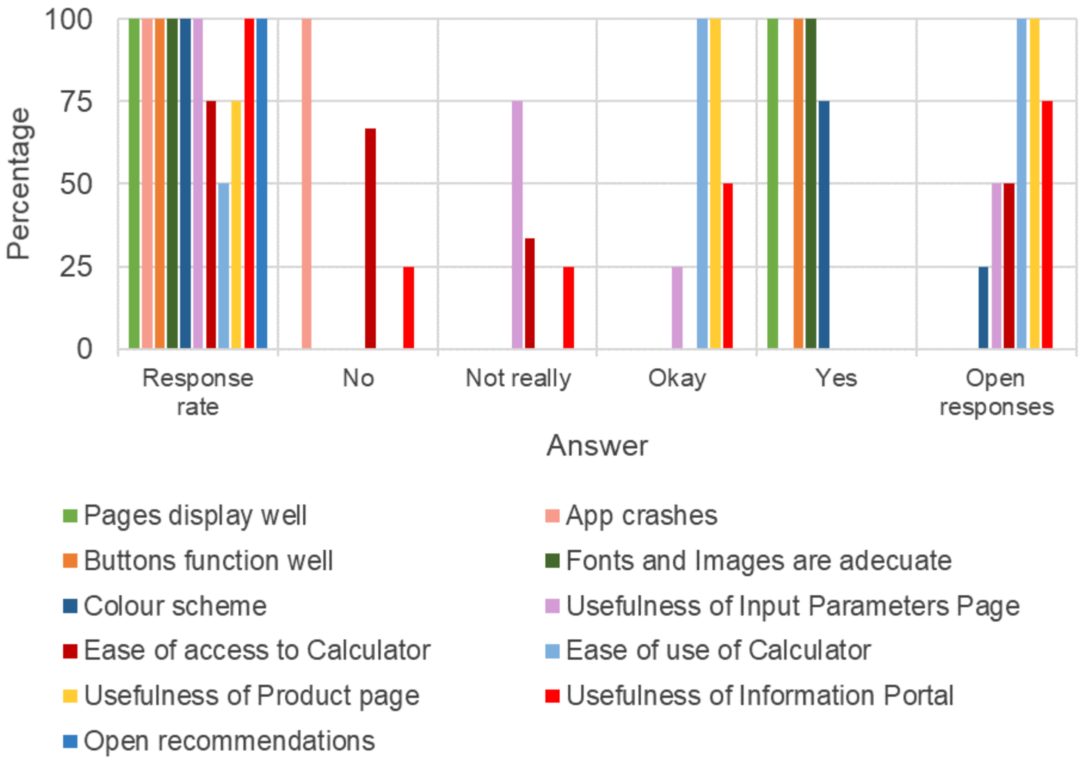


Figure 29 Closed responses to the questionnaire of the online workshop 2. The data was categorised by the questions shown in the legend. The graph horizontal axis organises the data in the "No" to "Yes" scale as possible answers to questions presented in the legend plus the response rate and the rate of open responses of each question category. The vertical axis expresses the occurrence as the frequency of the answer in units of percentage.

Open answers

The data that could not be categorised in pre-defined answers is presented in Figure 27. This group of data comprised of open responses expressed in any of the questions of the questionnaire and included opinions, recommendations, etc. This data was grouped by question as presented in the vertical axis. Figure 30 shows on the one hand the number of respondents that offered an open response, and on the other, the number of open responses, or comments, were isolated for each the questions. Additionally, the graph presents the overall mean rate for the app deducted from the questionnaire.

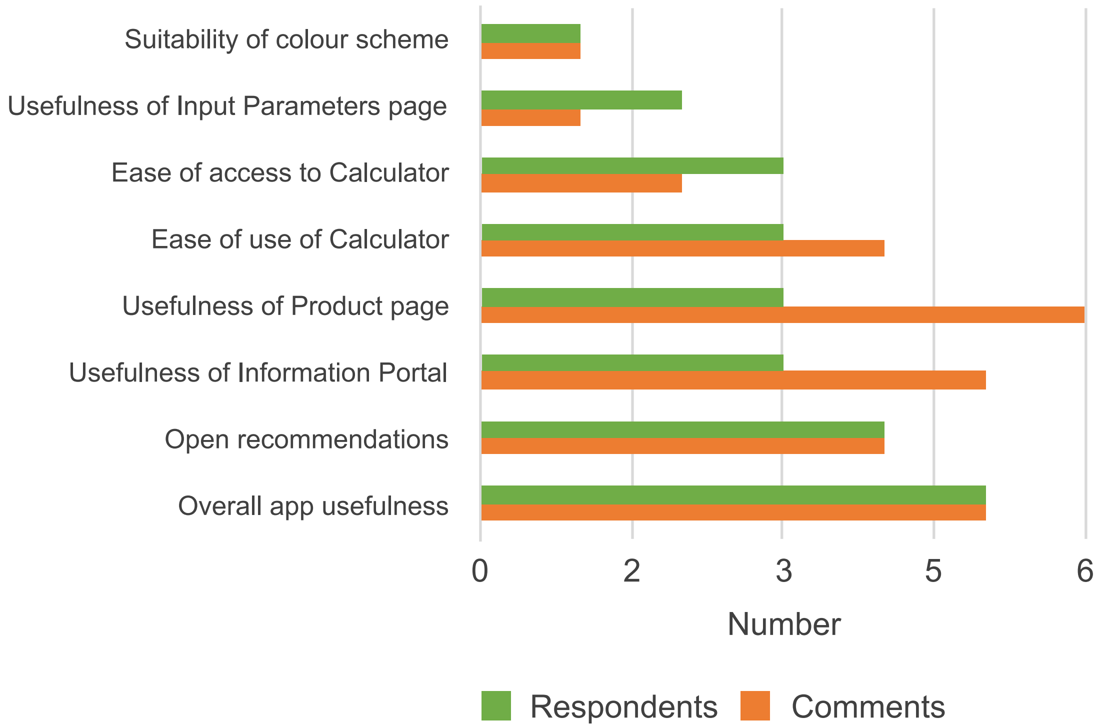


Figure 30 Open responses to the questionnaire of the online workshop 2 categorised by question (vertical axis) and occurrence (horizontal axis) expressed as the number of respondents and number of comments the question generated.

6. Wikipedia page content

Contents

Basic igneous silicate rocks[edit source]

Basic igneous silicate rocks are a subgroup of Igneous Rocks that share the characteristic of having an alkaline or basic pH. Igneous rocks that compose this subgroup are both extrusive and intrusive mafic and ultramafic igneous rocks. Rocks that compose the mafic group are gabbro, dolerite or diabase and basalt, and the ultramafic group are peridotite and komatiite.

Chemical composition[edit source]

Basic igneous silicate rocks are composed of silicon oxides (SiO2), or silica, bound together by metallic ions forming packed three-dimensional crystalline structures named silicate minerals. Isomorphous substitution of silicon ions by aluminium ions renders silicate mineral structures composed of silicon and aluminium oxides. Metallic ions that bind silica structures in basic silicate minerals are calcium (Ca), magnesium (Mg), and iron (Fe), and in minor proportion sodium (Na), manganese (Mn), and potassium (K) among other trace elements. Table 1 shows the chemical composition of basic igneous rocks.

Chemical composition of basic igneous silicate rocks of the Whin Sill (Scotland, UK) [0]

Molecule	Mafic rocks (wt%)	Ultramafic rocks (wt%)
SiO_2	49-51	57-64
Al_2O_3	12-15	12-15
Fe_2O_3	3-5	0.5-2.5
FeO	8-9.5	3-5
CaO	8-10	4-7
MgO	4-6	1-3
Na_2O	2.5	2-8
MnO	0-0.5	0-0.2
K_2O	0-1.5	1-3.5
TiO_2	2-3	1-1.5
P_2O_5	0-0.5	0-0.5

S	0-0.1	0-0.5
H_2O	1-2	1-3

Mineralogy[edit source]

The dominant minerals composing basic igneous silicate rocks are primary silicate minerals of the neosilicates (olivine), inosilicates (pyroxenes), and tectosilicates (plagioclase) groups.

Olivine minerals are composed of silica units bound together by Mg and Fe, with forsterite ($MgSiO_4$) and fayalite (Fe_2SiO_4) being the most common minerals. Pyroxenes minerals abundant in basic igneous silicate rocks are formed by chained silicate structures bound together by Ca, Mg, and Fe. Augite, ferroaugite, and pigeonite are the common solid solutions and representative end members of this group are wollastonite ($CaSiO_3$), diopside ($CaMgSi2O_6$), hedenbergite ($CaFeSi_2O_6$), enstatite ($MgSiO_3$), and to some degree hypersthene ($(MgFe)_2Si_2O_6$). Tectosilicates are the most complex silicate structures of the primary minerals, forming chained ring-like tridimensional structures. Tectosilicates are subdivided into several groups, namely quartz, feldspars, feldspathoids, and zeolites. Of these, the feldspars group is the most abundant in basic igneous silicate rocks. Feldspars are further subdivided into three families according to the elements that compose them. Plagioclase feldspars are the most abundant group of minerals in basic igneous silicate rocks forming between the albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$) solid solution series. The most abundant are the calcic members anorthite, bytownite, labradorite and to a lesser extend andesine.

Mineralogical composition of mafic and ultramafic rocks of the Whin Sill (Scotland, UK) [0]

Mineral	Mafic (wt%)	Ultramafic (wt%)
Quartz	1-3	5
Micropegmatite	12-13	30-40
Plagioclase	40-45	35-45
Ferromagnesian	35	12-14
Ore	5-6	2-4
Calcite	0.1-0.5	0.5-2
Datolite	-	4
Pectolite	-	3.5

Weathering[edit source]

The rates at which rock dissolution occurs depend on intrinsic factors, such as mineral composition, weather-ability, and surface area, and extrinsic factors, such as solute chemical composition, solute saturation state (W), temperature, rainfall and topography [1]. Chemical weathering increases in far-from-equilibrium conditions ($W \lll 1$) and higher temperatures, therefore rainy temperate climates accelerate weathering.

The capacity of minerals to withstand chemical weathering, known as weather-ability, varies across minerals. The weather-ability of primary silicate minerals follows the order: olivine < pyroxene ~ amphibole < plagioclase < potassium (K)-feldspar. This means that olivine and pyroxene weather faster than K-feldspars. On the other hand, relative mobility of elements in silicate , on a wt.% basis, follows calcium (Ca) > sodium (Na) > magnesium (Mg) > potassium = manganese (Mn) > silicon (Si) > iron (Fe) = titanium (Ti) > aluminium (Al) [2] . The mineral weatherability and the relative mobility of elements sequences favours the preferential release of Ca and Mg ions in solution as the rock weathers.

When basic igneous rocks weather its chemical components are released into solution. In basic silicate rocks Ca and Mg ions are abundant and are released into the environment upon weathering. These two ions have a high flocculating effect of soil organic matter, clay and small soil particulates, favouring the development of brown flocculated soils. Soils developed on basic igneous silicate rocks are rich in divalent cations. These soils develop into montmorillonite clays, which with further leaching weather into kaolinite clays, iron oxides and hydroxides, eventually turning into bauxite and lateritic soils. The released cations are rapidly removed from the soil profile, whereas oxides of iron, titanium and aluminium develop at different stages of the weathering sequence [3] [4].

Occurrence and extraction in the UK[edit source]

Basic silicate outcrops are common and abundant in the UK. Most of these are located at the North East of England, but are more prominent in Scotland. Outcrops of basic silicate rocks are occur to a lesser extend in the south east of England, Wales and North Ireland.

The terms ‘quarry fines’ and ‘quarry dust’ are used in the mining sector for particle fractions smaller than 4 mm resulting from crushing, milling, scalping, dry-sieving and washing aggregate processes in quarries. The ENV23 – UK Statistics on Waste estimates total annual quarry fines production to be 24·6Mt. The market options of this by-product are limited and has been reported to be environmentally costly. The latest report on UK minerals yearbook 2015 estimate 43·7Mt of aggregate production from igneous rocks in 2014, while the efficiency of the aggregate production process is low resulting in abundance of production of this by-product annually [5].

Carbon Capture and Storage Capacity[edit source]

Weathering of basic silicate rocks is associated with being a natural mechanism for regulating CO_2 concentration atmosphere levels at geological time scales.

Release of Ca and Mg into water occurring during weathering of the rock accompanied by the basic pH of the mineral surface favours capture of inorganic carbon dissolved in water as calcium bicarbonate, and to some extent precipitation of inorganic carbon as the secondary mineral calcium carbonate or calcite.

Recent studies report scientific evidence that application of basic silicate rocks on land increased to certain degree the capacity of the system to sequester carbon inorganically through enhanced weathering.

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