UNDO
PUTTING CARBON IN ITS PLACE

Measurement, Reporting and Verification Proposal

1. Summary

UNDO's MRV approach is built around data integrity and comprehensive empirical in-field measurement to provide confidence in quantifying carbon sequestration through enhanced weathering. This will enable us to generate verified carbon credits now. In order to meet the challenge of cost-effective, gigatonne scale removal in the future, we use this quantification data in combination with rigorous lab-to-field research activities to increase the accuracy of our peer-reviewed predictive geochemical weathering model.

UNDO currently applies two separate and established measurement approaches to quantify carbon removal. One is the using a weathering proxy that allows for estimation of how much rock has weathered via ICP-MS measurements to estimate a maximum theoretical carbon dioxide removal by cation loss due to weathering (henceforth called the "**mass balance approach**"). This approach uses mobile cation to immobile trace element ratios measured in soils before and after weathering to trace concentration changes of elements that are present in the feedstock material, relative to the concentrations that persist in the soil after weathering. This approach is coupled with the more traditional approach of measuring the direct products of weathering in pore waters from field trials and soil mesocosms (e.g., major cation, anion and alkalinity), which allows for estimation of carbon dioxide sequestration by charge balance. In combination, the two approaches compliment each other, where pore water analysis helps negate some of the limitations of ICP-MS, specifically the inability of the mass balance approach to distinguish non-carbonic acid based weathering.

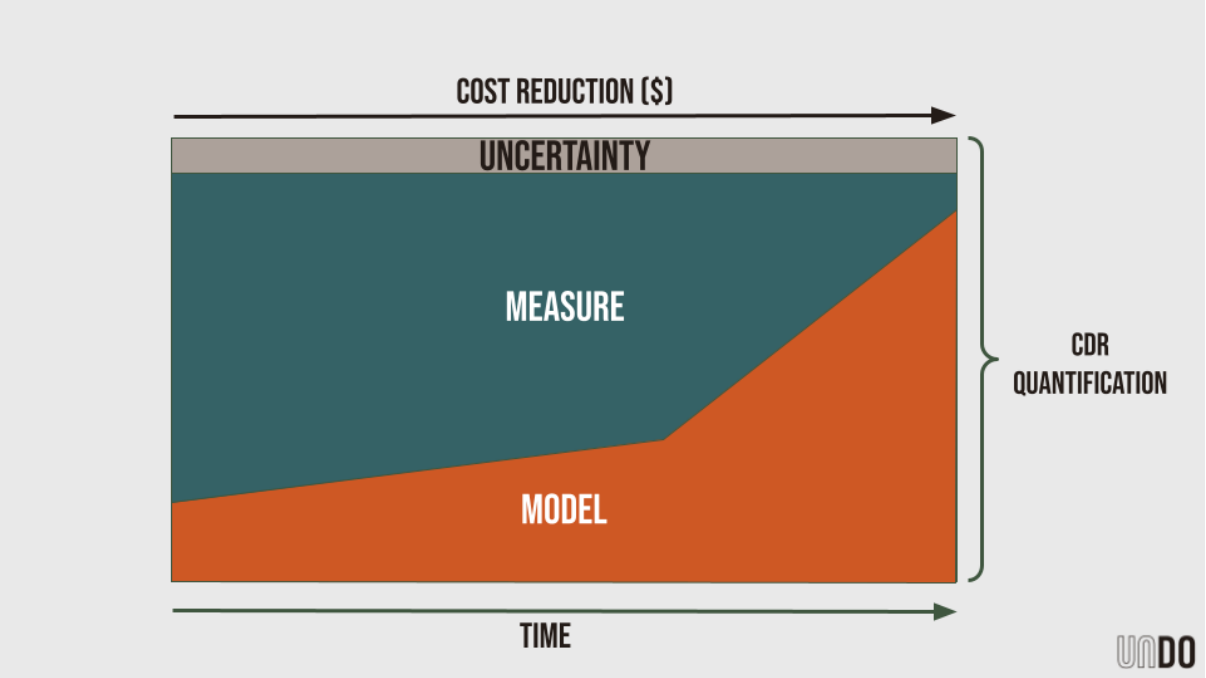
We undertake these measurements in parallel on intensively monitored sites to generate a detailed data set which accounts for variability in climate, soil conditions and crop type across our project area, allowing us to generate significantly stronger evidence of CDR.

As part of our on-going research to improve the accuracy of our geochemical weathering model, we deploy a broad range of measurement techniques, from traditional soil sampling to advanced sensors designed to measure weathering proxy parameters across a wide range of soil types, crop types and weather conditions. Specifically, UNDO is running humidity cell dissolution experiments on mineralogically complex feedstock materials to assess dissolution rates, as well as larger scale soil mesocosm experiments (both in highly controlled laboratory conditions and the field), small plot field experiments and larger split field experiments. Across the breadth of these experiments, we will be collecting and analysing soil and pore water samples, as well as determining agronomic impact. We routinely measure alkalinity, pH, and electrical conductivity (EC), major cations and anions, as well as soil exchangeable cation concentrations and potentially toxic metal concentrations. By direct comparison of these experimental and field results with our geochemical weathering model, we are able to validate our model, giving increased confidence in its predictive power under a range of climate, crop type and soil conditions.

Additionally, we are also combining advanced machine learning techniques (e.g., deep neural networks and supervised autoencoders) with precise hydrological measurements from satellite data and global datasets to develop a predictive model that can predict CO_2 leakage from river/stream transport in our areas of operation.

We record detailed data across our entire supply chain ensuring our life cycle analysis of carbon expenditure, where possible, relies on primary data (such as GPS or calibrated weigh cells). We do this via our proprietary operational data management system, Newton, which guarantees that feedstock material is tracked from quarry to field.

UNDO will continue to innovate as we build upon our understanding through density of data. In time, we will be able to transition into a model heavy, measurement light approach unlocking scale to gigatonne delivery in a cost-effective manner.



2. Introduction

Enhanced Weathering principles

The physical and chemical breakdown of silicate rocks on the Earth's surface, i.e., weathering, is a fundamental process controlling atmospheric CO_2 levels and in turn, the climate. Over geological time scales, the natural weathering of rocks of basaltic composition alone sequesters ~180 million tonnes of CO_2 per annum (Dessert et al., 2003).

Atmospheric CO_2 dissolves in rainwater to form weak carbonic acid, which in combination with soil CO_2 from microbial respiration and root exudates, dissolves silicate minerals such as wollastonite, olivine, pyroxene, plagioclase. This releases solutes such as bicarbonate (HCO_3^-) and carbonate (CO_3^-) anions, as well as cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) into soil porewaters, which are transported to the oceans via rivers and groundwater. These solutes can be precipitated as pedogenic carbonate minerals in soils (a short term sink), or transported via rivers to the oceans. The addition of bicarbonate ions to the ocean contributes to the alkalinity of seawater, thereby enhancing the buffering capacity of the seawater. This can help counteract ocean acidification caused by the absorption of anthropogenic CO_2. On geological time scales (100,000-1 million years), the dissolved bicarbonate react with cations such as Ca^{2+} and Mg^{2+}, leading to the precipitation of stable carbonate minerals (e.g., $CaCO_3$ and $MgCO_3$) (Berner et al., 1983). The precipitation of carbonate minerals provides long-term CO_2 sequestration, effectively sequestering CO_2 from the dissolved form.

In enhanced weathering, the natural process of weathering is sped up through the spreading of highly reactive, finely crushed silicate rock such as basalt, or minerals such as olivine or wollastonite, across forests, and urban and agricultural soils (see Campbell et al., 2022 for a review). Enhanced weathering has the potential to sequester gigatons of atmospheric carbon dioxide and help mitigate climate change (Hartmann et al., 2013), with estimates from global adoption of ERW with basalt varying from 0.5 to 4.0 Gt CO_2 a^{-1} (Beerling et al, 2020; Goll et al, 2021; Strefler et al, 2017). A recent geochemical modelling study suggests that enhanced weathering can account for up to 45 % of removals required to meet the UK's net-zero emission targets by 2050 (Kantzas et al., 2022).

Equations

By tracing the products of weathering (Ca^{2+}, Mg^{2+}, bicarbonate or alkalinity (HCO_3^-)), we can calculate how much CO_2 is sequestered by charge balancing the chemical equations with bicarbonate, where it has a residence time in the oceans of 100,000 years. Ultimately, bicarbonate is precipitated in the oceans as calcium- or magnesium carbonate ($CaCO_3$ or $MgCO_3$). The amount of CO_2 that is sequestered is modelled using predicted major ion release based on the dissolution of the minerals present within the crushed Ca- and Mg-rich silicate rocks; this modelling is trued up through the life of the project by using the measured pore water major ion concentrations (including alkalinity) from field studies or soil mesocosms, or cation loss from mass-balance measurements. The geochemical calculations are performed using PHREEQC (a geochemical modelling program; Parkhurst and Appelo, 2013), using the proportions of the minerals in the basalt, and using published experimentally derived kinetic and thermodynamic data (Palandri and Karaka, 2004; Voigt et al., 2018).

An example of the chemical equation for the weathering of a Ca-silicate mineral - anorthite plagioclase is shown below:

Weathering of representative Ca-silicate mineral - anorthite plagioclase

$$2CO_2 + 3H_2O + CaAl_2Si_2O_8 \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^- \quad (1)$$

Carbon dioxide + water + anorthite → amorphous clay + calcium + bicarbonate

When 1 mol of Ca^{2+} or Mg^{2+} is released into solution by weathering of basalt minerals, it stabilises 2 mol of atmospheric CO_2 as bicarbonate (HCO_3^-) by charge balance (Eq. 1). However, where carbonate is precipitated (either as pedogenic carbonate or in the oceans), 1 mol of CO_2 is released back into the atmosphere (Eq. 2).

Carbonate precipitation in oceans

$$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O \qquad (2)$$

Bicarbonate + calcium → calcium carbonate + carbon dioxide + water

When atmospheric CO_2 dissolves in the ocean, it is chemically speciated into HCO_3^- and CO_3^{2-}. The residence time of bicarbonate in the ocean is tens to hundreds of thousands of years, and thus is considered to be a permanent sink for atmospheric CO_2 over geological timescales. Due to thermodynamic constraints, only a certain proportion of CO_2 can precipitate as carbonate, with the excess remaining in solution as bicarbonate. The weathering of silicate minerals (Eq. 3) is irreversible, and results in a net drawdown of CO_2 from the atmosphere, at a ratio of 2 mol CO_2 from the atmosphere are removed for each mol of Mg or Ca. However, to account for both the speciation effect, and the release of 1 mol CO_2 where carbonate precipitation occurs, we conservatively apply a factor of 1.72 (Renforth and Henderson, 2017). A number of assumptions are made when using this factor to account for precipitation of carbonate (i.e. seawater pH, salinity, temperature, and the partial pressure of CO_2 in equilibrium with seawater), however it does not take into account the differences in timescales between abiotic precipitation of carbonate (which releases CO_2) and biological production of organic C, which can take up oceanic CO_2.

Overall reaction

$$CO_2 + H_2O + CaAl_2Si_2O_8 \rightarrow Al_2Si_2O_5(OH)_4 + CaCO_3 \qquad (3)$$

Carbon dioxide + water + anorthite → amorphous clay + calcium carbonate

Conversely, the weathering of carbonates is a reversible reaction (Eq. 4), that is not a net sink for atmospheric CO_2 over geologic timescales, however can contribute to ocean alkalinity and act as a short term sink for CO_2 over 100 to 10,000 year timescales.

Weathering of carbonate

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^- \tag{4}$$

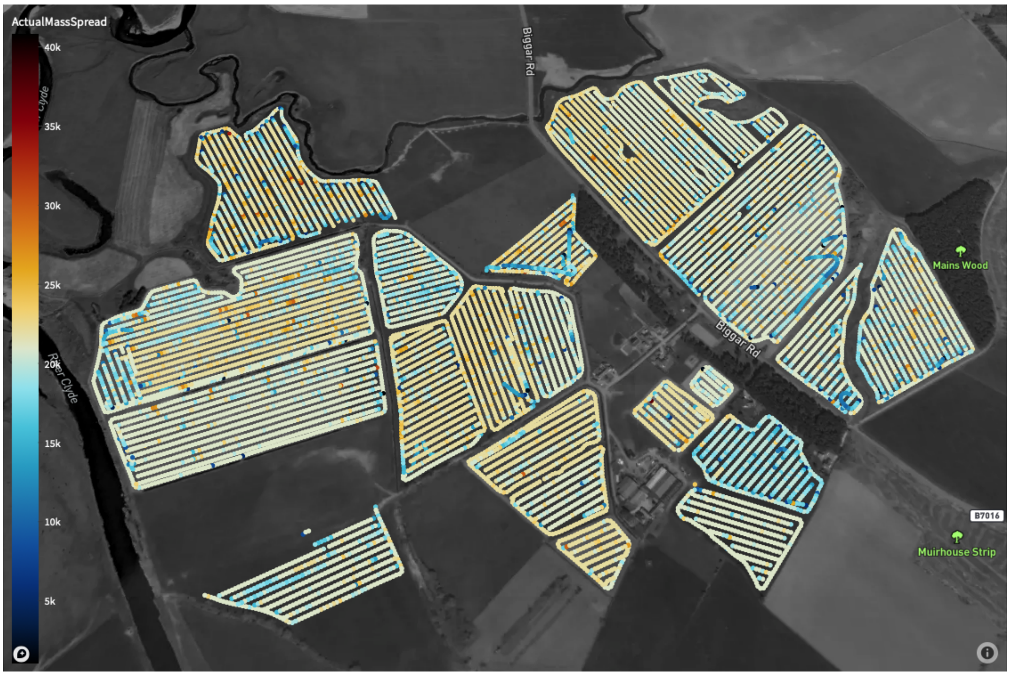
Calcium carbonate + carbon dioxide + water → calcium + bicarbonate

3. Operational Data Management

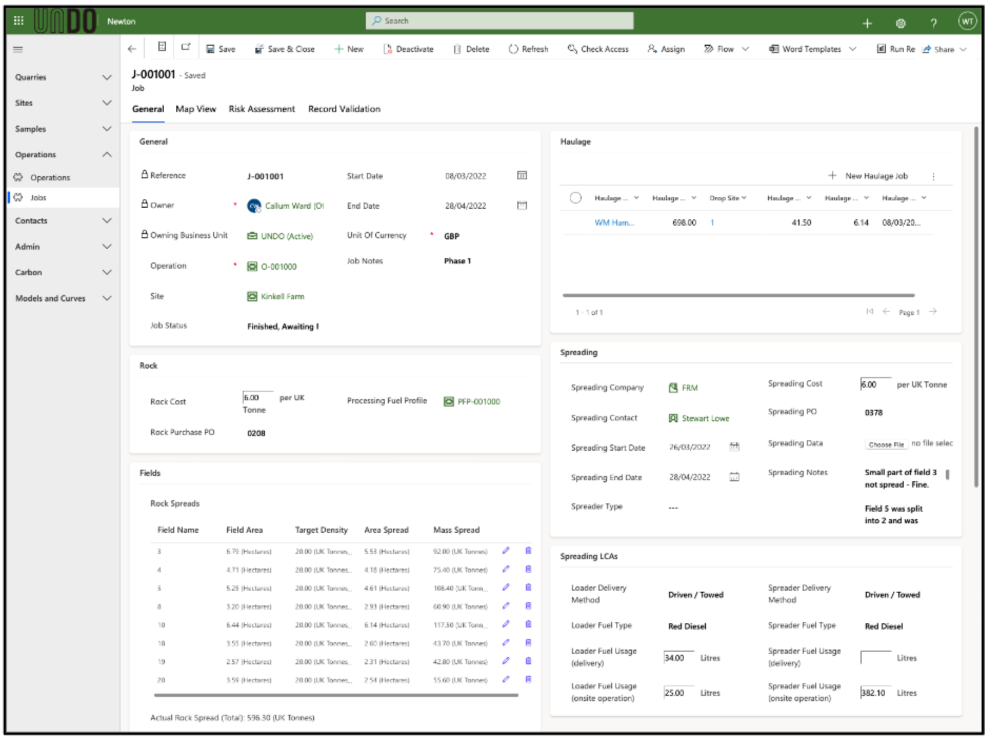
Trustworthy project data is critical in order to maintain trust in the carbon being removed from the atmosphere, especially in an open CDR system like enhanced rock weathering. We need to know exactly the geochemical, mineralogical and structural detail of the rock, where that rock has been spread, and be able to prove that these operations have been delivered, all whilst tracking accurate project emissions from quarry to field (and back). This data may be simple to collect manually when spreading hundreds or even thousands of tonnes of rock in a single location or region, but this presents a significant challenge when scaling to the gigatonne levels required, which will see global operations being delivered 24/7.

At UNDO, we have built ‘Newton’, our proprietary data platform, which enables accurate project data to be collected in real-time across global operations. All activities are tracked from quarry to field in order to support our rigorous LCA calculations, whilst detailed lab results obtained from regular rock sampling are combined with data recording exactly how much rock has been spread where, and granular data sets for climate, rainfall and soil chemistry to enable precise location-specific modelling of carbon sequestration.

Together this provides a robust end-to-end data management solution for ERW which ultimately enables 100% data traceability from a single tonne of CO_2 back to a specific type of rock spread on a specific field (and all of the activities involved in carrying out the operation).



Above (a,b,c) - a) Displaying the raw geo-located data recorded showing the path taken during spreading operations. b,c) Showing spreading and fuel usage data. This data is tracked for every operation and stored in Newton.



J-001001 - Saved
Job

General

Reference	J-001001	Start Date	08/03/2022
Owner	Callum Ward (O	End Date	28/04/2022
Owning Business Unit	UNDO (Active)	Unit Of Currency	GBP
Operation	O-001000	Job Notes	Phase 1
Site	Kinkell Farm		
Job Status	Finished, Awaiting I		

Rock

Rock Cost	6.00 per UK Tonne	Processing Fuel Profile	PFP-001000
Rock Purchase PO	0208		

Fields

Rock Spreads

Field Name	Field Area	Target Density	Area Spread	Mass Spread
3	6.79 (Hectares)	20.00 (UK Tonnes...	5.53 (Hectares)	92.00 (UK Tonnes)
4	4.71 (Hectares)	20.00 (UK Tonnes...	4.18 (Hectares)	75.40 (UK Tonnes)
5	5.25 (Hectares)	20.00 (UK Tonnes...	4.61 (Hectares)	108.40 (UK Tonn...
8	3.20 (Hectares)	20.00 (UK Tonnes...	2.93 (Hectares)	60.90 (UK Tonnes)
10	6.44 (Hectares)	20.00 (UK Tonnes...	6.14 (Hectares)	117.50 (UK Tonn...
18	3.55 (Hectares)	20.00 (UK Tonnes...	2.60 (Hectares)	43.70 (UK Tonnes)
19	2.57 (Hectares)	20.00 (UK Tonnes...	2.31 (Hectares)	42.80 (UK Tonnes)
20	3.59 (Hectares)	20.00 (UK Tonnes...	2.54 (Hectares)	55.60 (UK Tonnes)

Actual Rock Spread (Total): 596.30 (UK Tonnes)

Haulage

+ New Haulage Job

Haulage ...	Haulage ...	Drop Site	Haulage ...	Haulage ...	Haulage ...
WM Ham...	698.00	1	41.50	6.14	08/03/20...

1 - 1 of 1 Page 1

Spreading

Spreading Company	FRM	Spreading Cost	6.00 per UK Tonne
Spreading Contact	Stewart Lowe	Spreading PO	0378
Spreading Start Date	26/03/2022	Spreading Data	Choose File no file selec
Spreading End Date	28/04/2022	Spreading Notes	Small part of field 3 not spread - Fine. Field 5 was split into 2 and was
Spreader Type	---		

Spreading LCAs

Loader Delivery Method	Driven / Towed	Spreader Delivery Method	Driven / Towed
Loader Fuel Type	Red Diesel	Spreader Fuel Type	Red Diesel
Loader Fuel Usage (delivery)	34.00 Litres	Spreader Fuel Usage (delivery)	Litres
Loader Fuel Usage (onsite operation)	25.00 Litres	Spreader Fuel Usage (onsite operation)	382.10 Litres

Above - A visual of 'per job' data recorded for every spreading event, which includes key spreading locational data and fuel emissions to measure an accurate LCA for every job.

4. Measurement

Elemental Mass Balance Approach

The extent of weathering of a feedstock material can be estimated by measuring the difference in the concentrations of a mobile element in the feedstock after weathering, relative to before weathering.

Elements such as titanium and rare earth elements (REEs) can be used as an immobile tracer to calculate Mg^{2+} and Ca^{2+} release rates. Titanium and other REEs are present as insoluble primary minerals, or form stable secondary minerals that are not readily removed from the solid phase. The original ratio of these immobile tracers to major cations (Mg^{2+} and Ca^{2+}) within the basalt can be used to calculate the concentration of released weathering products based on the change in the concentration of the immobile tracer in pre and post amendment soils. This approach represents a maximum amount of CDR, as cations may be lost due to weathering by non-carbonic acids, plant uptake, or removed onto soil exchangeable sites. The ICP-MS technique will be used to calculate these elemental concentrations in rock and soil samples. Pairing the mass balance approach with soil pore water analysis of nitrite/nitrate and sulfate concentrations allows for estimation of non-carbonic acid based weathering. In order to account for cations adsorbed onto exchangeable sites, the samples will be leached with ammonium acetate. To estimate cation loss via plant uptake, analysis of cation concentration in crop biomass (roots, shoots and grain) will be performed on all of our split field and small plot monitoring sites and experiments.

To date, there are limited published studies which have quantified the effects of non-carbonic acids on the efficacy of ERW. A recent study by Kantola et al. (2023) showed that base cations such as Ca and Mg released by the weathering on meta-basalt in maize/soybean and miscanthus were minimally affected by nitric acid weathering (*ca* 0.1 %), and *ca* 1.1 % by plant uptake, with the remaining 98.9 % leaching into the subsurface.

Pore Water Analysis

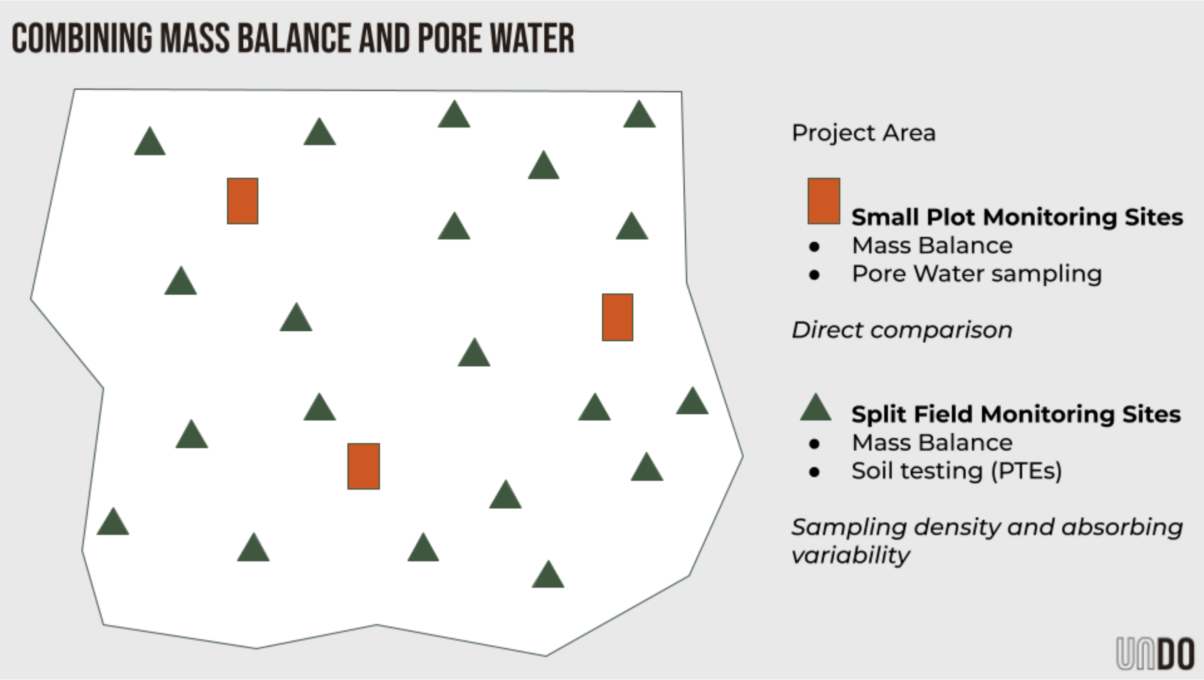
During silicate weathering in acidic conditions, protons are ‘consumed’ during the mineral dissolution reactions, base cations (e.g. Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) are released from the mineral structure, and carbonic acid (H_2CO_3) is converted to bicarbonate (HCO_3^-). Pore water analysis allows for characterisation of the products of weathering, such as pH, EC, major cations and anions, and alkalinity, in order to be able to estimate CO_2 sequestration. An increase in (1) pore water pH, (2) base cation concentrations and (3) bicarbonate concentrations (which can be inferred from alkalinity) can be observed when basalt is amended into soils.

In our small plot monitoring sites we are measuring changes in pH, cation concentration and alkalinity in pore water at different soil depths, which will be used to quantify carbon dioxide removal in combination with the mass balance approach as well as being integrated into the weathering model for calibration.

Quantification of Carbon Dioxide Removal

UNDO combines mass balance measurement with pore water analysis to provide an unprecedented level of understanding of impact to CDR as a result of soil types, farming practices and crop type. We sample intensively over a number of small plot monitoring sites where we take both pore water and mass balance data at high sampling rates to ascertain the delta between total weathering and carbonic acid weathering - therefore CDR. This delta is then applied as a correction factor to our mass balance results for our samples within the Project Area. In order to absorb greater variability in our project area, we also emplace multiple split field monitoring sites where we conduct the mass balance measurement approach. We use the empirical data from these two intensive monitoring sites to interpolate data for all of our operations in the project area as it relates to the geochemical model produced for those operations.

A “Project Area” is structured around a group of application sites that share the same legal jurisdiction. As such, a Project Area has the same laws governing environmental regulations that include requirements for Potentially Toxic Elements (PTEs)



COMBINING MASS BALANCE AND PORE WATER

Project Area

🟧 **Small Plot Monitoring Sites**
- Mass Balance
- Pore Water sampling

Direct comparison

▲ **Split Field Monitoring Sites**
- Mass Balance
- Soil testing (PTEs)

Sampling density and absorbing variability

a. Split Field Monitoring Sites

Example of split field monitoring site

Split Field Monitoring Sites are designed to measure the quantification of carbon sequestration through the mass balance approach in addition to monitoring soil acidity and electrical conductivity following applications of Ca- and Mg- rich silicate rock. Further, due to the side-by-side nature of the design, we are able to show empirically and anecdotally changes in the crop that we use to develop our farmer proposition - critical to unlocking land access for expansion.

Split Field Design

- Treatments: 2 (control and operational application rate)
- Site density: 1 split field monitoring site for every 1000 ha up to a maximum of 20 within the project region.
- Plot size: Approximately 1 hectare - dependent on cropping system and equipment.

- Sampling: 10 samples taken from each plot (5 per treatment). Each sample is made up of 10 composite samples. These sample locations are geolocated via GPS.
- Measurement interval: Dependent on the weathering rate of the material, but generally samples will be taken at baseline and annually thereafter.

b. Small Plot Monitoring Sites

Example of small plot monitoring site

Small plot monitoring sites are designed to measure mass balance and pore water in combination across an increasing application density - increasing the chance of seeing a weathering signal. Further, they provide an understanding of the agronomic co-benefits through the application of the crushed basalt rock to agricultural fields. The field is split into 1 × 4 m strips with a buffer zone - Six replicate strips of 4 application densities (Control, operational application rate, 2× application rate, 10× application rate).

Soil Sampling

Baseline soil sampling is completed prior to any basalt rock application using a single sample derived from a mix of 10 sub samples within the plot boundaries. As well as mass balance, pH, EC, base cations, cation exchange capacity, soil organic and inorganic carbon, soil texture and concentrations of potentially toxic elements (PTEs) are all measured annually. Sampling depth in arable fields is 15 cm and 7 cm in grassland fields, following standard agronomic practices.

Pore water extraction

Macro rhizon samplers are installed shortly after the time of basalt application to sample pore water at regular intervals. The rhizon samplers are installed in 5 and 10 cm depth to ensure that extracted pore water has been in direct contact with the basalt amended horizon. 30 ml of soil pore water will be extracted from each sampler with a dedicated syringe at each sampling date. Given that weather conditions permit adequate pore water to be extracted, extraction will be conducted every second week. During the small plot trials the extraction interval will be evaluated continuously, to ensure best practices. Macro rhizon samplers can be removed and replaced to prevent damage from freezing or soil tillage. Pore water will be analysed for pH, electric conductivity (EC), cations, anions and total alkalinity.

Crop observations

Observations of the crop are made at regular intervals, depending on the crop planted, to determine critical stages in development and observe differences between treatments. Observations are likely to include differences in emergence, stand establishment, early season vigour, stand counts, relative greenness and biomass. Ad hoc observations will be made as conditions warrant to capture unexpected differences between treatments. Observations will be made from the ground or drone when needed. Plant grain samples will be collected and sent to third-party labs to assess plant health and nutrient content.

5. Model

Geochemical weathering model overview

We are using an open-sourced peer-reviewed, published one-dimensional geochemical reactive transport soil process basalt weathering model to estimate CO_2 removal and mineral weathering over multi-decadal timescales (Kelland et al., 2020; Vienne et al., 2022).

Detailed information of this model can be found in Kelland et al. (2020), but a brief overview of the model and its processes are listed below:

a. Model concept: The 1D Reactive Transport Model (RTM) soil column with a depth of 50 cm, split into 10 individual 5 cm-cells with basalt amended into the top 25 cm (or top 5 cells of the model).
b. Model platform: The RTM was constructed with the PHREEQC platform (Parkhurst & Apello, 2013) using the T&H.dat geochemical reaction database (Appelo & Postma, 2005), with nitrogen species decoupled.
c. Modelled processes:
   I. Basalt dissolution
      - Chemical dissolution of the minerals within the rock (kinetic inputs from Palandri and Kharaka (2004) and Flaathen, Gislason, and Oelkers (2010); saturation information from Blanc et al (2012) and Aradóttir, Sonnenthal, and Jónsson (2012)).
      - Changes in surface area, with weathering of material (shrinking core model, Rimstidt (2014)).
   II. Soil processes

- Sorption of cations to solid phases (e.g.,cation exchange capacity of clay; sorption to organic matter and to hydrous ferric oxide).
- Reversible precipitation-dissolution of several secondary mineral phases (amorphous $Al(OH)_3$, SiO_2 and $Fe(OH)_3$ and calcite).

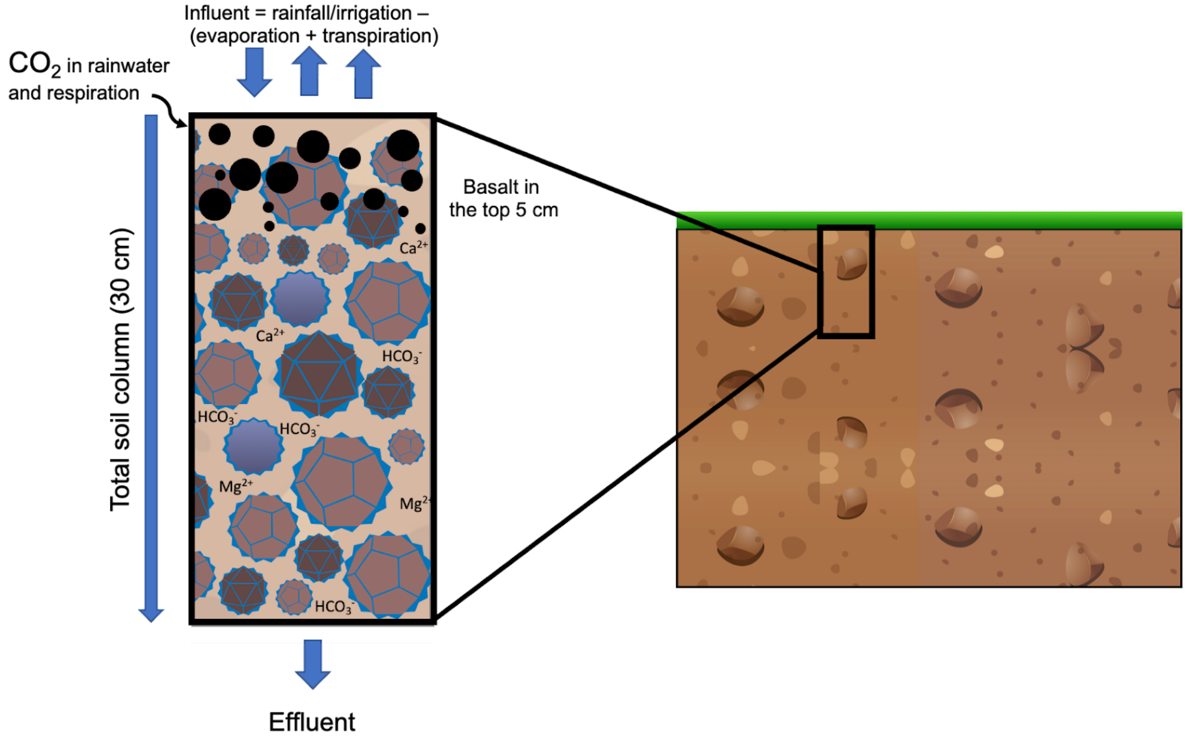
III. Biological processes

- CO_2 respiration profile from a maize crop.
- Linear uptake of elements released from the sorghum crop on a 120-day period.

In this 1D model, we assume the downward migration of rainwater or irrigation water through a 30 cm soil profile with crushed Ca- and Mg-rich silicate rock mixed into the top 5 cm, though these depths can be automatically changed to account for deeper or shallower amendment depth. The model inputs are information on the crushed Ca- and Mg-rich silicate rock mineralogy, specific surface area and density of application. These are coupled with local site-specific soil chemical (starting soil pH, cation exchange capacity) and physical parameters (bulk density and water-filled porosity) and high-resolution, long-term climate (precipitation, soil temperature) data.

For operational usage, the local site-specific soil chemical and physical parameters, as well as climate parameters, are either taken directly or calculated from parameters present in a globally-harmonised dataset at 0.1° resolution produced from the Harmonized World Soil Database (Sabater, 2019) and EU Copernicus ERA5-Land climate datasets (Wieder et al., 2014). These parameters are automatically taken from this dataset based on the longitude and latitude of the quarry, and an average value based on the weighted-average of cropland for each grid-cell is produced, excluding areas with less than 15% cropland.

Carbon sequestration is modelled using the PHREEQC geochemical platform (Parkhurst and Appelo, 2013), using published experimentally derived kinetic and thermodynamic data (Palandri and Karaka, 2004; Voigt et al., 2018).



The model simulates the change in mineral solubility over time as weathering progresses and reactive minerals dissolve. From the chemical weathering reactions, the model shows the evolution of pH in the soil pore waters, as well as element release rates (e.g., HCO_3^-, Ca^{2+}, Mg^{2+}). By tracing the products of weathering (Ca, Mg, bicarbonate (or alkalinity)), we can calculate how much CO_2 is sequestered by balancing the chemical equations with bicarbonate (HCO_3^-). From these data, the model generates a 'weathering curve' that provides an estimation of the cumulative tonnes of CO_2 sequestered per hectare over time.

Uncertainty Analysis

In order to comprehensively address the inherent uncertainty present in our predictive modelling, we have carried out a Monte Carlo-based sensitivity analysis. This approach is consistent with the guidelines recommended by the IPCC for Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. The primary objective of this analysis is to account for variations in CO2 sequestration stemming from fluctuations in model input parameters. These include, but are not limited to, crushed Ca- and Mg-silicate rock mineralogy and surface area, soil chemical and physical parameters, and various climate variables.

The Monte Carlo method involves assigning a probability density function (PDF) to each model input parameter. Each PDF is constructed using a mean value and a standard deviation. The weathering model is then run multiple times - each execution being referred to as a 'job'. For each job, the input parameters are selected at random from their respective PDFs.

To facilitate this sophisticated modelling approach, we've created a custom modelling framework. Originally, it was hosted on Amazon Web Services' (AWS) EC2. However, to gain improved orchestration for running thousands of jobs concurrently, we've transitioned to Microsoft Azure Batch. This automated, high-performance, and efficient system ensures a rapid and straightforward workflow for our modelling and analysis.

The data generated from each job is collated and used to create a two dimensional histogram, as shown in Figure 2. This plot illustrates the cumulative amount of CO_2 sequestered over time for all the modelling jobs, represented as a probability heatmap.

Subsequent analysis allows us to establish the standard deviation profile resulting from the Monte Carlo jobs. This involves scanning the two-dimensional histogram month by month, from which we create a one-dimensional histogram for that time slice. The mean and standard deviation for that specific month can then be determined. The progression of these statistics is shown in the bottom pane of Figure 3, with a peak standard deviation around the 150th month of 0.18 tCO_2.

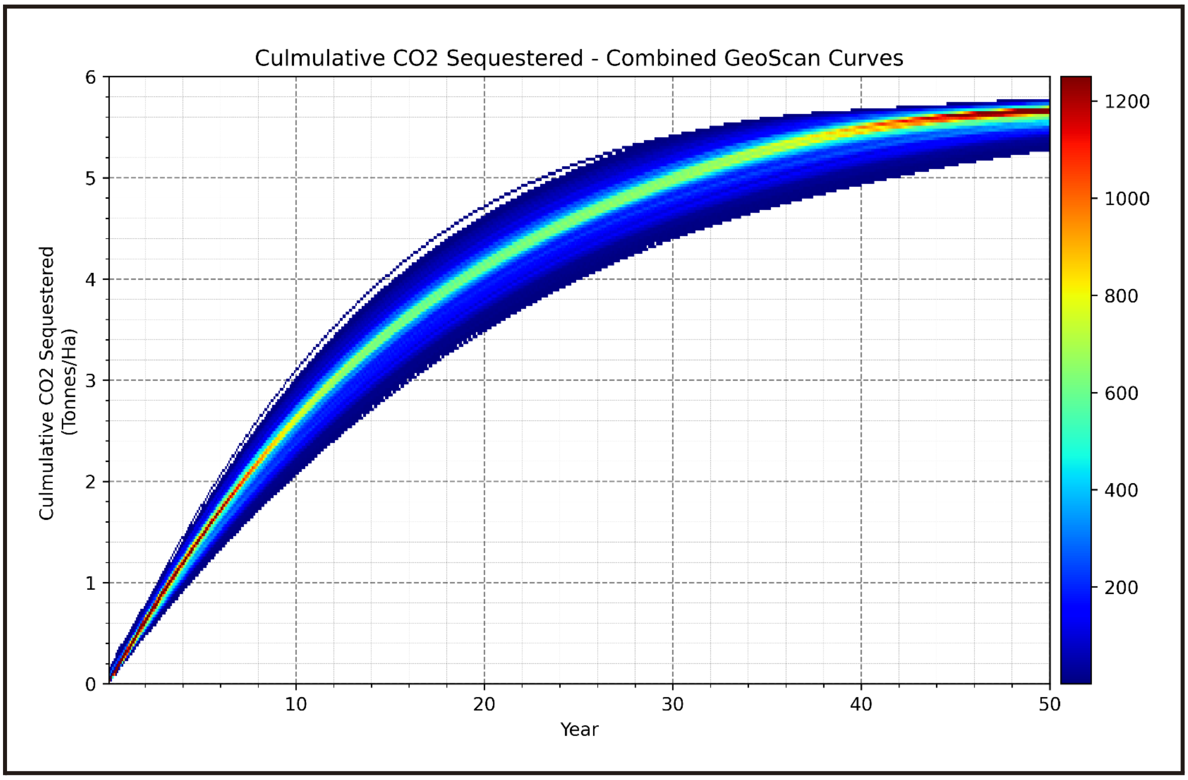


Figure 2 - A two dimensional histogram displaying the cumulative CO_2 *sequestered for every modelling job that was carried out during the monte carlo analysis.*

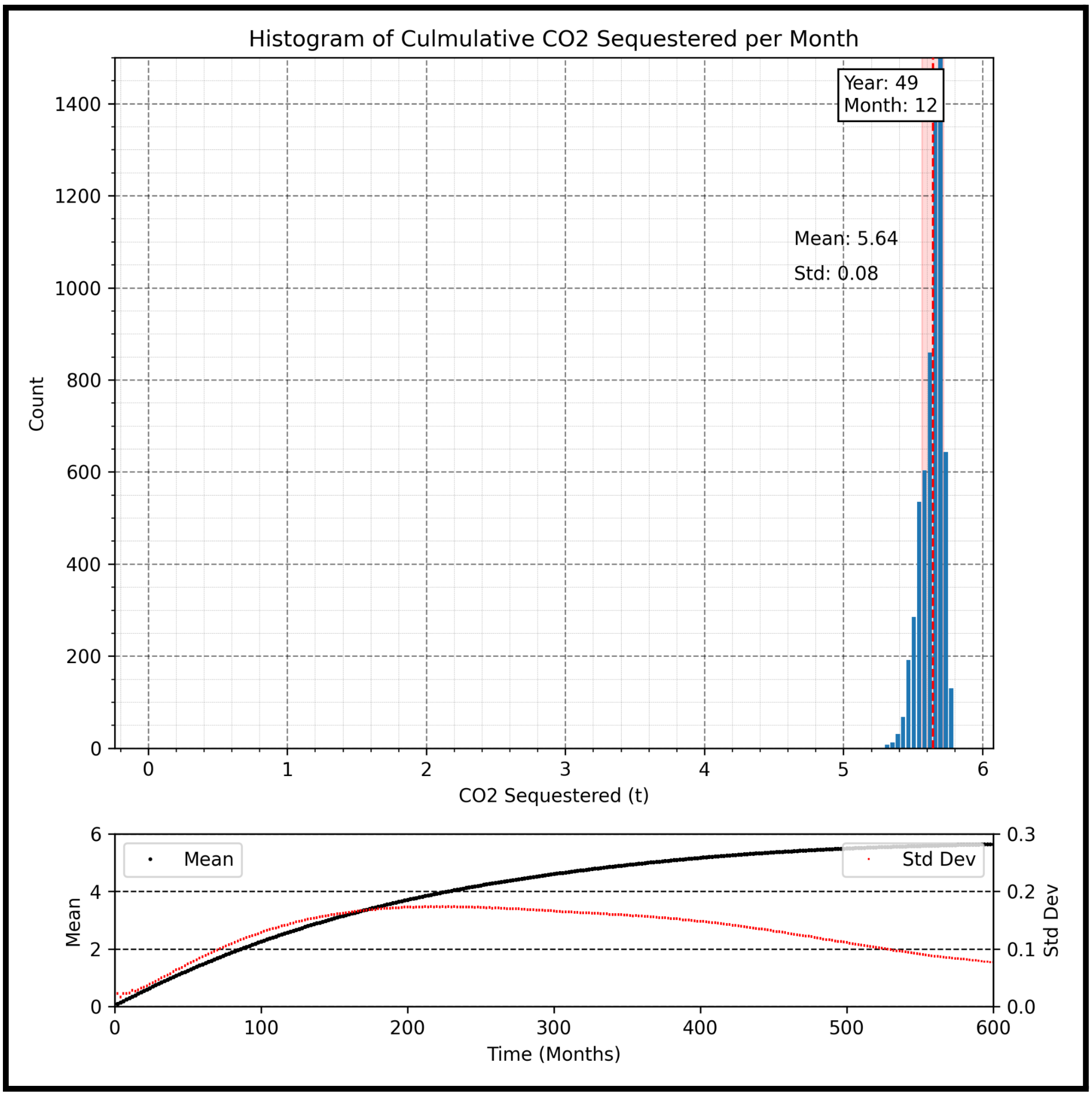


Figure 3 - The result of analysis to determine the standard deviation profile resulting from the MC modelling jobs. The history of these statistics is shown in the bottom pane of the above figure, showing a peak standard deviation around month 150.

Model Improvements

Presently, we are using an updated version of the Amm_T-H.dat database which includes dissolution rates for primary rock forming silicate minerals, as well as wollastonite.

We are updating the model to reference a new thermodynamic and kinetic database (KINEC.v1.dat) which compiles mineral dissolution rates under far-from-equilibrium conditions as a function of pH and temperature for primary rock forming silicate minerals and glasses (Heřmanská et al., 2022) and secondary silicate minerals such as clays and zeolites (Heřmanská et al 2023).

This will allow us to model 36 primary minerals using kinetic dissolution rates, as well as the thermodynamic constants for 375 solid phases (e.g.,silicate, oxides, hydroxides), 15 gases (including CO_2, O_2, N_2, ammonia, N_2O etc), 31 independent basis aqueous species (HCO_3^-, Ca^{2+}, Mg+, K+, Na+ etc), 156 dependent aqueous species ($CaHCO^{3+}$), 40 redox couples (including Fe^{2+}/Fe^{3+}, oxidised and reduced forms of N, nitrate and ammonia) and 3 types of soil organic matter, (including monoprotic carboxylic, monoprotic phenolic and diprotic carboxylic-phenolics).

Our model is under continual refinement as the knowledge of enhanced weathering and associated geochemical processes increases. Our current 1D model simulates soils with a fixed amount of saturation. We are moving towards a variably saturated 2D model using VS2DRT which will enable us to model the hydraulics of the soil under more representative environmental conditions such as periods of intermittent rainfall and irrigated systems.

6. Rock Sampling and Analysis

UNDO conducts detailed and regular rock sampling to enable the measure and model MRV approach. For each operational quarry, geochemical (XRF, ICP-MS), mineralogical (XRD) and physical property (PSD, SSA, moisture content) data is directly imported from the laboratory into UNDO's operational data platform 'Newton'. This is conducted before the commencement of operations and for each 3000 tonnes of material produced by an extraction site.

Feedstock characterisation

X-ray diffraction (XRD) is used to determine the sample's mineralogy, to assess the suitability of a rock source for enhanced weathering operations prior to application. The feedstock mineralogy is an input parameter in our geochemical weathering model. The mineral composition, in addition to published solubility and dissolution rate constants, allow for estimation of cation release, and hence CO_2 sequestration by charge balance.
Additionally, XRD also has the capability of identifying small quantities of carbonate minerals. While carbonate minerals weather quickly, they remove 50% of the CO_2 from the atmosphere via weathering relative to that of a silicate mineral. Knowing if a significant (> 1%) proportion of carbonate is present in the rock is therefore crucial for interpreting both model and field results.

Surface area is also a crucial variable for understanding mineral dissolution and is a critical input parameter in the geochemical weathering model. We measure whole-rock BET data for every feedstock sample.

To assess heterogeneity in the feedstock geochemistry and mineralogy, UNDO is analysing the feedstock once every 3000 t of material taken from the quarry. This allows us to monitor changes in PTE concentrations and mineralogy (which may affect the rate and amount of CDR for that rock source).

All of our feedstock geochemical (XRF, ICP-MS), mineralogical (XRD) and physical property data (PSD, SSA, moisture content) data are directly imported into Newton to allow for generation of quarry specific weathering curves.

Potentially Toxic Elements (PTEs)

The risks associated with the application of crushed silicate rock for the purpose of enhanced weathering include accidental contamination of farmland with potentially toxic elements (PTEs), ensuing loss of social licence to operate, fines by regulators, and prosecution under environmental protection legislation.

To date, there are no environmental regulations specifically around PTE limits for addition of silicate rock to agricultural land (Suhrhoff, 2022). Soil guideline values vary from country to country, and in some cases, the use of soil guideline values (SGVs) is only advised, and not obligatory. In many instances, there are no agricultural SGVs. In order to ensure best practice, we screen the elemental composition (determined through Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) or Inductively Coupled Plasma - Mass Spectrometry (ICP-MS), for mercury) of all silicate rock against EU inorganic soil improver limits. The elemental composition of the feedstock material is checked for every 3000 tonnes of material sourced from a particular quarry.

UNDO estimates the PTE contribution to the soil background concentrations using the background soil PTE concentration, the feedstock PTE concentration and an assumed soil bulk density.

$$Contribution\ to\ soil\ =\ \frac{C_{Basalt} \cdot m_{Basalt}}{d_{Topsoil} \cdot D_{Soil} \cdot A}$$

Where the contribution to the soil is per application (mg kg^{-1}), C_{Basalt} is the concentration of a particular PTE in the basalt (mg kg^{-1}), m_{Basalt} is the mass of basalt applied to a certain area of soil (e.g., an application rate of 20000 kg ha^{-1}), d_{Soil} is the depth of the topsoil (0.3 m), D_{Soil} is the density of the soil (set to a conservative estimate of 1100 kg m^{-3}) and A is the area over which the basalt is spread (set to 1 ha).

The background soil concentration is determined on a subset of solid baseline samples from our operational fields and global datasets (where these are available). Results have shown that complying with the EU soil improver limits results in a maximum change of soil PTE concentrations of up to 5%, assuming complete release of PTEs from the moment of application. The theoretical increase in soil PTEs did in no cases lead to exceedance of EU agricultural SGVs, unless the background soil concentration was already exceeding these.

Notably, monitoring samples from one of our MRV sites have shown that resolving this increase with actual soil samples is not possible, even for a plot with six times the assumed application rate (i.e., 126 tonnes ha^{-1}). Furthermore, no significant differences in nickel and chromium were found between the control plot and treated plots, most likely due to the natural variability of PTE concentrations in soil.

The evaluation of the risk associated with PTE content in silicate rocks is an ongoing area of research for UNDO. Baseline and monitoring soil samples from the MRV small plot trials, where input of other materials to the soil is known to UNDO, will be analysed for PTEs. Likewise, tissue or grain samples from the same plots will be analysed for PTEs to ensure crop safety. Furthermore, UNDO is collaborating with external research partners to evaluate the risks associated with feedstock where one or more PTE exceeds the EU soil improver limits.

7. Research and Model Development

Our research approach focuses on tracking the dissolution of silicate rocks in soils over a continuum of highly-controlled laboratory based dissolution experiments and soil mesocosms, to more complex field scales (e.g. small-plot trials). The approach allows us to build a large dataset which we can compare and validate our model against and understand the processes affecting the efficacy of enhanced weathering in detail. Our current experiments are as listed below:

- Published peer-reviewed model comparison
- ‘Humidity Cell Test’ dissolution experiment
  - 5 feedstock materials
- Mesocosms
  - 36 soil cores
  - 2 treatments × 6 replicates × 3 soil types
  - Pore water (10 cm and 20 cm depth) - fortnightly
  - Leachate (30 cm) - fortnightly
- Small plot field experiments (*13?)
  - 3 treatment x 6 replicates
  - Pore water (10 cm and 20 cm depth) - fortnightly
  - Soil sample - minimum 6 months depending on rock weathering rate
- Split field plot experiments (*21)
  - Split field trials
  - Sample density of 1 sample per hectare - annually

At UNDO, we are operationally amending soils with slower weathering but abundant mafic rock sources (e.g. basalt) and faster weathering but limited in supply (e.g. wollastonite skarn) rocks. Even though these rocks are different in rate of weathering, the concept of mineral dissolution remains the same even if the speed of silicate rock/mineral weathering varies considerably. This means that we can track the same parameters that indicate weathering either directly or by proxy for both slower and faster Ca- and Mg-rich silicate rock sources.

Weathering Model Calibration and Validation

To date, UNDO’s weathering model is the only published model that has been compared to basalt weathering (Kelland et al., 2020; Vienne et al., 2022).

In order to calibrate the weathering model, we adjust the input parameters and constants of the weathering model to better represent real-world data. To achieve this, we employ non-gradient based (derivative-free) optimisation algorithms using a 'trial-and-error' approach to refine the model's input parameters. Our goal is to enhance the model's accuracy and ability to simulate real-world behaviour, allowing us to assess the dissolution of Ca- and Mg-rich silicate minerals and predict CDR across diverse soil, cropping systems, and climate conditions. We are using peer-reviewed and published datasets from field, mesocosm or pot trials to calibrate our model for a range of minerals and rocks including wollastonite, olivine and basalt (e.g., Renforth et al. 2015; Ten Berge et al., 2015; Haque et al., 2020; Wood et al., 2022; Amann et al., 2020; Amann et al., 2022, Te Pas et al., 2023). It is essential to have data from a diverse range of environmental conditions in order to ensure the weathering model is not hyper-calibrated for specific soil/climatic conditions, and that the model performs well in other environmental contexts.

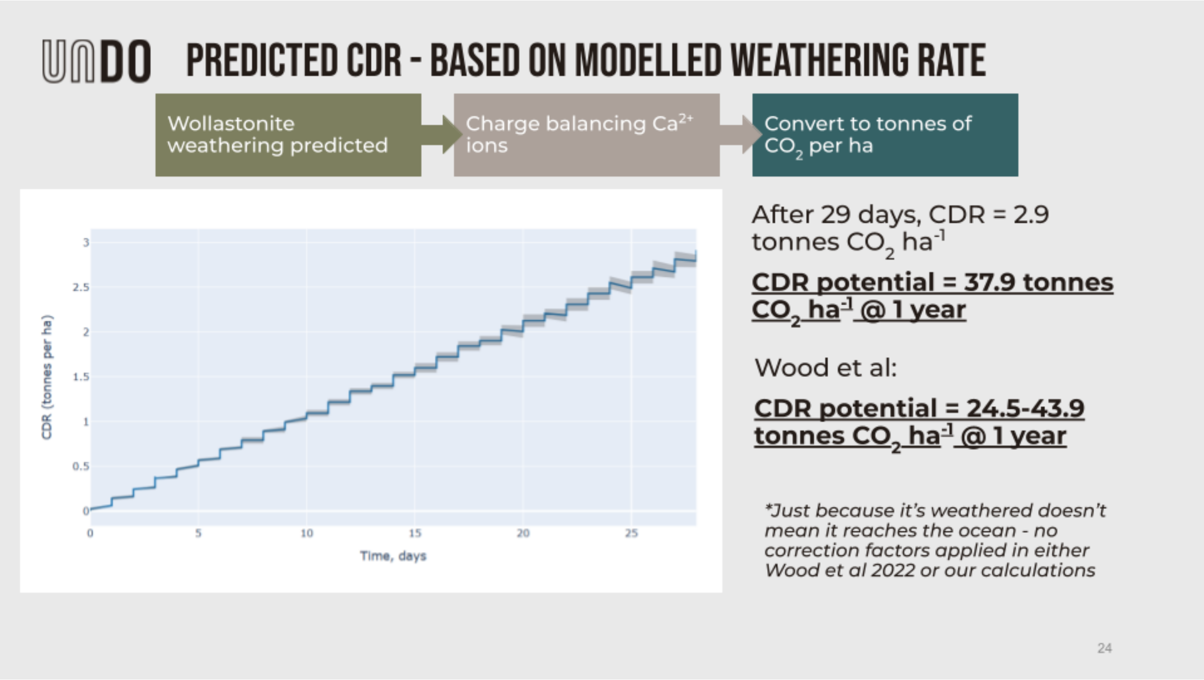
Geochemical modelling of rock amendment weathering within soils has a key role to play in predicting carbon dioxide removal via enhanced weathering over multi-year to decadal timescales. It’s important, however, to build a robust geochemical model that replicates reality; a model can output any result based on a given range of input parameters. It is crucial that these results are comparable, within a defined range of error, to reality to make them feasible to use.

UNDO is currently in the process of collecting an in-house dataset that can be used to validate our geochemical model using experiments set up earlier this year (January to April 2023). Both our mesocosm and field trials are based outside, exposed to the climatic conditions unique to each individual site. This means that the interpretation of this data is quite complex.

When comparing a model against reality, it is important to start simpler, to ensure that parameters that are easier to control are well replicated within the model before attempting to replicate and compare models against systems with more variable data. For this, we are attempting to model peer-reviewed experiments, starting with monomineralic studies (e.g., wollastonite, olivine), and evolving towards increasingly complex systems such as basalt. The published experimental results are compared against model output.

To date, we have collected input data from 113 experiments, published in 24 peer-reviewed papers. Each experimental paper has a differing level of detail. The more detail, and the more time-series data, that we are provided with, the better the comparison will be. We have reached out to a number of the authors to find out more about the experiment to ensure we understand the experiment in order to best replicate the experiment.

In a recent presentation at the international Goldschmidt conference, we presented an update on our modelling efforts (Lewis et al., 2023). We presented a comparison of our weathering model against the disturbed wollastonite + soil columns of Wood et al. (2022). These experiments were kept at a constant temperature of 22°C and were regularly watered with a high equivalent rainfall rate (~16,000 mm/yr). The authors of the paper suggest that the column was continually saturated, and that the leachate was ‘forced’ out of the column by additional watering. We found that our weathering model broadly agrees with the experimental data for calcium release in the leachate.



PREDICTED CDR - BASED ON MODELLED WEATHERING RATE

Wollastonite weathering predicted → Charge balancing Ca^{2+} ions → Convert to tonnes of CO_2 per ha

After 29 days, CDR = 2.9 tonnes CO_2 ha^{-1}

CDR potential = 37.9 tonnes CO_2 ha^{-1} @ 1 year

Wood et al:

CDR potential = 24.5-43.9 tonnes CO_2 ha^{-1} @ 1 year

**Just because it's weathered doesn't mean it reaches the ocean - no correction factors applied in either Wood et al 2022 or our calculations*

24

We also modelled carbonate precipitation, and the model predicted that 0.47-0.51 wt.% would precipitate, which is similar to the measured values of 0.36-0.96 wt.% in the Wood et al (2022) study. Extrapolating the results of this study from one month to a year, our model suggests that 37.2 tonnes CO_2 can be removed per ha after one year, which is in agreement with Wood et al (2022), who based on their experiment data, estimates sequestration of 24.5 to 43.9 tonnes CO_2 per ha after one year.

We are in the process of making our way through the list to model both mesocosm and field experiments, and plan to conduct these types of studies for appropriate enhanced weathering feedstock.

A limitation trying to model many of the current published studies, including the Wood et al. (2022) study, is that not all of the potential sinks for CO_2 are quantified - namely bicarbonate in pore water or leachates, cation uptake into plants, pedogenic carbonate formation and cations held on exchangeable phases. This may lead to the model overestimating CDR, which is why it is crucial to quantify all potential CO_2 and cation sinks within the agricultural system. This is why our own mesocosm and field data are important to obtain - so that we can have a complete mass balance of the weathering products and have the most accurate comparison with our weathering model, we are measuring all potential sinks for CO_2 in our studies.

‘Humidity Cell Test’ dissolution experiment

HCTs are laboratory experiments designed to simulate the natural weathering conditions of rocks by monitoring the associated mineral dissolution and chemical reactions. These tests involve flushing 1 kg of feedstock material within a plastic cylindrical cell (200 mm × 100 mm). The cell is constructed in such a way as to allow air to be circulated over the sample, and to allow for leachate to be collected from the base. The collection vessels are rotated and flushed by spray irrigation from the top of the cell without disturbing the feedstock material.

The experiments are kept at 25°C, and are flushed with 120mL of 0.45 μm filtered rainwater, and sampled on the day the cells were flushed. The flushing took about 2–3 h, and the flooded sample was left to rest inside the cell for approximately 1 h prior to sampling to ensure the feedstock pores were saturated.

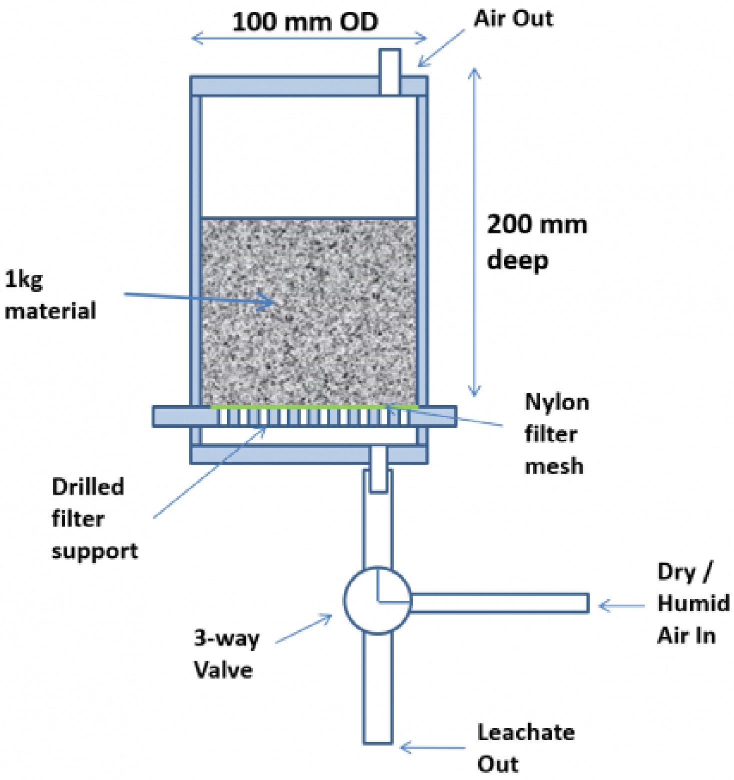


Figure x: Schematic of the humidity cell used in this study.

We are running a total of 5 HCTs on 4 basalt samples and one wollastonite. The tests were performed for a duration of 10 weekly cycles, with more flushing events in the earlier part of the experiment, decreasing to weekly flushing by week 10.

The majority of fast weathering fine particulate matter will react during the beginning of the experiment, as such the sampling schedule is planned to ensure higher frequency at the start of the experiment. Water and oxygen from the atmosphere dissolve the minerals, thereby releasing different elements.

The collected leachates were analysed for pH, electrical conductivity and oxidation-reduction potential. In addition, alkalinity, acidity and DIC/DOC content were also determined to trace any sulphide mineral oxidation or carbonate mineral dissolution. The leachates were measured by ICP-OES and ICP-MS to determine cation and trace element concentrations, and by ion chromatography for anions.

From the HCT's we will be able to determine the weathering rate of our basalt samples which can be used in our modelling of CDR rates.

Mesocosm experiment

Duration: 3 years
Treatment: 0 and 100 tonnes ha^{-1}
Replicates: 6
Soil Types: 3
Crop type: Grass

Total Samples per year

- Pore water - 1872 total
- Leachate - 936 total

Objective

Soil mesocosms allow for a higher degree of control of drivers of weathering processes, as compared with field trials. UNDO is searching for weathering proxies such as pH, EC, alkalinity, and cations in both field and mesocosm trials. However, these proxies can be influenced by various soil processes and may vary seasonally. Therefore, conducting experiments with a higher degree of control could enhance our confidence in the results.

UNDO's mesocosm experiments will be exposed to the same environmental conditions that the fields that UNDO are operating in also experience. Hence the mesocosms are placed outdoors, with the soil core moisture maintained at field like conditions. The design of UNDO's mesocosms ensures that cross contamination between soil cores is prevented. Hence, each extracted soil core is a true replicate and the soil pore water samples representative of that specific hydrology and soil environment. Furthermore, the mesocosm design is advantageous in that soil pore water can be extracted both from different depths in the soil column, as well as collected at the bottom, providing an insight into leachate chemistry. We will then use the time series soil pore water pH, EC, cation and anion concentrations to further calibrate, validate and verify the geochemical weathering model.

Mesocosm design

Mesocosms will be constructed from a 370 mm length of polyvinyl, allowing for a 70 mm upstand and a core depth of 300 mm. The outer diameter of the soil core pipes will be 200 mm to reduce edge-effects (e.g. preferential flow). Ports for rhizon samplers at 10 and 20 cm, and support structure attachments are pre-drilled (Fig. 1), and the lower rim slightly sharpened. Each pipe will then be used to core out a single soil monolith from the field site with the use of a blunt impactor.

Soil cores will be transported immediately to the experimental site. This experiment includes three different soil types excavated from different field sites, each with a total number of 12 soil cores (6 control and 6 amended). To ensure a uniform crop across all three soil types, the native crop from the three different soil types will be removed by removing the upper 2 cm of each core, directly below the root zone. Prior to seeding rye grass, basalt or wollastonite skarn will be mixed into the upper part of the soil cores (see next section). Following seeding, the cores will be irrigated from the top and fertilised according to the manufacturers' specifications, to ensure good establishment in the soil cores. A healthy crop is important in relation to the dissolution of minerals due to the influence on the profile of the partial pressure of carbon dioxide in the soil columns. An increase in the partial pressure of carbon dioxide leads to a decrease in pH in the soil solution, favouring a faster dissolution rate. The reduction in pH can be optimised through selection of optimal crop types, for example C4 plants like Maize, but grass is chosen for this experiment because it is 1) a perennial crop covering the soil for the entire experimental period and 2) is highly represented in UNDO's commercial spreading activities.

Based on experiences from one of UNDO's existing trials where we have field pore water sampling and mesocosms running in parallel, it's clear that maintaining a realistic soil moisture level in the soil cores disconnected from the field requires extra attention. The main reason for this is that the soil core is detached from the hydrological flow regime in the soil, but unavoidable differences in temperature and wind conditions may also play a role. In order to mitigate this unfortunate discrepancy in soil moisture, we'll install trays under the soil cores and an automated irrigation system (Fig. 1). The trays serve two purposes: the primary purpose isto reduce the effluent flow rate, compensating for some of the disconnection from the hydrological flow regime, and secondly, they can act as irrigation ponds at time of low column moisture.This will prevent irrigation water from directly affecting the dissolution rate, which would be the case if the soil cores were irrigated from the the top of the amended part of the core. All soil cores will receive a set amount of irrigation, in order to avoid the amount of irrigation plus precipitation becoming an independent variable in the experiment. The amount of irrigation needed will depend on continuous observations and assessments by the field personnel. The cores will be irrigated using deionised water, and the solution will be delivered into the trays under the soil cores, to ensure that the soil moisture is maintained. Maintaining a realistic soil moisture level improves conditions for mineral dissolution by increasing the mineral wetted reactive surface area, reducing mineral saturation states and reducing the pH in the weathering zone, through improved conditions for the crop.

The trays will be installed to compensate for the detachment of the soil cores from the groundwater level and hydrological flow regime that the soil cores would experience in the field. In periods with low precipitation, where the trays will be used to compensate for excess drying of the soil cores, soil pore water, including cations may be transported towards the soil surface. This is, however, similar to the effect of soil capillary forces and plant uptake has in the field.

The trays will be equipped with a tube running into a leachate bottle. On the tube a valve is installed, which can be closed in periods of irrigation (usually most of the summer) and opened during periods without irrigation (usually most of the winter). In cases where the valve is closed and excess amounts of precipitation flow through the core and into the tray, this water will be collected through an overflow tube connected to the top of the tray. The leachate will be collected in a high-density polyethylene (HDPE) bottle (Fig. 1).

Once the cores are installed in the mesocosm framework, each core will be outfitted with two rhizon-samplers (in 10 and 20 cm depth). Any gaps remaining in the pipe after instrument installation will be infilled with a polyurethane-based adhesive sealant. It is advisable to use initial geochemical modelling to determine the optimal placement of deployed rhizon samplers. However, a certain volume of soil is required to retain sufficient moisture to allow for pore water sampling, hence the placement in 10 cm depth for the upper most rhizon sampler.

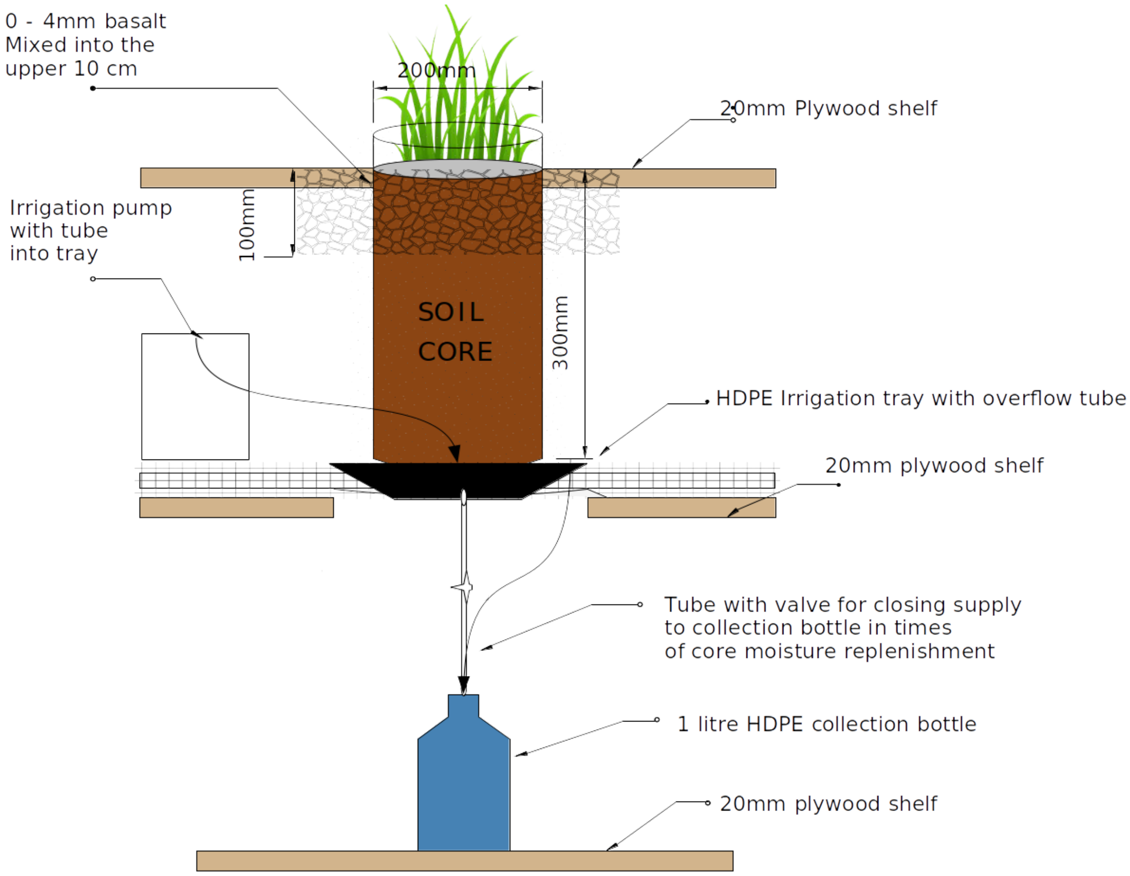


Figure 1: Schematic representation of a single soil core, outfitted with rhizon samples, irrigation/leachate collection trays and collection bottle.

Crushed Ca- and Mg-rich silicate rock preparation and application

Existing mineralogical and particle size data will be used to determine the desired source rock and particle size distribution, which will be engineered using a series of sieves with progressively smaller mesh size. Prior to basalt or wollastonite skarn application the mineralogy in different particle size distribution bins will be analysed for mineralogy, reactive surface area and modelled to determine which size fraction has the highest weathering potential. The batch of basalt or wollastonite skarn material must be sufficient to amend the 6 treated mesocosms at the experimental application rate (100 tonnes ha^{-1}), plus an additional 5% by mass for analytical samples (including mineralogical, physical and chemical analysis). A riffle box or spinning riffler will be used to split the batch into representative samples (using suitable PPE). Following learnings based on pore water samples taken from field and mesocosm experiments using a top dressing of basalt, it is advised to incorporate the amendment into the upper 10 cm of each soil core in order to get pore water results within one year. The upper 10 cm of soil in the control cores will likewise be mixed, but without any amendment to simulate the same tilling conditions.

Sample collection and analysis

A sample of initial soil should be collected from the site where the monoliths are cored, and should be characterised promptly for pH, EC and soil texture. It is advisable to conduct a depth-wise analysis of this soil at the same depths as the planned analyses for post-experiment soils, given the heterogeneity likely to be present in the strata. Additional initial soil samples (from all depths) will be dried and stored for future comparisons. Post-experiment soils will be excavated in discrete depths corresponding to the placement of the rhizon-samplers, and analysed separately to determine depth-related changes in key soil parameters, such as pH, EC and exchangeable cations.

Due to the mixing in of the amendment in the soil cores at the beginning of the experiment, baseline aqueous samples will not be collected. This will be similar to field operations where the treatment is also incorporated into the soil, with no stabilisation period before mineral dissolution is commenced. The assessment of the variance in the study will be based on solid soil samples and the control cores. The frequency of aqueous sample collection following application would ideally be guided by the results of initial geochemical modelling. Nevertheless, it is likely that more frequent sampling will be required in the early stages of the experiment, to capture the initial pulse of mineral weathering that will occur due to the faster reaction kinetics of the finest fraction of the particle size distribution. Ultimately, the maximum sampling frequency will be constrained by costs, workload considerations and potential bottlenecks in the analysis pipelines.

Biomass will be harvested periodically, at regular intervals, to assess the effect on crop performance. These samples will be oven-dried to preserve tissues for future batch analyses (e.g., measuring uptake of potentially harmful elements).

Small plot field experiments

Duration: 5 years
Number: 6
Crop type: Typical agricultural crops for the region of interest
Treatments: 0, 20 and 40 tonnes ha^{-1}
Replicates: 6
Design: Randomised complete block
Plot target size: 4 × 10 m

Total Samples per year

- Pore water - 936 per trial × 6 = 5,616 total
- Soils Samples - 216 per trial × 6 = 1,296 total

Objective

Observations in small plot trials conducted by UNDO Carbon have two general objectives; supporting the understanding of measurement of carbon dioxide sequestration (MRV) - and by doing so provide data for model calibration. Secondly, provides understanding of the agronomic co-benefits that are provided by the application of the crushed basalt rock to agricultural fields.

Soil Sampling

Baseline soil sampling is completed prior to any basalt rock application using a single sample derived from a mix of 10 sub samples within the plot boundaries. pH and EC will be determined in house using UNDO lab facilities to establish continuity of process for later sampling. Sub samples will be sent to a third-party lab to determine baseline values of base cations, cation exchange capacity, soil organic and inorganic carbon, soil texture and concentrations of potentially toxic elements (PTEs). Furthermore, a sub sample will be dried, sieved and stored for future advances in the field of weathering quantification methods.

Sampling depth in arable fields is 15 cm and 7 cm in grassland fields, following standard agronomic practices.

Pore water extraction

Macro rhizon samplers are installed shortly after the time of basalt application to sample pore water at regular intervals. The rhizon samplers are installed in 5 and 10 cm depth to ensure that extracted pore water has been in direct contact with the basalt amended horizon. 30 ml of soil pore water will be extracted from each sampler with a dedicated syringe at each sampling date. Given that weather conditions permit adequate pore water to be extracted, extraction will be conducted every second week. During the small plot trials the extraction interval will be evaluated continuously, to ensure best practices. Macro rhizon samplers can be removed and replaced to prevent damage from freezing or soil tillage. Pore water will be analysed in house for pH, electric conductivity (EC), and total alkalinity using UNDO facilities. A 10 ml sub sample of pore water will be retained and sent to a third party lab for anion and cation analysis.

Crop observations

Observations of the crop are made at regular intervals, depending on the crop planted, to determine critical stages in development and observe differences between treatments. Observations are likely to include differences in emergence, stand establishment, early season vigour, stand counts, relative greenness and biomass. Ad hoc observations will be made as conditions warrant to capture unexpected differences between treatments. Observations will be made from the ground or drone when needed.

Crop nutrient analysis

Plant grain samples will be collected and sent to third-party labs to assess plant health and nutrient content.

Yield testing

Assessments of plot yield will be collected from each plot. For grains, plots will be harvested with a plot combine when available to determine yield. A subsample of grain may be counted to determine average grain size and density if differences in treatments are observed.

Split Field Experiment

Design: Split field

Replicates: 1 or 2

Treatments: 2 (control and operational application rate)

Plot size: Dependent on cropping system and equipment. Typically the field should be split into two or four strips running the length of the field. Each strip should be a minimum of four spreader bouts wide.

Plot buffer: Care should be taken to minimise interference between adjacent plots and to ensure the correct application rate as a result of overlapping spreading bouts. To achieve this there should be a buffer area of at least half a spreader bout between plots.

Time period: 3 years/growing seasons. Cultivations between crops should be conducted as normal, in accordance with good agricultural practice. Repeat applications are not currently planned within 3 years but may be reviewed after 3 years.

Objectives

Measure and monitor soil acidity and electrical conductivity following applications of Ca- and Mg- rich silicate rock. Monitor levels of potentially toxic elements (PTEs) in soil and crop. Monitor levels of macro and micronutrients in soil and crop. Measure crop biomass, yield and quality.

Site Location

The field should be chosen typical of the region and good agricultural practice with an even soil type, and without any obvious changes in soil type or texture. The field should be well drained with no history of waterlogging or flooding. The field should be located on a slight slope (2-3 degrees) so that any movement of soil or water is predictable. Site must be marked, triangulated and geolocated to enable relocation in subsequent seasons. More likely to see effects on sites with lower pH and with low P, K Mg indices.

Crop Details

Various crops and crop rotations typical of the region and farm selected. Crop should be managed in accordance with good agricultural practice including typical cultivation,fertilisation and effective weed, pest and disease control. All treatments are fully approved so any crop can be intermingled with the remainder of the crop in the field and sold as normal.

Treatment Details

Crushed Ca- and Mg- rich silicate rock will be supplied by UNDO and applied at 20 tonnes per hectare for basalt and 5 tonnes per hectare for wollastonite. Application will be conducted using commercial equipment as per normal operating procedures. Applications will be recorded using GPS monitoring equipment to generate an actual application map.

Soil sampling

Baseline sampling completed prior to rock application with 6 sample locations per plot with location data recorded. The sample itself should be a composite sample of 5 samples around the sample location. The samples should be taken down the centerline of each plot.

Soil samples will be collected at a minimum every 12 months in the same manner as baseline sampling. Samples will be processed by air drying and sieving. The pH and EC will be measured in UNDO labs and the remaining sample retained and archived pending further analysis.


Colliery Farm


Littledean Farm


Brandon White House Farm