
unDO

OUTLINE

- Introduction
- Scientific Motivation
- Enhanced Rock Weathering (ERW)
- Co-benefits
- UNDO approach to Measurement, Reporting and Verification (MRV)

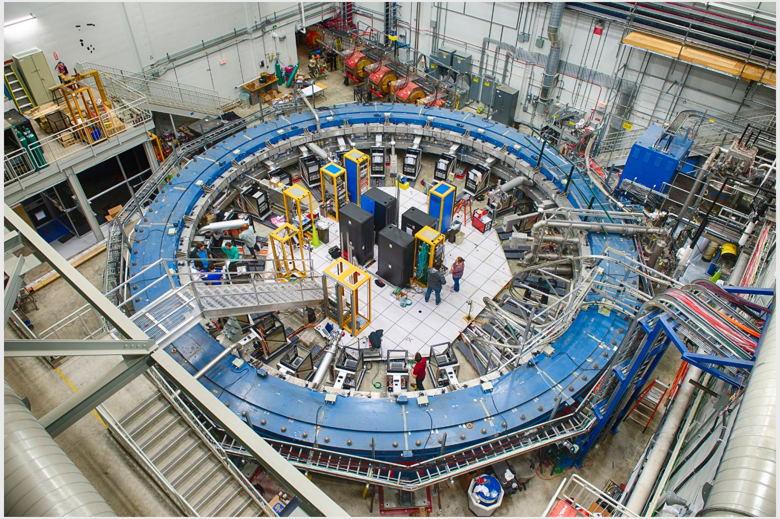
ABOUT ME

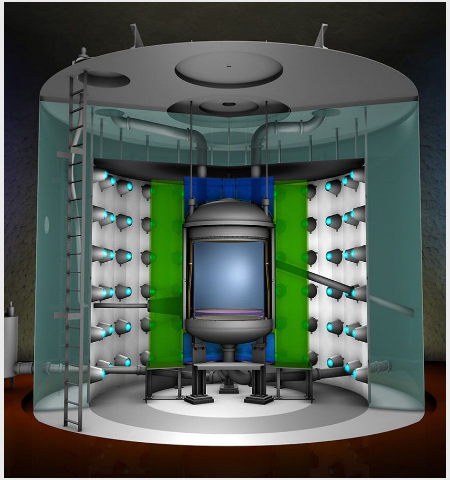
Undergrad: Physics UoL

PhD: UoL + Fermilab Chicago

Post Doc: UoL + Sanford Underground Research Facility South Dakota

Head of Data Science, UNDO Carbon



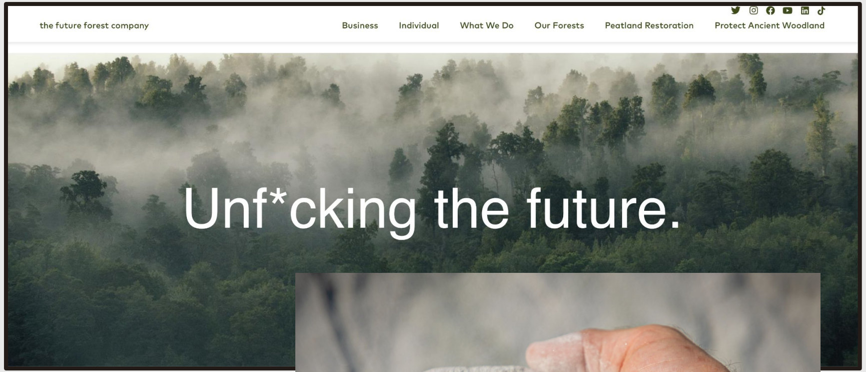


ABOUT UNDO

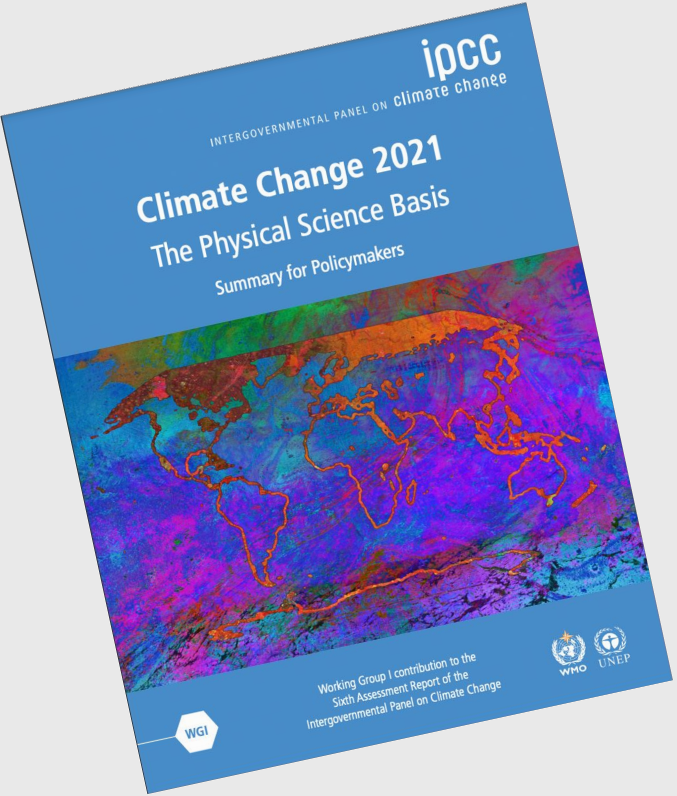
We spread crushed silicate feedstocks on agricultural land to sequester carbon through Enhanced Rock Weathering.

Committed to responsbily scaling ERW to remove as much carbon as possible as quickly as possible.

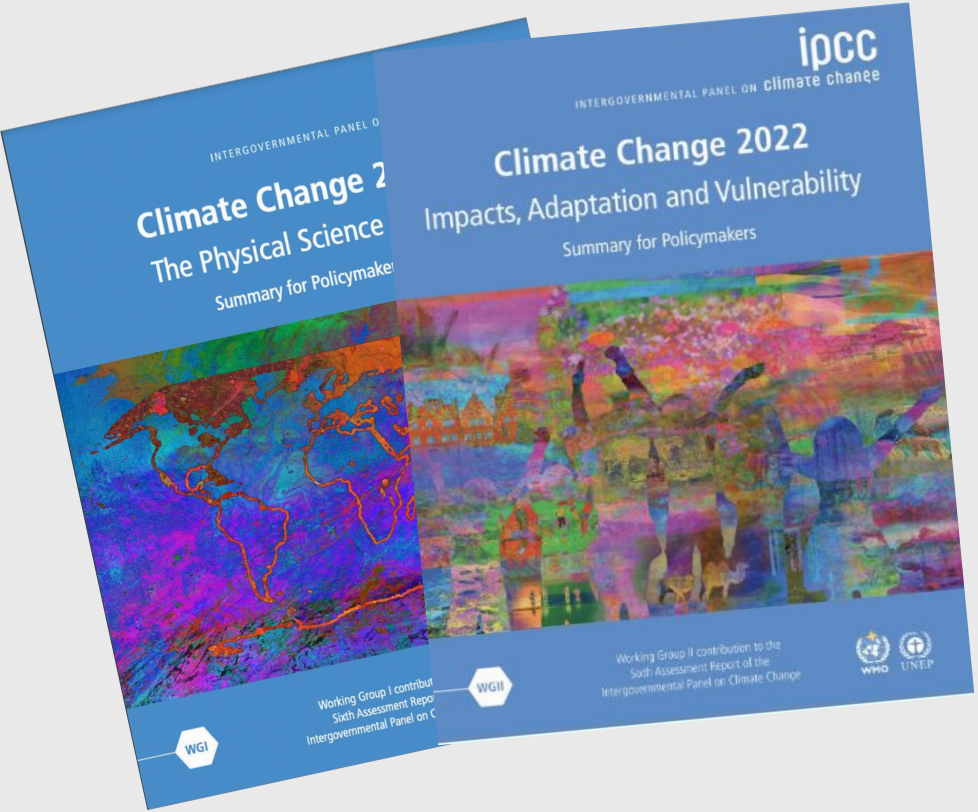
Operating in Scotland (basalt) and Ontario (wollastonite) and building the tech layer to allow others to scale up fast!



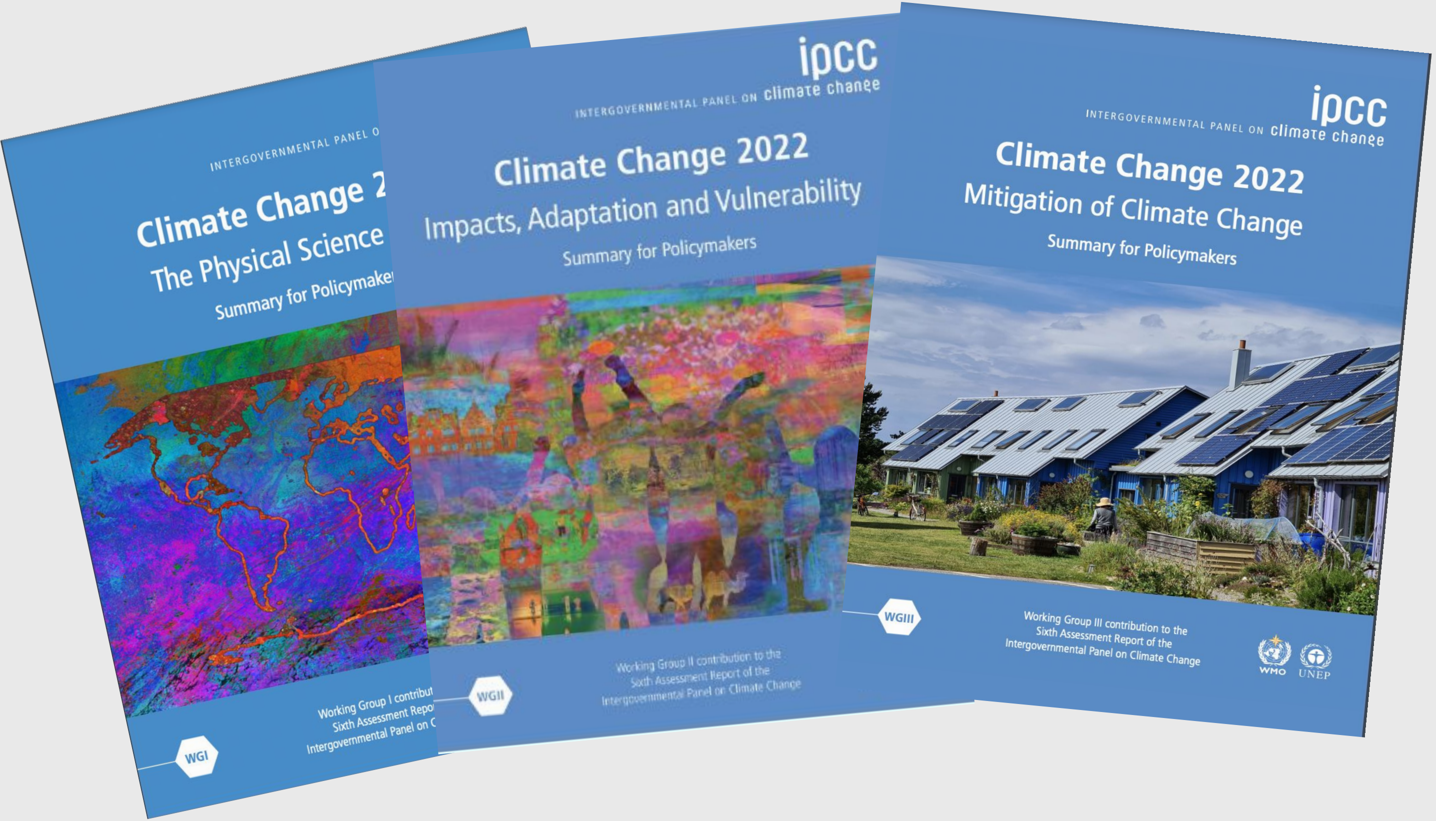
“Climate change is widespread, rapid, and intensifying and unequivocally a result of human-induced greenhouse gas emissions”



“All life on earth, from ecosystems to human civilisations, is vulnerable to a changing climate”



“The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable to achieve net zero”



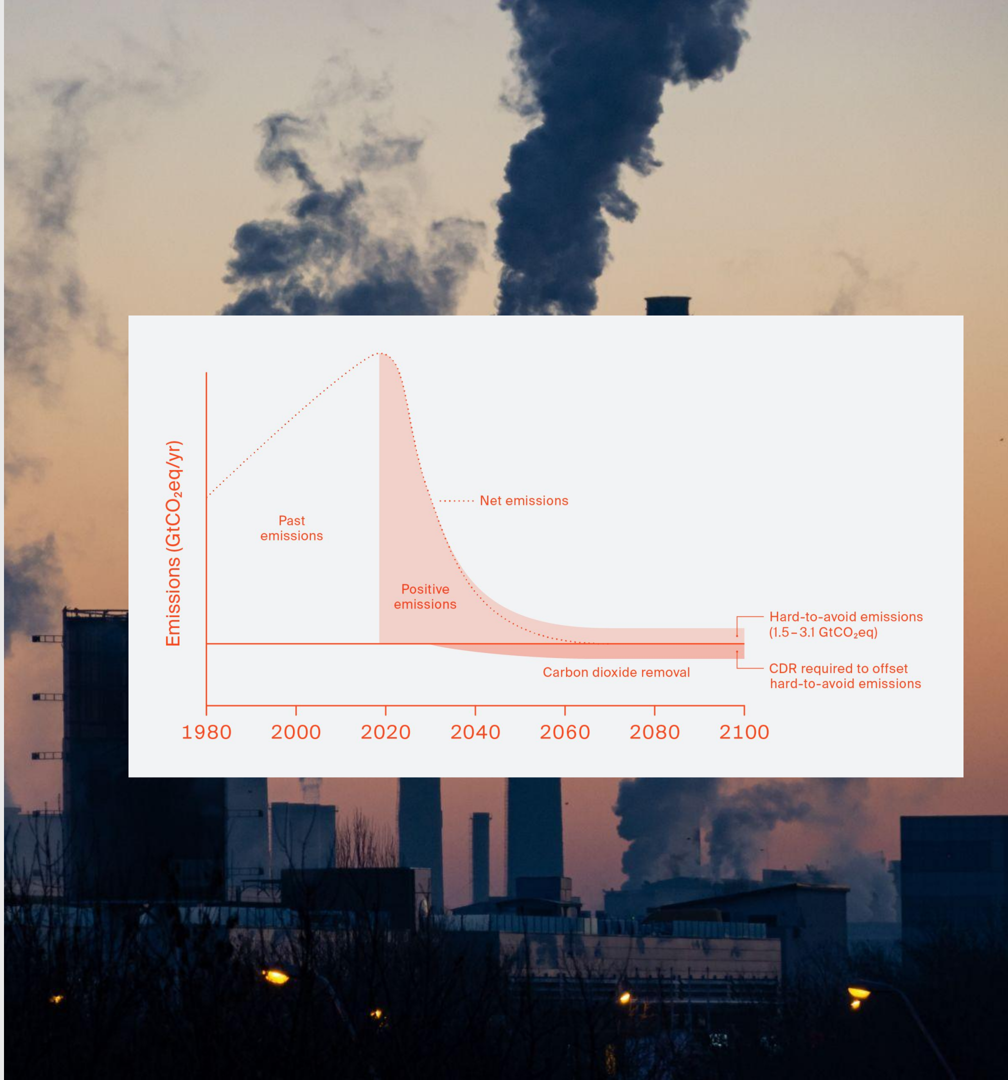
“There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all.”

THE CLIMATE CRISIS WE FACE

There is a removal need of **10 billion tonnes by 2050 per year** in order to stay within the SBTI goals and achieve net zero by 2050.

Reducing emissions alone isn't enough, we need to remove and we need to do it at scale.

Everything we do at UNDO is designed to carry out ERW at scale.



EARTH'S NATURAL CO_2 REMOVAL MECHANISM

CO_2 in atmosphere dissolves in rainwater forming carbonic acid, which falls onto land through rain.

Exposed rock will react with the carbonic acid generating bicarbonate, releasing elements into solutions.

Bicarbonate (negative) and cations (positive) are transported to the ocean.

Bicarbonate is stable in the ocean where it has a long residence time (~100,000 yr)

$$2CO_2 + 3H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4$$

Carbon dioxide + Water + Wollastonite → Dissolved Ca^{2+} Bicarbonate and Silicic acid.

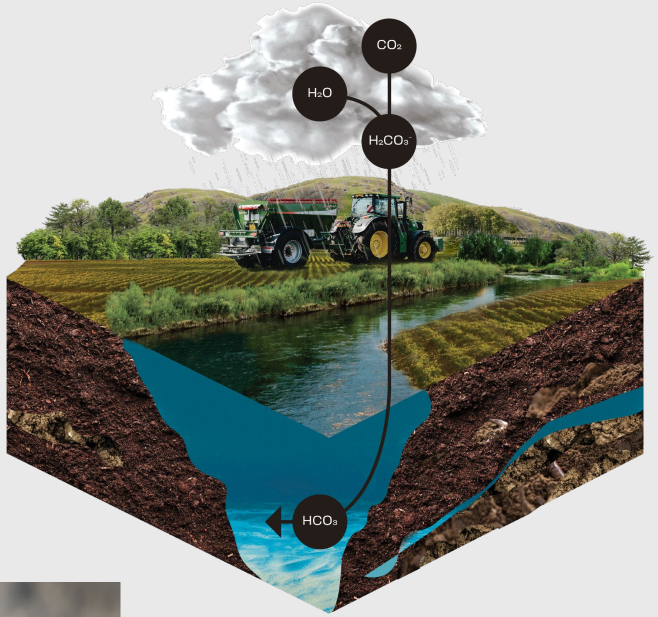
SPEEDING THE PROCESS UP

Select rock that weathers quckily

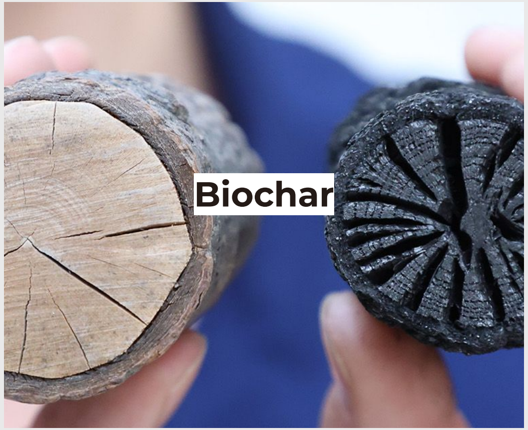
Abundant (and actively mined)

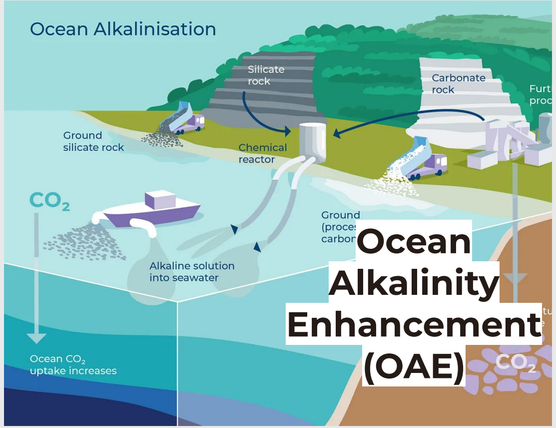
Smaller particle size → higher surface area

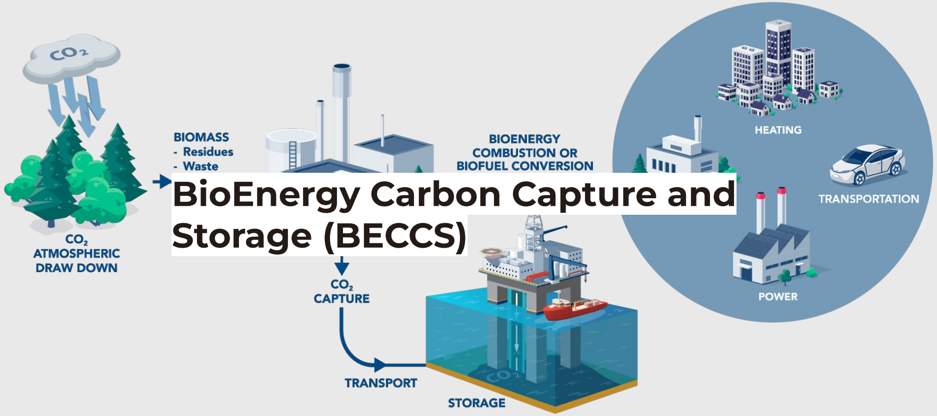
Spread over suitable land



CDR SOLUTIONS







HIGH PERMANENCE SOLUTION THAT CAN SCALE FAST

		Scalability			
Technology	Permanence	Deployment Speed	Does Not Compete For Land	Capex	Co-Benefits
Enhanced Rock Weathering	H	H	✓	$	✓
Biochar	M	H	✓	$$	✓
Direct Air Capture	H	L	✓	$$$	X
Bioenergy Carbon Capture & Storage (BECCS)	H	M	X	$$$	X
Afforestation	L	L	X	$	✓
Soil Carbon	L	M	✓	$	✓

XPRIZE - ERW CONFIDENCE

Mati Carbon
(ERW)

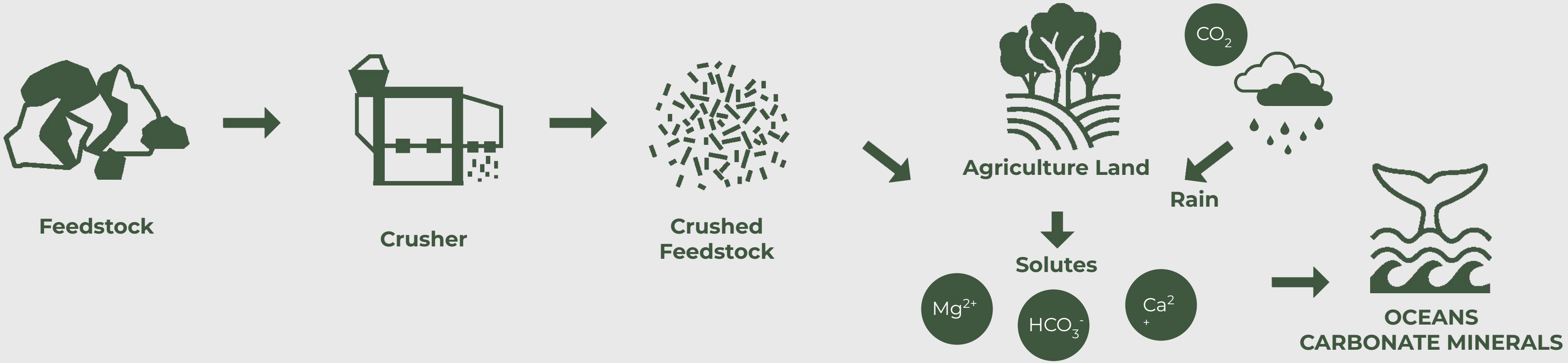
3
UNDO
(ERW)

1
NetZero
(BioChar)

2
Vaulted Deep
(BiCRS)

4 Year Competition
1400 Entrants
100M USD Prize Pot

ENHANCED WEATHERING PROCESS



Quarry operations

Feedstock

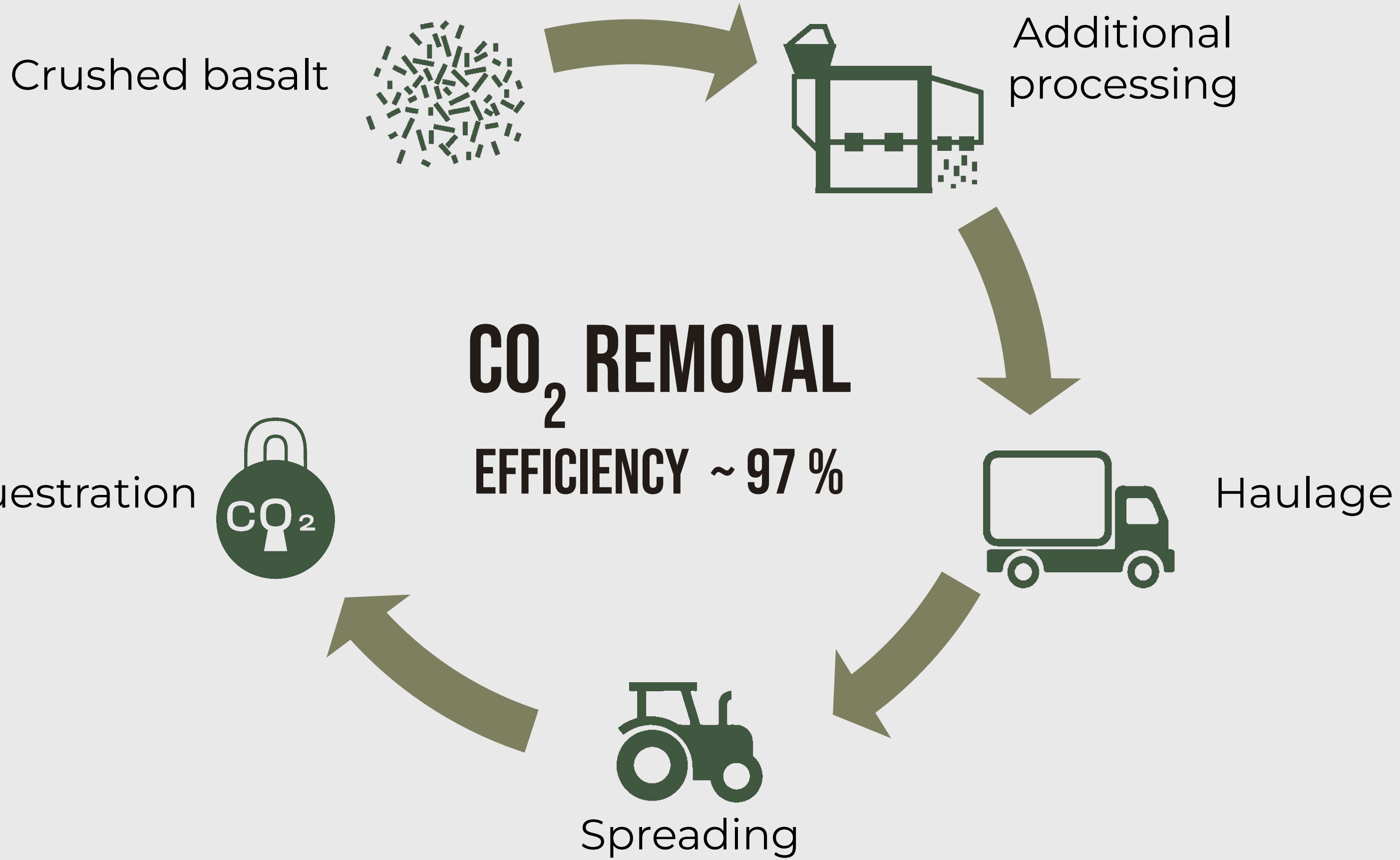
Spread

....

Wait for a ***long*** time

White Cliffs of Dover

LCA


Crushed basalt
Additional processing
Haulage
Spreading
CO_2 sequestration
CO_2
CO_2 REMOVAL
EFFICIENCY ~ 97 %

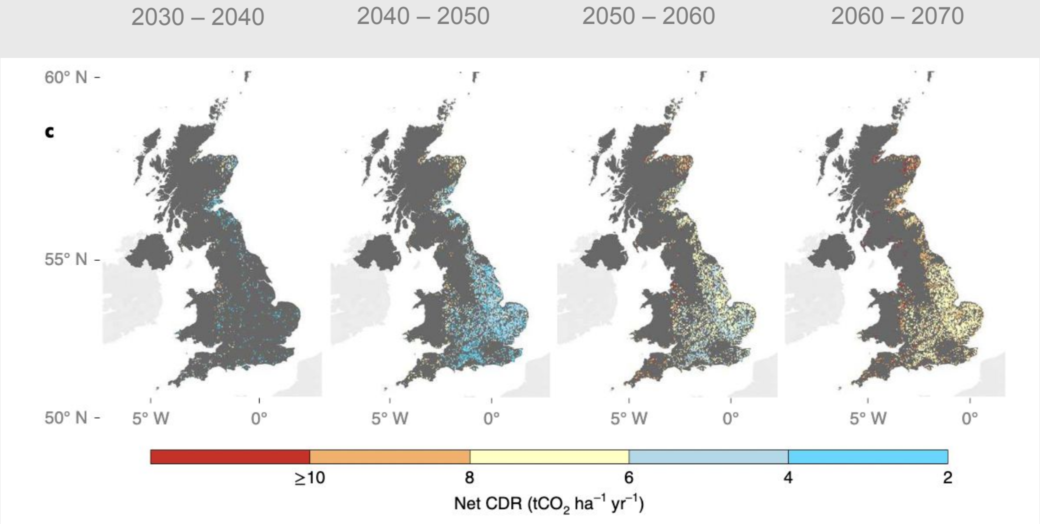
NOT ALL ROCKS ARE MADE EQUAL

Potentially Toxic Elements (PTEs), aka. *heavy metals* or *trace elements*, are a broad group of elements that can be hazardous at elevated concentrations. Some PTEs such as **Cu, Zn, Mn, and Fe** are *essential micronutrients* for plants at low levels, others such as **Cd, Pb, Ni, Hg, and Cr** are toxic even at trace concentrations.

In the context of ERW, the main elements of concern are **nickel (Ni)** and **chromium (Cr)**, as their concentrations in certain silicate rocks may exceed established soil guideline values or inorganic soil improver limits. PTEs tend to **bind strongly to soil particles**, particularly clays and organic matter, which limits plant uptake and leaching so can lead to **long-term accumulation in soils**.

Name	CDR Potential	PTE Risk	Abundance	Grinding Energy
Ultramafic–mafic silicates *(**olivine**, dunite, serpentinite)*	V High 1.25 *tCO2/tRock*	High	**Low-Moderate** ~1% of continental crust; limited surface exposure, concentrated in specific belts	**High** Very hard and dense (Mohs 6.5–7)
Mafic silicates *(**basalt**, gabbro)*	Low 0.30 *tCO2/tRock*	Low-Medium	**High** ~8 - 10% of continental crust and dominant in oceanic crust; widely distributed and accessible in many regions	**Medium** Moderately hard (Mohs 5.5–6.5)
Calcium silicates (***wollastonite***)	High 0.70 *tCO2/tRock*	Low	**Low** rare mineral (~0.005% of crust); deposits occur in metamorphic skarns, often associated with ore zones; limited but mineable reserves in specific locations.	**Low-Medium** softer (Mohs 4.5–5.0)

ENHANCED WEATHERING ON UK ARABLE CROPLANDS

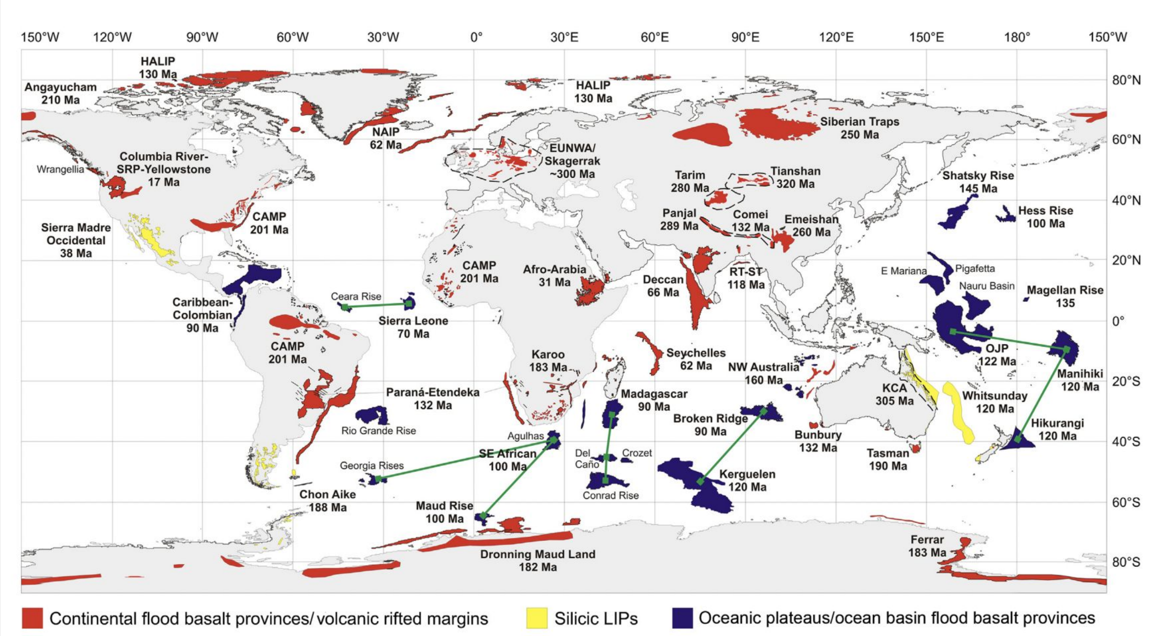


Kantzas et al. (2022)

Carbon removal potential
6 – 30 Mt CO_2 per year by 2050

Potential for ~**45 %** of the removals required to meet the UK's net-zero emission targets

POTENTIAL FOR SCALE

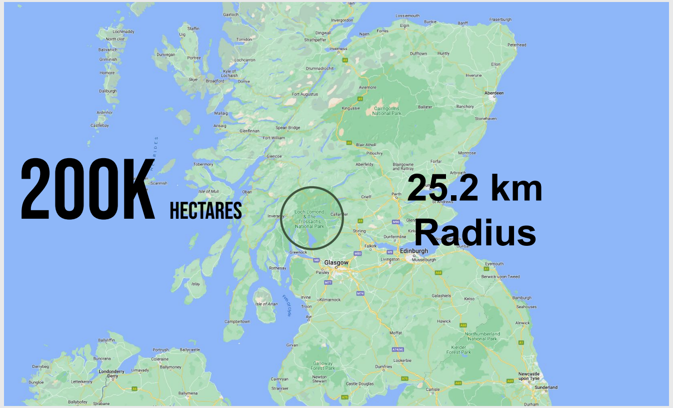


(Self et al. 2015)

BILLIONS OF TONNES OF BASALT GLOBALLY

4MT ROCK

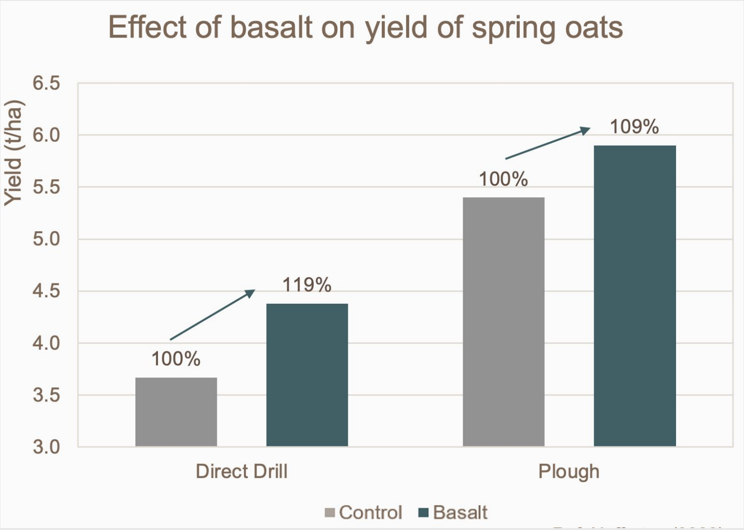
1MT CO_2E

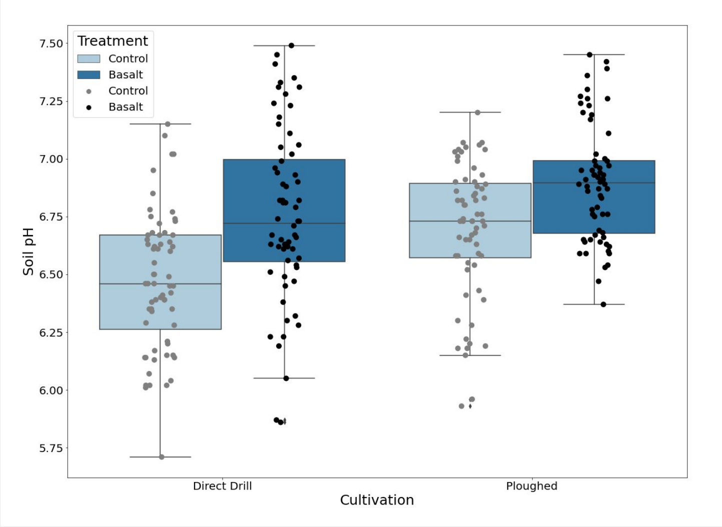


CO-BENEFITS TO SOILS AND PLANTS

Nafferton Farm - Newcastle University

1. Yield Response
2. Increase in pH
3. No PTEs uptake





CO-BENEFITS TO SC

Nafferton Farm - N

1. Yield Response
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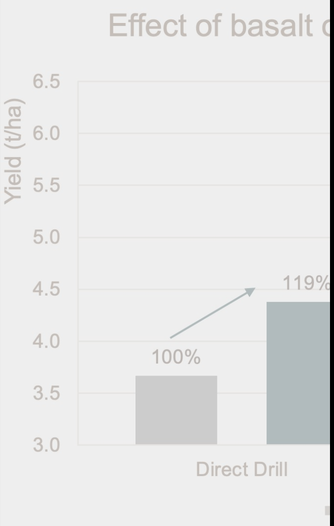
3. No PTEs uptake



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Environment

Spreading rock dust on farms boosts crop yields and captures CO2

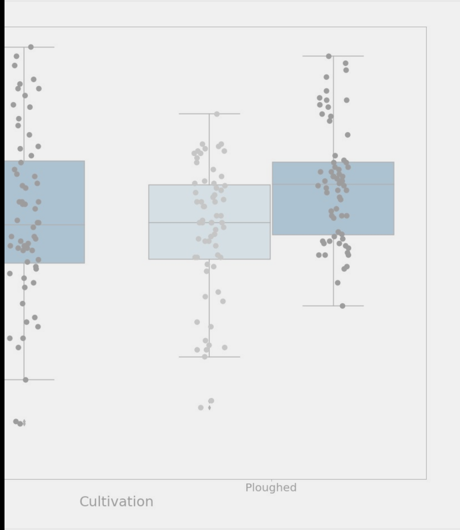
We already have evidence that rock dust can remove carbon dioxide from the air – now there are signs that spreading the dust on farm fields also enhances crop growth

By James Dinneen

28 March 2024

Basalt rock dust being scattered on a field in the UK

Image courtesy of UNDO



ERW HAS GENUINE POTENTIAL TO REACH GIGATONNE SCALE AT LOW COST

WHAT IS MRV?

MRV (measurement, reporting, verification) is a multi-step process that examines the amount of CO2 sequestered from CDR project, with the aim of generating verified carbon removal credits.

UNDO's measurement approach consists of:

1) Measure (in-field measurements)
2) Assign Simalarity (deployment soil samples)
2) Model (sequestration prediction)

Both of these steps help us prove that weathering and carbon sequestration has occurred.

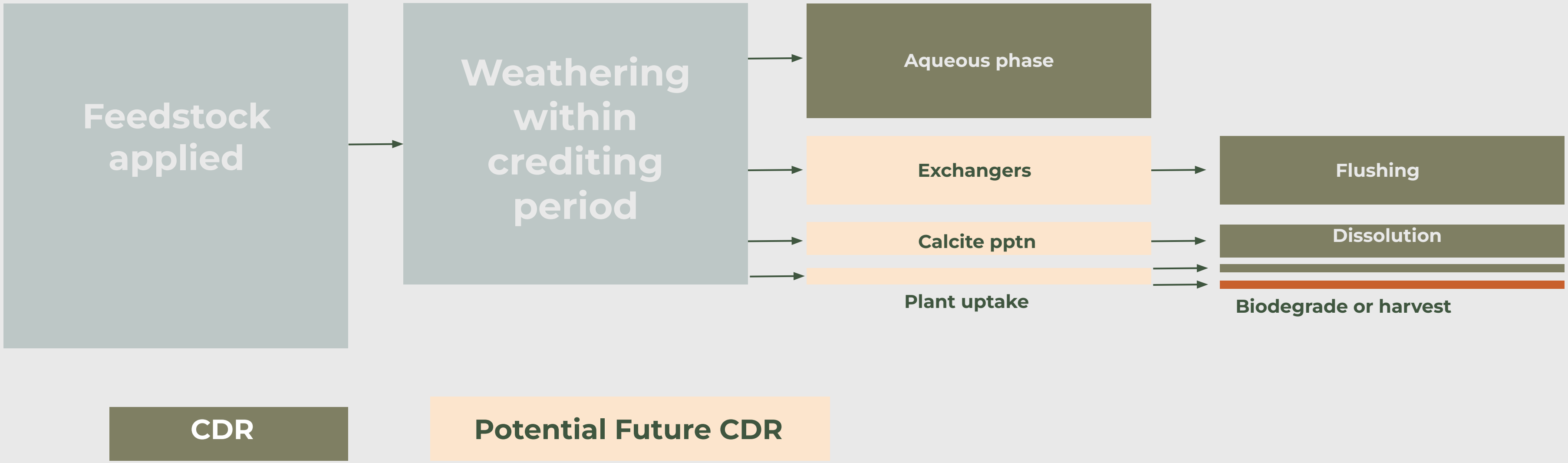
CDR IN THE NEAR FIELD ZONE

Step one: Minerals in the feedstock break down and release cations into pore water.

Step two: In the short term, cations can remain in the aqueous phase, or:

- Sit on exchange sites.
- Precipitate as secondary minerals.
- Be taken up by plants.

Step three: Cations can be released from these temporary pools, re-entering the aqueous phase.



HOW WE MEASURE

Soil electrical conductivity (proxy for TA in porewater)

[see: Amann and Hartmann, 2022]

Soil pH, buffer pH (constraining DIC in porewater)

Soil exchangeable pool cations

[see: Dietzen and Rosing, 2023]

Soil TIC

[see: e.g., Haque et al., 2020]

Plant biomass, cation content

Soil CO2 flux, eddy covariance CO2 flux

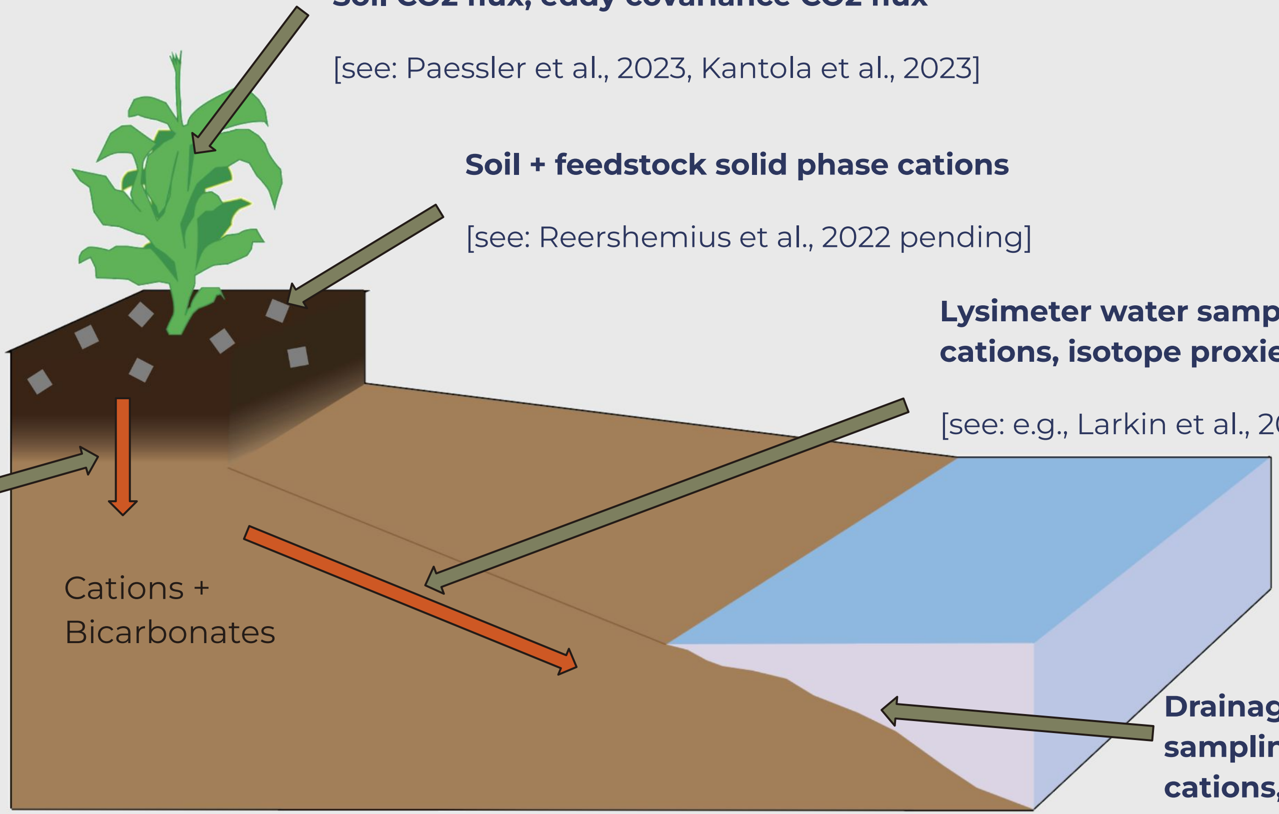
[see: Paessler et al., 2023, Kantola et al., 2023]

Soil + feedstock solid phase cations

[see: Reershemius et al., 2022 pending]

Lysimeter water sampling (TA, DIC, cations, isotope proxies)

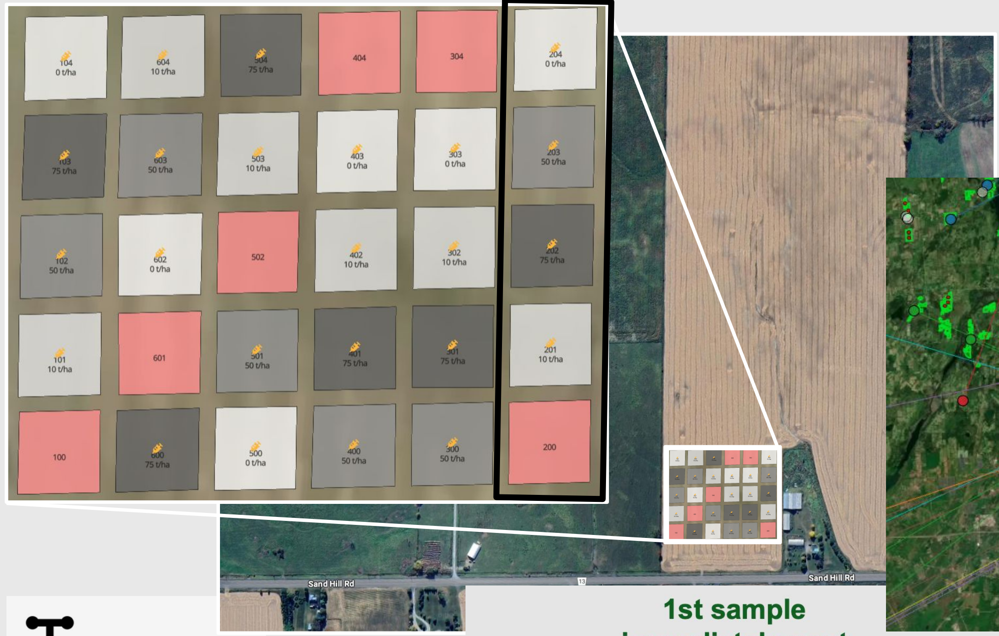
[see: e.g., Larkin et al., 2022]

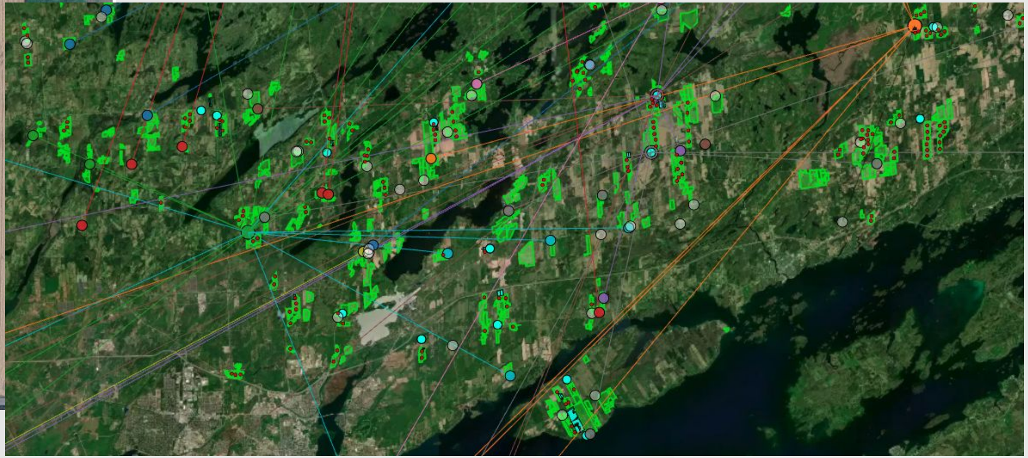


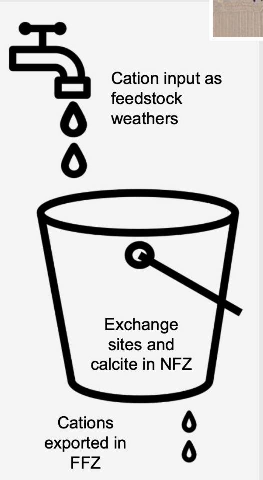
Drainage/river water sampling (TA, DIC, pH, cations, isotope proxies)

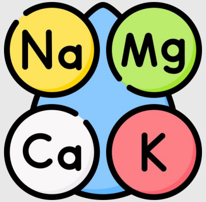
[see: e.g., Larkin et al., 202

HOW WE MEASURE CDR









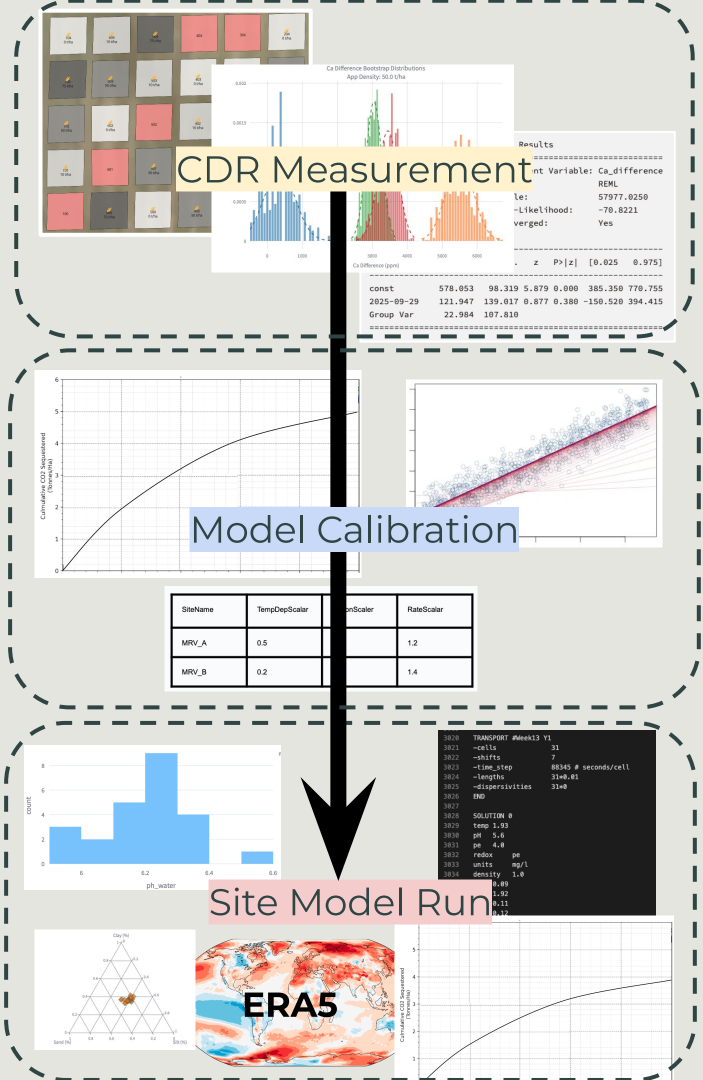
(Baum et al., 2024)

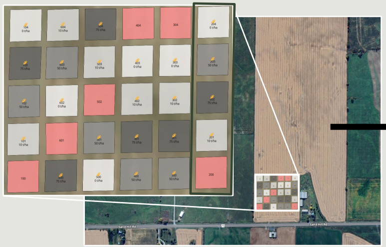
EXTRAPOLATING MEASURED CDR

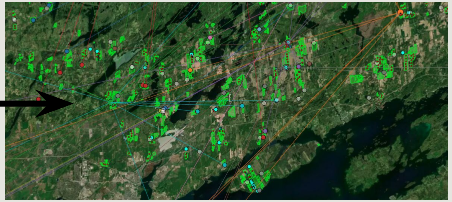
To account for rock not being spread at the MRV site and operational site on the same day we have to apply small, model-based adjustments.

- Geochemical model is calibrated using empirical data
- Modelled weathering kinetics are tuned to reproduce observed CDR signals.
- MRV site models become reliable reference systems that define the measured relationship between site conditions and CDR.
- Results in a site-specific calibrated model that forms the quantitative basis for CDR determination at all operational fields assigned via the similarity measure.

The approach ensures scientific rigour, traceability, and scalability providing a transparent bridge between field measurements and operational-scale crediting.



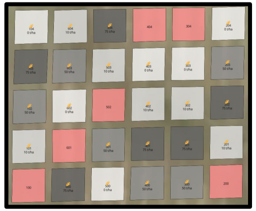




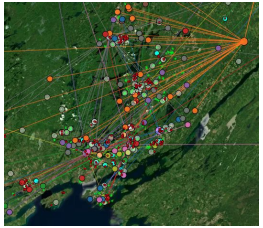
RECAP

Ensure operational area is well constrained

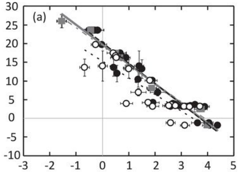
Take deployment baseline soil samples across fields



Set up MRV sites across the operational area

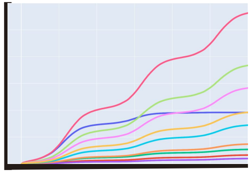


Match operational sites to MRV sites based on soil properties.



Calibrate geochemical model to data from MRV Sites

Run MRV site calibrated model against all deployment sites



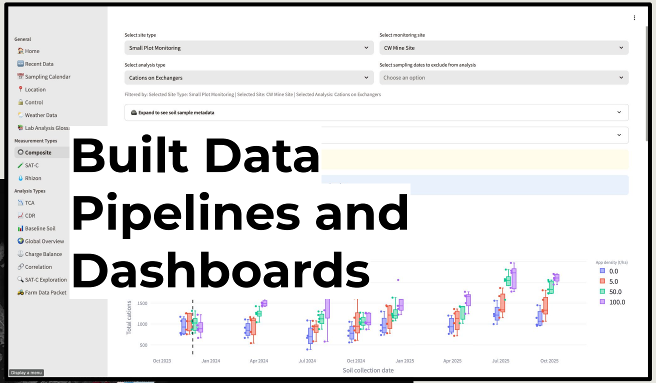
Combine all output to produce an operational wide CDR curve

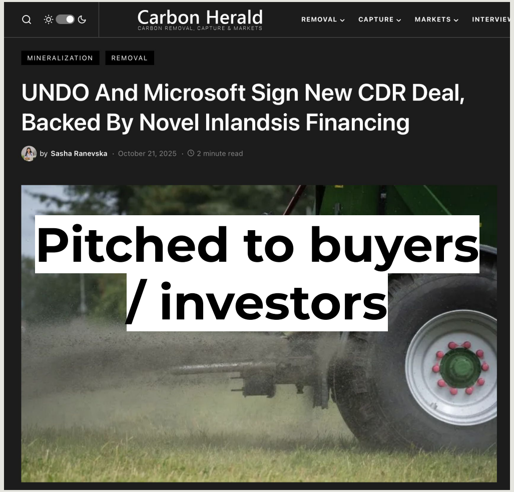
Measurement Aligned Spatial Translation

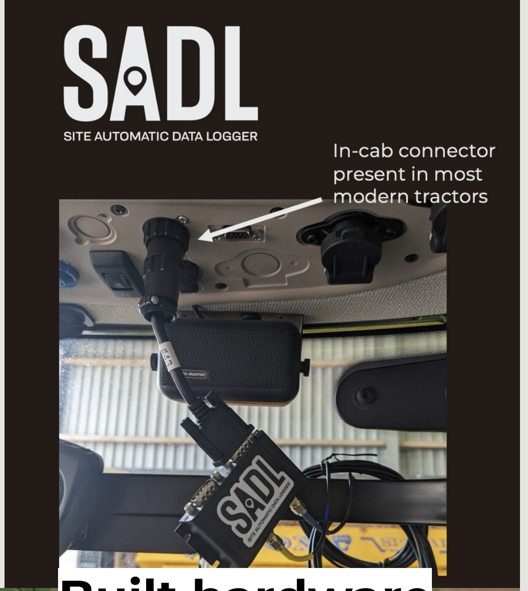
MAST

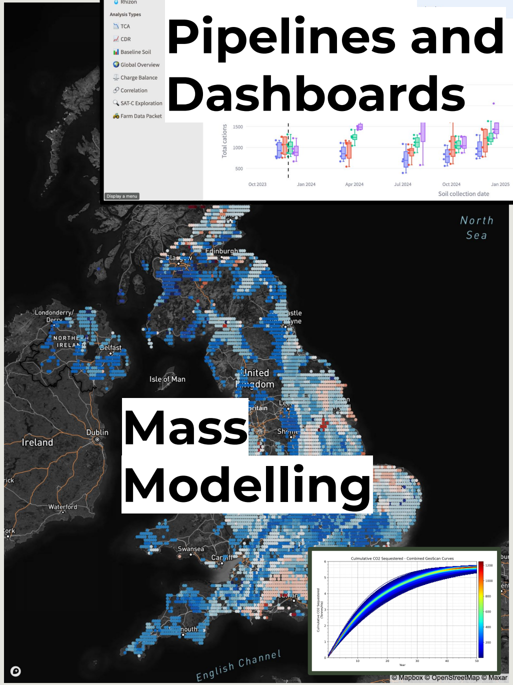
WHAT CAN A PHYSICIST DO?

Since I joined UNDO..









THE CLIMATE CRISIS WE FACE

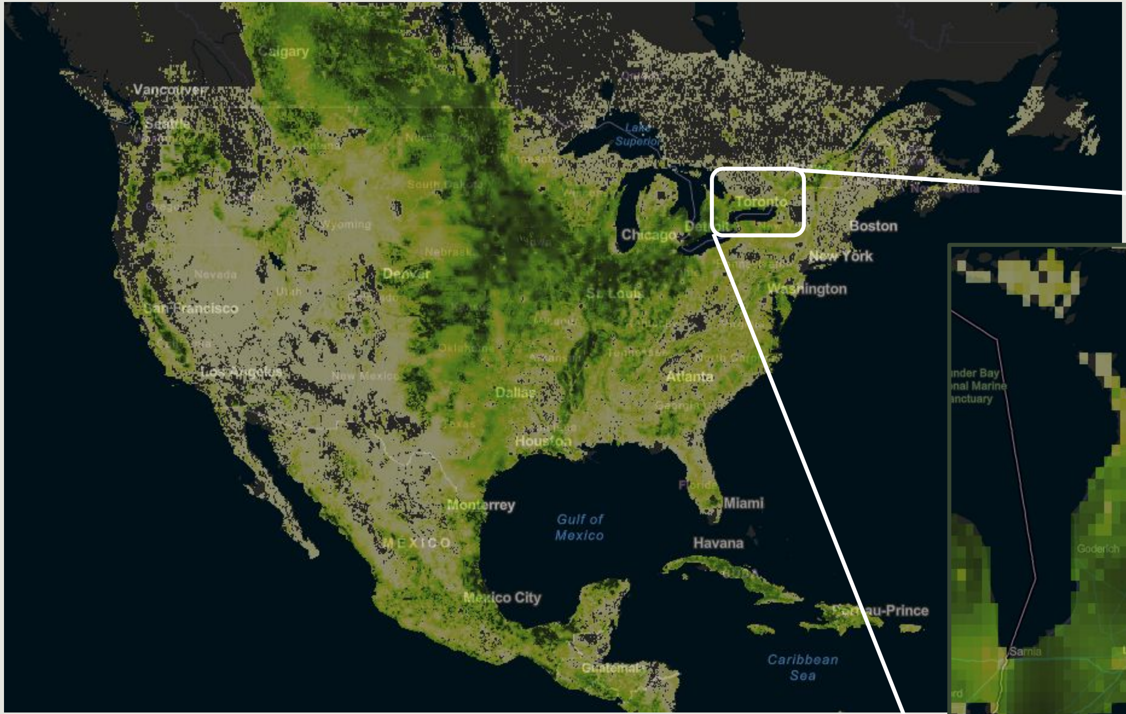
There is a removal need of **10 billion tonnes by 2050 per year** in order to stay within the SBTI goals and achieve net zero by 2050.

Reducing emissions alone isn't enough, we need to remove and we need to do it at scale.

Every one of the world's top 200 research universities have to figure out how to remove 50 million tonnes of CO_2 per year


THANK YOU
UNDO

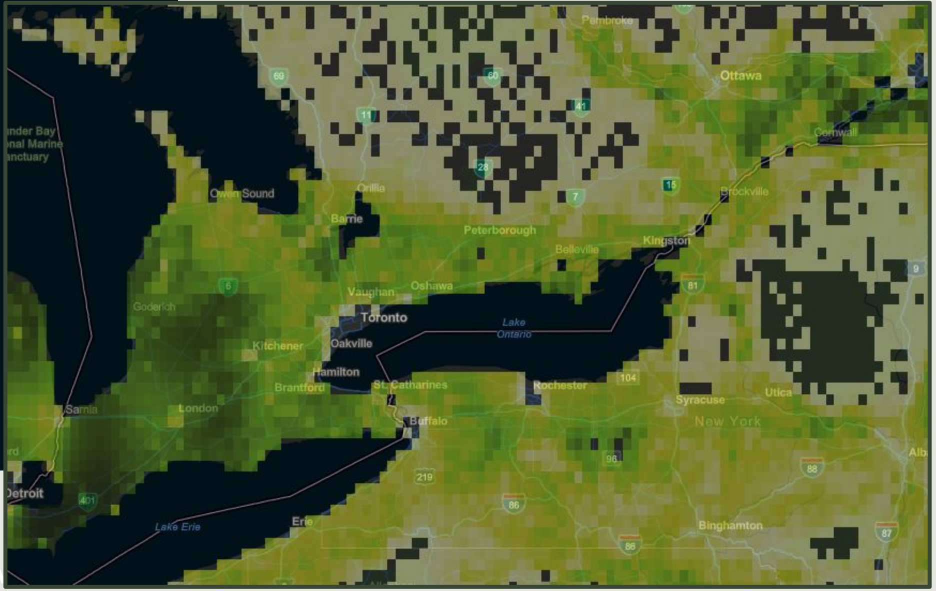
SCALE PROBLEM - ONTARIO OPERATIONAL AREA



1.2M HA CROPLAND

25% = 300,000 HA

2 *SAMPLES* / HA = 600,000 *SAMPLES/YR*



Assuming you can detect a statistically significant signal at operational spread density…

CLIMATE ACROSS AREA OF INTEREST

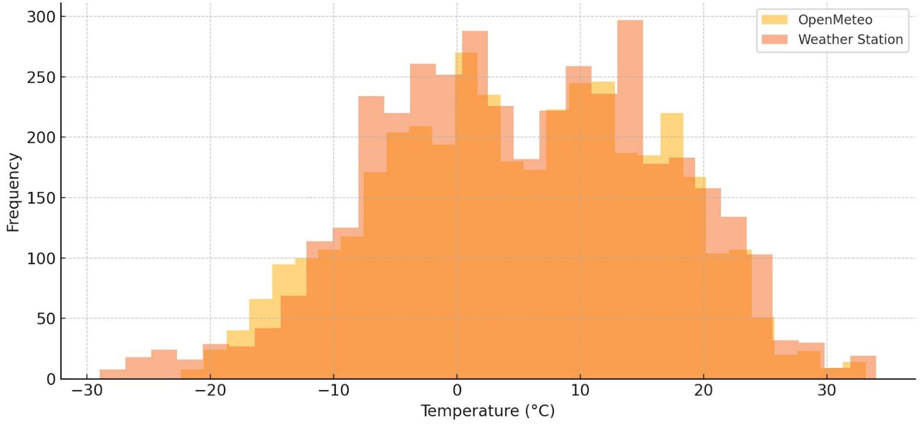
ERA5 datasets provide continuous, high-resolution temperature and precipitation data across the operational area.

In-field weather stations are used to validate ERA5 performance under local field conditions.

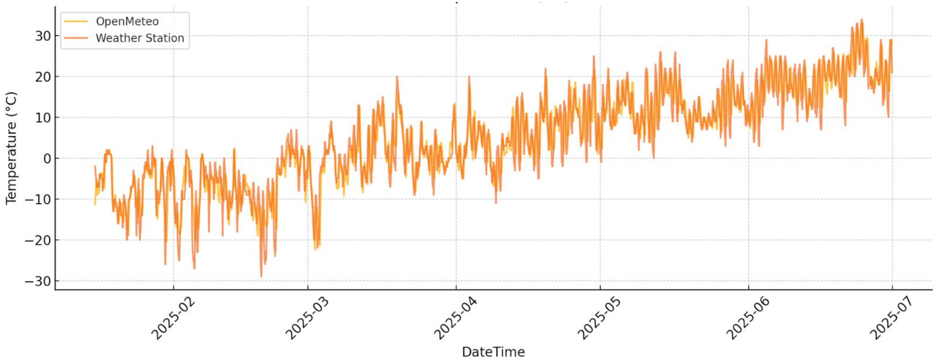
The strong alignment confirms ERA5 captures real climatic variability, making it reliable for MRV and model inputs.

This ensures all subsequent analyses and model calibrations are grounded in accurate, site-specific climate data.

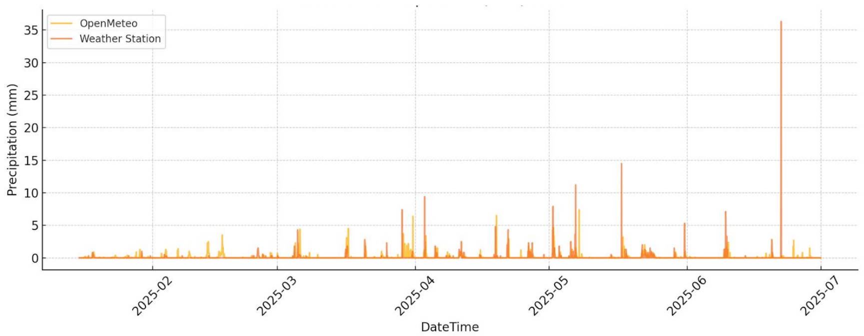
TEMPERATURE (° C) DISTRIBUTION



TEMPERATURE (° C) OVER TIME



TEMPERATURE (MM) OVER TIME

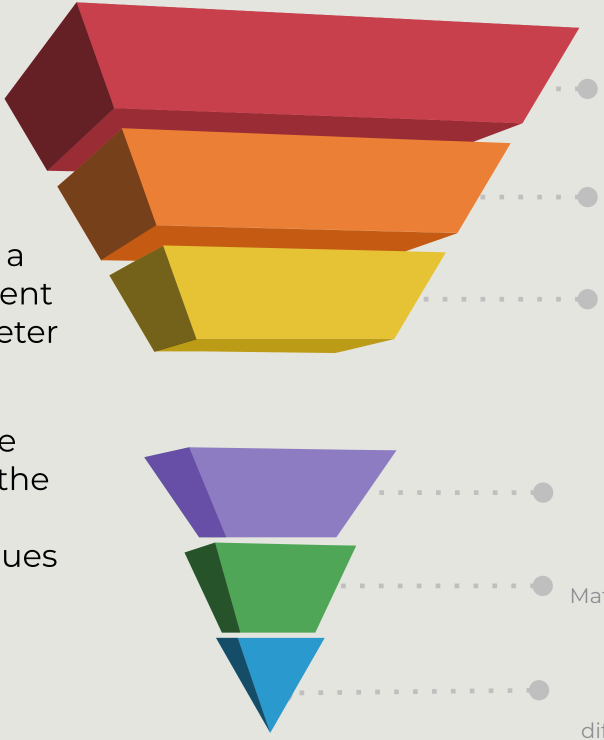


CARRY OUT MEASUREMENTS IN THE VARIABLES YOU CAN'T CONSTRAIN

We have discussed the variables that are tightly controlled across our operational area, the key drivers of weathering, and the extent to which they can be standardised. However, residual variability remains.

To capture this residual variability, we deploy a network of intensively monitored measurement sites designed to span the remaining parameter space.

These measurements allow us to quantify the similarity between each operational job and the monitored sites - avoiding unnecessary dimensional complexity - and derive CDR values that are representative for each matched operational context.



Rock (Mineralogy & Surface Area)

Consistent mineral composition, including reactive surface area and PSD

Climate / Seasonal Variation

Constrain Temperature and rainfall

Land / Crop

Consistent crop rotation and land management practices across the operational area

Intra-Operational Area Soil Variation

Relate measured CDR to the site-specific soil characteristics observed

Time Alignment for CDR Accounting

Match measurement periods with the corresponding operational job timelines

Localised Climate

Adjust measured CDR for any microclimatic differences between measurement and operational sites

CARRY OUT MEASUREMENTS IN THE VARIABLES YOU CAN'T CONSTRAIN

Make measurements of CDR in locations that cover the variables that control weathering and export rate using Small Plot Monitoring Sites (SPMS). A randomised block design with 6 replicates of control blocks and 3 different treatments blocks, this data feeds into a linear mixed-effect statistical model. Exposed to regular land management practises.

LINEAR MIXED-EFFECTS MODEL (LMM)

Fixed effects

Application density (continuous variable)

Date (categorical variable)

Random effects

Block (accounts for spatial variability).

$$y_{ij} = \beta_0 + \beta_1\,\mathrm{density}_{ij} + \sum_{t=2}^{T} \beta_t\,\mathbf{1}\{\mathrm{date}_j = t\} + u_{b(i)} + \varepsilon_{ij}$$

Fitting by REML gives variance components, which lets us calculate Intraclass Correlation -> how much variability lives at the block level (spatial heterogeneity)

Partial pooling improves estimates and handles unequal n across blocks.


```
Mixed Linear Model Regression Results
==============================================================
Model:              MixedLM Dependent Variable: Ca_difference
No. Observations: 12      Method:               REML
No. Groups:       6       Scale:                57977.0250
Min. group size:  2       Log-Likelihood:       -70.8221
Max. group size:  2       Converged:            Yes
Mean group size:  2.0
--------------------------------------------------------------
              Coef.  Std.Err.   z   P>|z|  [0.025   0.975]
--------------------------------------------------------------
const        578.053   98.319 5.879 0.000  385.350 770.755
2025-09-29   121.947  139.017 0.877 0.380 -150.520 394.415
Group Var     22.984  107.810
==============================================================
```

CLIMATE REPRESENTATIVENESS

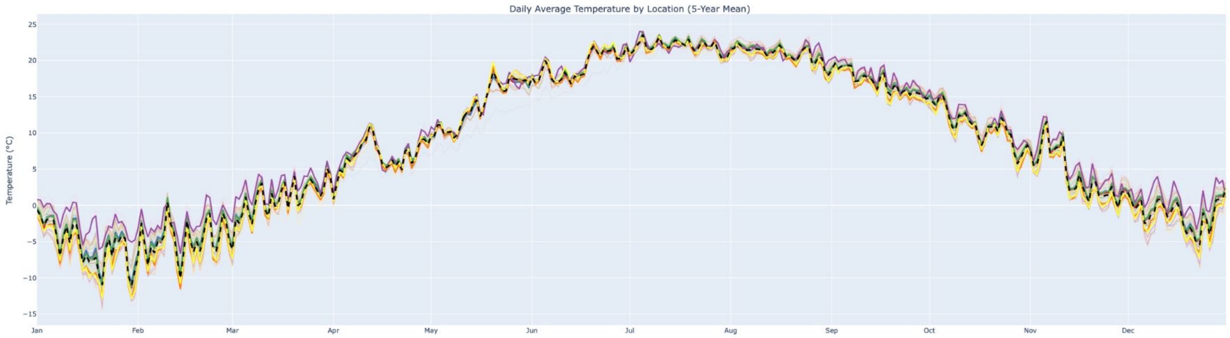
ERA5 validated climate datasets lets us compare daily temperature and precipitation trends for every operational job with those at MRV monitoring sites.

Tight overlap between these datasets shows that our MRV network captures the full climatic variability of the deployment area.

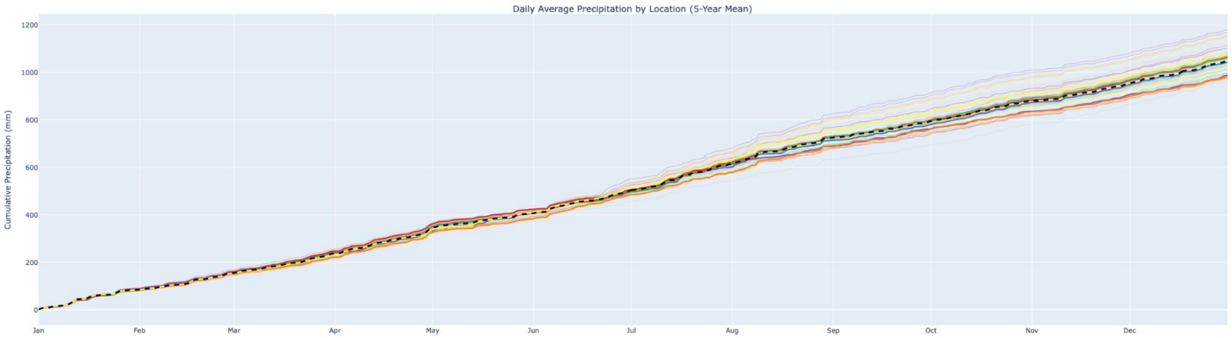
This confirms that measured weathering rates are transferable to operational fields within the same climatic envelope.

ERA5 data, (validated by onsite weather stations), ensures hydrological realism in PHREEQC transport blocks and accurate soil–climate coupling.

DAILY TEMPERATURE ANALYSIS: OPERATIONAL VS MONITORING SITES



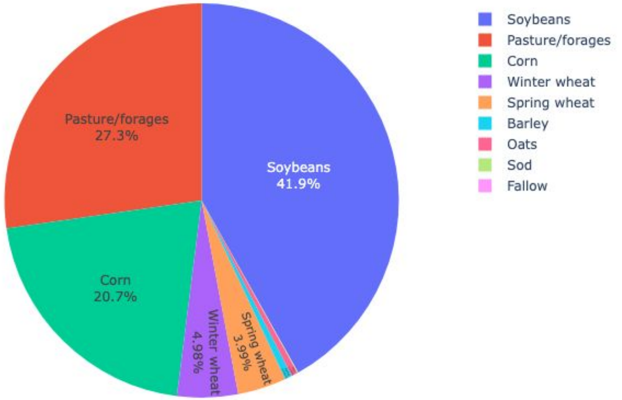
DAILY PRECIPITATION ANALYSIS: OPERATIONAL VS MONITORING SITES



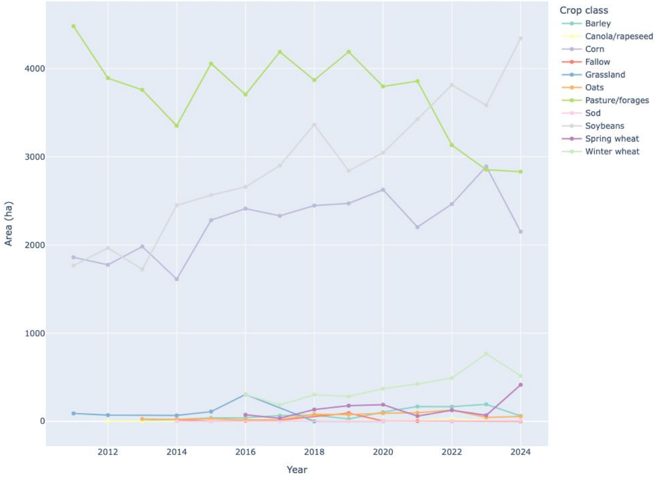
CROP ACROSS AREA OF INTEREST

AAFC Annual Crop Inventory (2011-present) provides field level crop classification across our operational area.
This dataset allows us to reconstruct historic crop rotations and land-management practices, including fertiliser use, liming frequency, and tillage intensity.
Long-term trends show stable crop composition dominated by soy, corn, and forage systems - the same crop types represented in our MRV sites. Visible is a recent conversion of pasture to cash crops.
Ensures our MRV sites reflect the agronomic reality of the operational area, representative of the crops, soils, and management systems in which ERW occurs.

OPERATIONAL AREA CROP COVERAGE COMPARISON FOR 2024



CROP AREA OVER TIME: FIELD-LEVEL POINTS WITH YEARLY TOTALS



OUR GEOCHEMICAL MODEL SO FAR

Four key categories of variables used by model:

1. FEEDSTOCK

- Mineralogy (wollastonite, plagioclase, pyroxene)
- Mineral dissolution rates
- Particle size and surface area
- Application density

2. CLIMATE

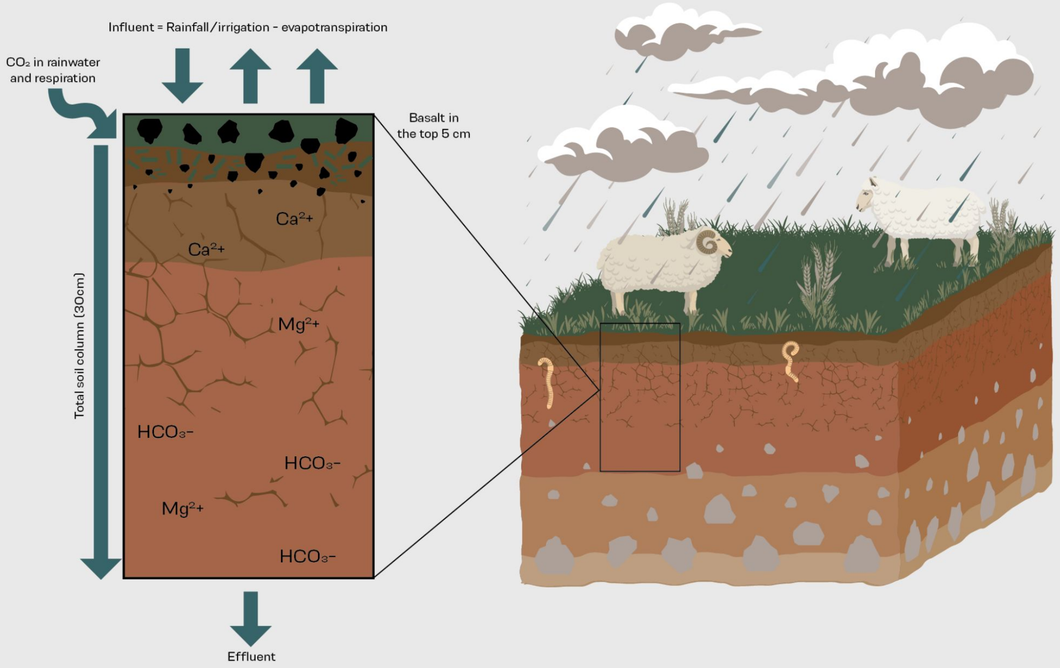
- Temperature
- Precipitation ± irrigation

3. SOIL (PHYSICAL & CHEMICAL) PARAMETERS

- pH
- Texture
- CEC (Cation Exchange Capacity)
- SOC (Soil Organic Carbon)
- Bulk density
- Water filled porosity

4. ATMOSPHERE

- Atmospheric CO_2
- Soil CO_2 partial pressure



Above: From model paper: carbon sequestration is modelled using PHREEQC (Parkhurst and Appelo, 2013), using published experimentally derived kinetic and thermodynamic data (Palandri and Karaka, 2004)

DEPLOYMENT SITE CHARACTERISATION

Define each deployment site in a way that lets us translate MRV measurements to operational jobs consistently, transparently, and within the applicability domain.

Baseline soil (per field / management unit) lab analysis for pH, CEC, Sand % (standard composite, ISO-accredited lab) from a composite “W” pattern across the field (walk a W and take multiple plugs along the transect, combine to one composite per field).

TRANSLATING MRV MEASUREMENTS WITH THE SIMILARITY MEASURE

DATA COLLECTION AND STANDARDISATION

Soil parameters measured at MRV and operational sites,
- **pH** (chemical reactivity and weathering control)
- **CEC** (ion retention and buffering capacity)
- **Sand %** (textural drainage and aeration control)

All parameters obtained through standard composite sampling and ISO-accredited lab analyses.

Each parameter is standardised (z-scored) using the population mean and standard deviation across all sites. Ensures comparability between variables with different units (pH vs %) and prevents any single variable from dominating the analysis.

DISTANCE CALCULATION

- For each operational<–>MRV site pair: $D = \max_i \left(w_i \left| f_i - s_i \right| \right)$ where f_i, s_i are standardised feature values for parameter i, and w_i is its weight.

- This weighted Chebyshev distance captures the largest standardised difference across parameters (a conservative, interpretable measure)

SIMILARITY SCORING & THRESHOLDING

- Distances are transformed to a bounded similarity score (0–1).
- Threshold = 0.5 corresponds to < 1 SD difference in any parameter.
- Fields with scores ≥ threshold are assigned to that MRV site; otherwise “Not Assigned.”

Results in assignments being inside a strict applicability domain

EXTRAPOLATING MEASURED CDR

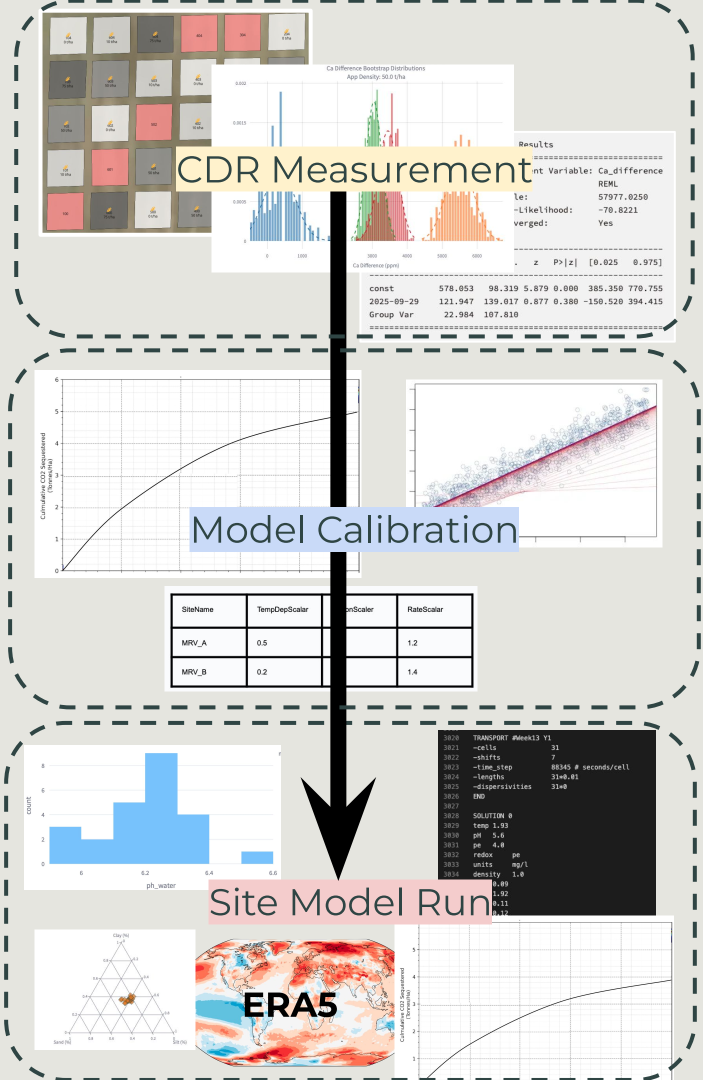
To account for rock not being spread at the MRV site and operational site on the same day we have to apply small, model-based adjustments to account for Seasonal and Climatic variations as well as Feedstock batch differences.

- Kellend 2020 model is calibrated using empirical data (pore water, soil cations, carbonates, TCA).
- Modelled weathering kinetics are tuned to reproduce observed CDR signals.
- MRV site models become reliable reference systems that define the measured relationship between site conditions and CDR.
- Results in a site-specific calibrated model that forms the quantitative basis for CDR determination at all operational fields assigned via the similarity measure.

This process creates a site-specific instance of the calibrated model, this enables consistent, auditable CDR quantification across all operational fields, tied directly to measured MRV data.

For each operational field assigned via similarity we run the model with site specific input params:
Experienced Climate (from ERA5) / **pH, CEC, and texture** (from baseline sampling) / **Feedstock composition** (from operational rock sample)

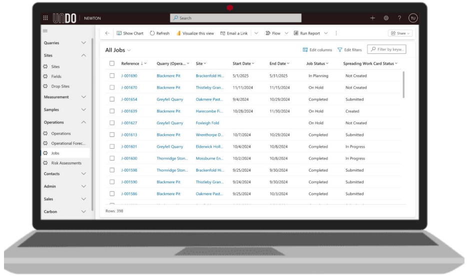
The approach ensures scientific rigour, traceability, and scalability providing a transparent bridge between field measurements and operational-scale crediting.

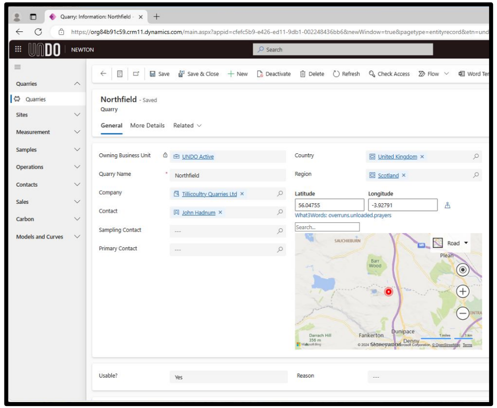


TECH THAT ENABLES SCALE

1. NEWTON (Web Platform)

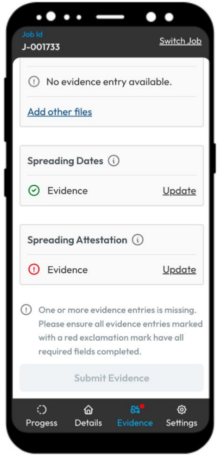
The central hub of the platform, accessed via desktop or laptop.

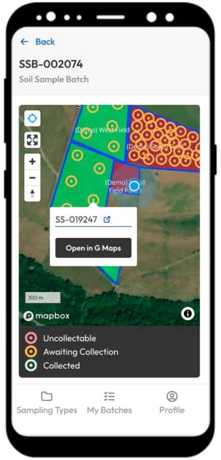




2. Contractor App

A mobile app for Android and iOS, designed for external contractors (e.g. tractor drivers) in submitting spreading evidence.





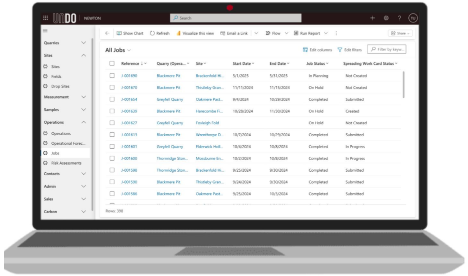
3. Sampling App

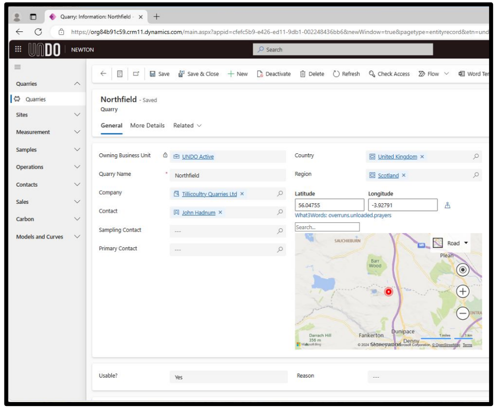
A mobile app for Android and iOS used during scientific trials and measurement activities

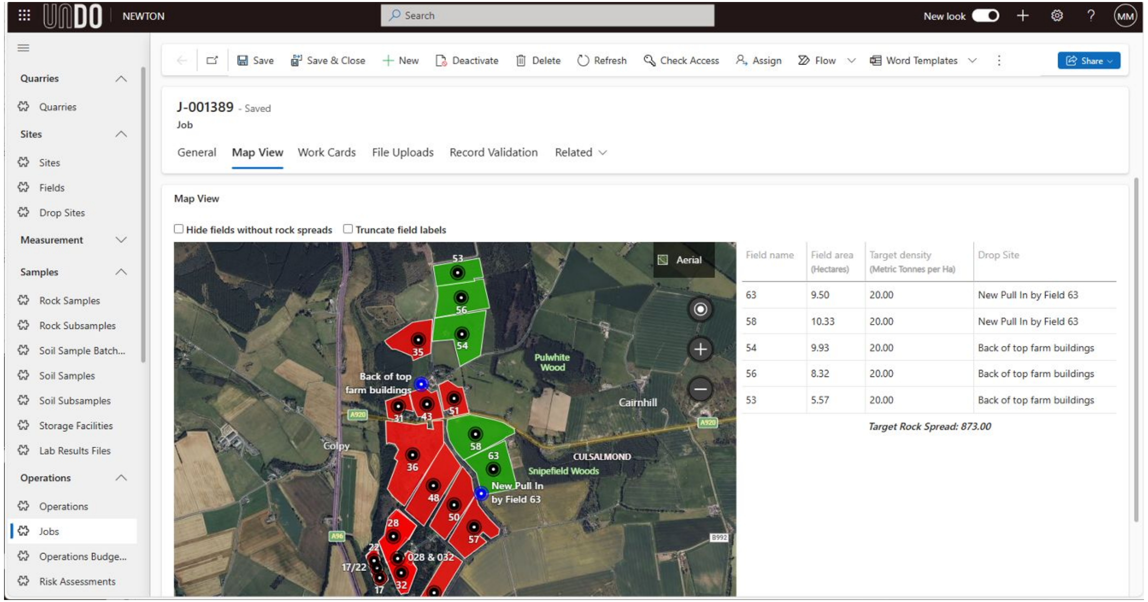
TECH THAT ENABLES SCALE

1. NEWTON (Web Platform)

The central hub of the platform, accessed via desktop or laptop.



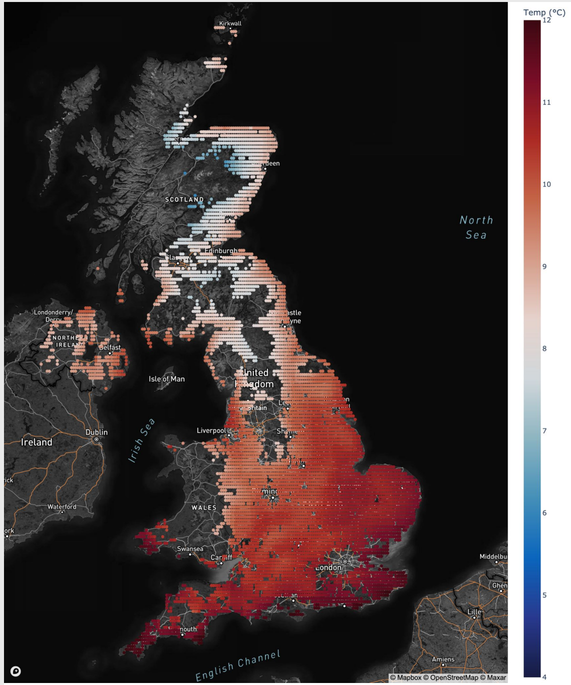


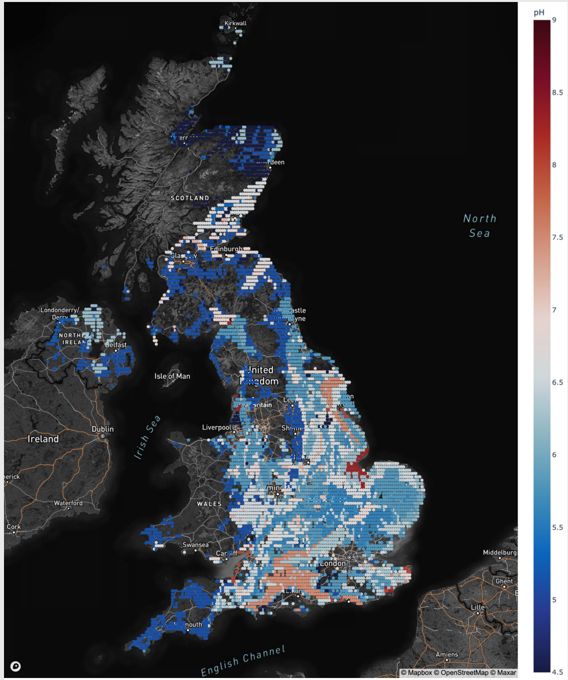


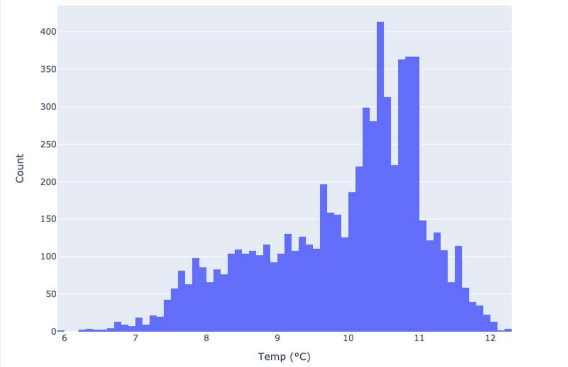
INTERNATIONAL PARTNERS

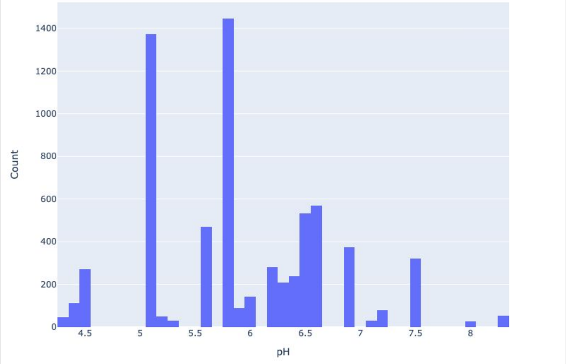
INPUT PARAMETERS

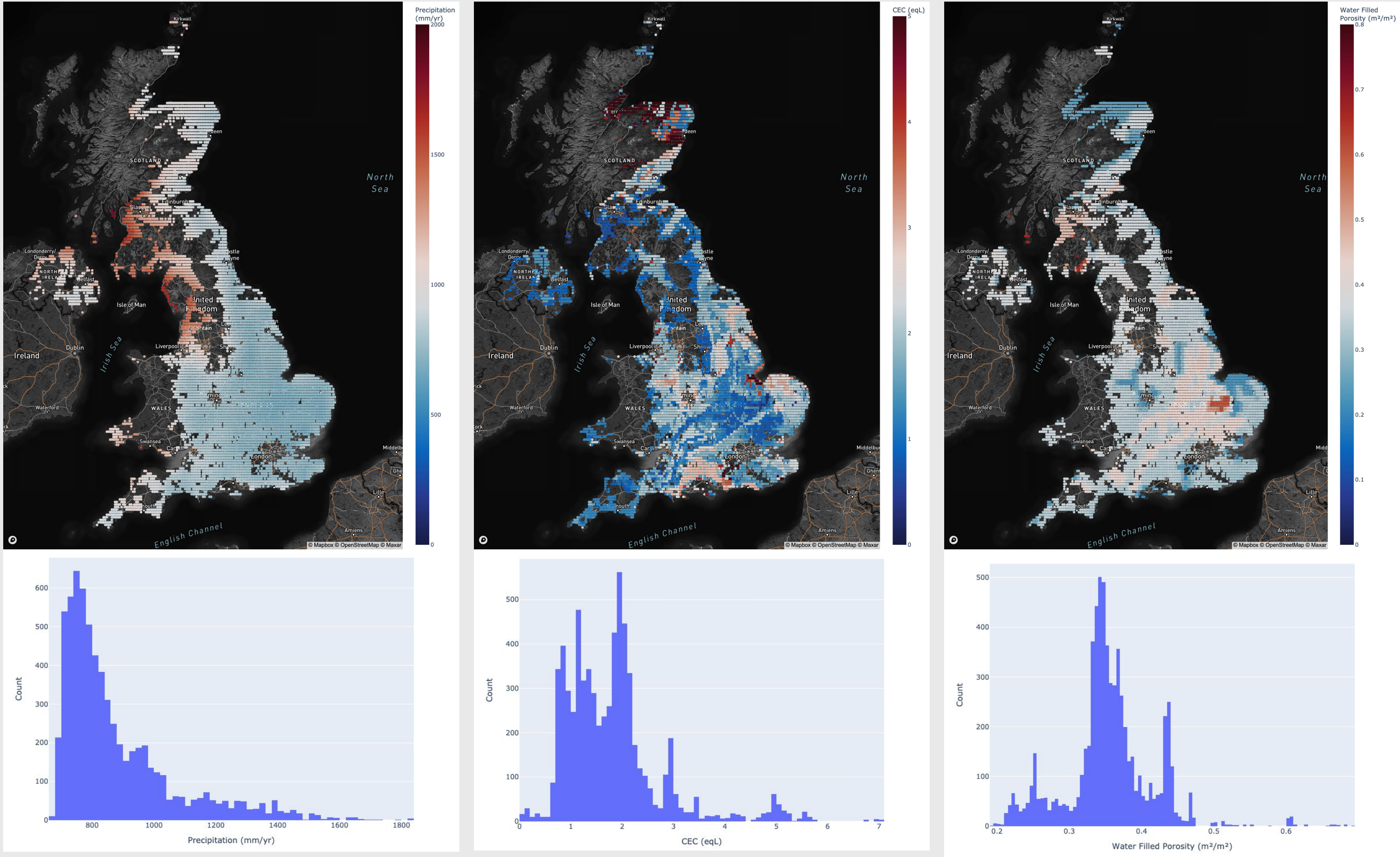
Yearly average climate and soil parameters for areas with >15% cropland visualised on a map as well as a histogram.







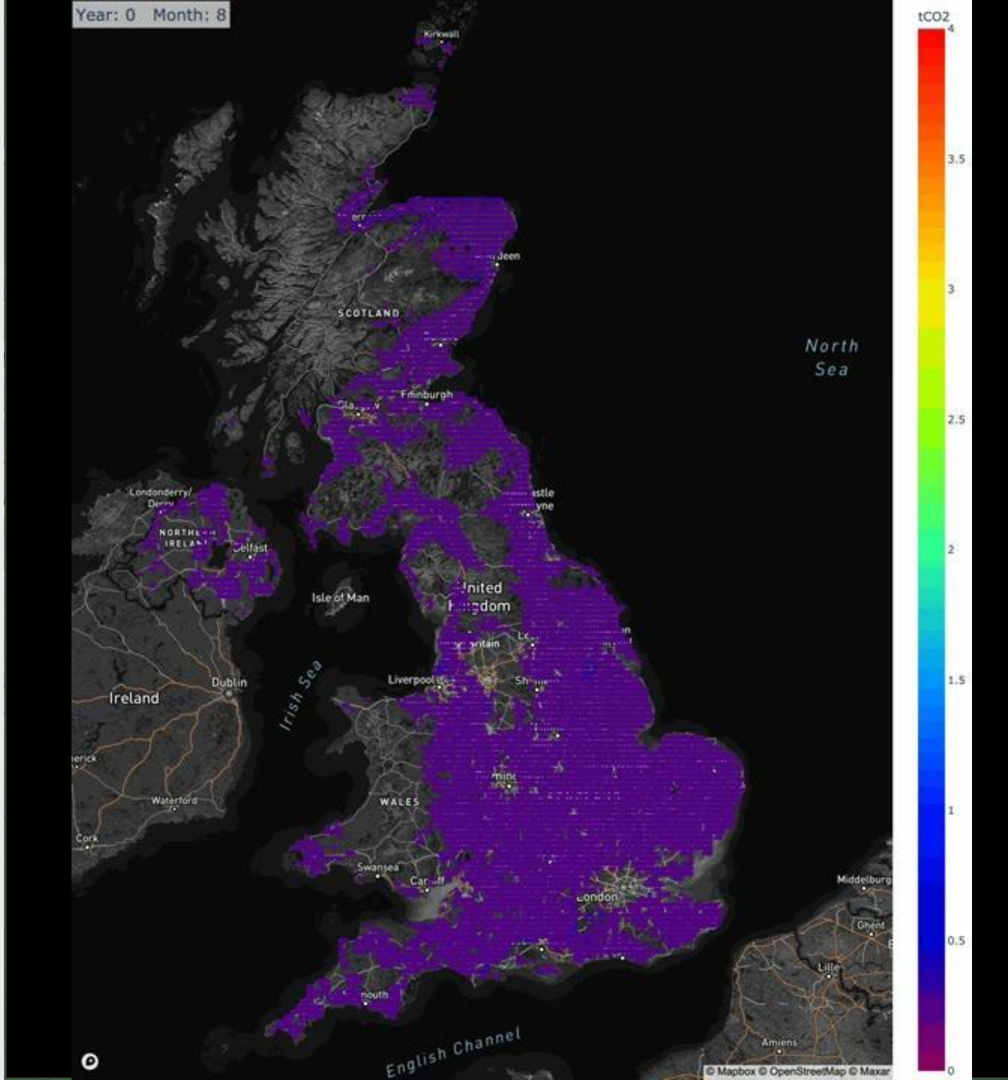



Precipitation (mm/yr)
2000
1500
1000
500
0
CEC (eqL)
5
4
3
2
1
0
Water Filled Porosity (m²/m²)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Kirkwall
SCOTLAND
Edinburgh
Glasgow
North Sea
Londonderry/ Derry
NORTHERN IRELAND
Belfast
Isle of Man
United Kingdom
Ireland
Dublin
Irish Sea
Liverpool
WALES
Waterford
Swansea
Cardiff
London
English Channel
Lille
Amiens
© Mapbox © OpenStreetMap © Maxar
Count
Precipitation (mm/yr)
800
1000
1200
1400
1600
1800
CEC (eqL)
Water Filled Porosity (m²/m²)

HEATMAP OF CUMULATIVE CDR ANIMATED OVER TIME

This graphic shows CDR in 4 month intervals between up to 20 years.

The colour range is between 0 tCO_2 (purple) and 4 tCO_2 (red).

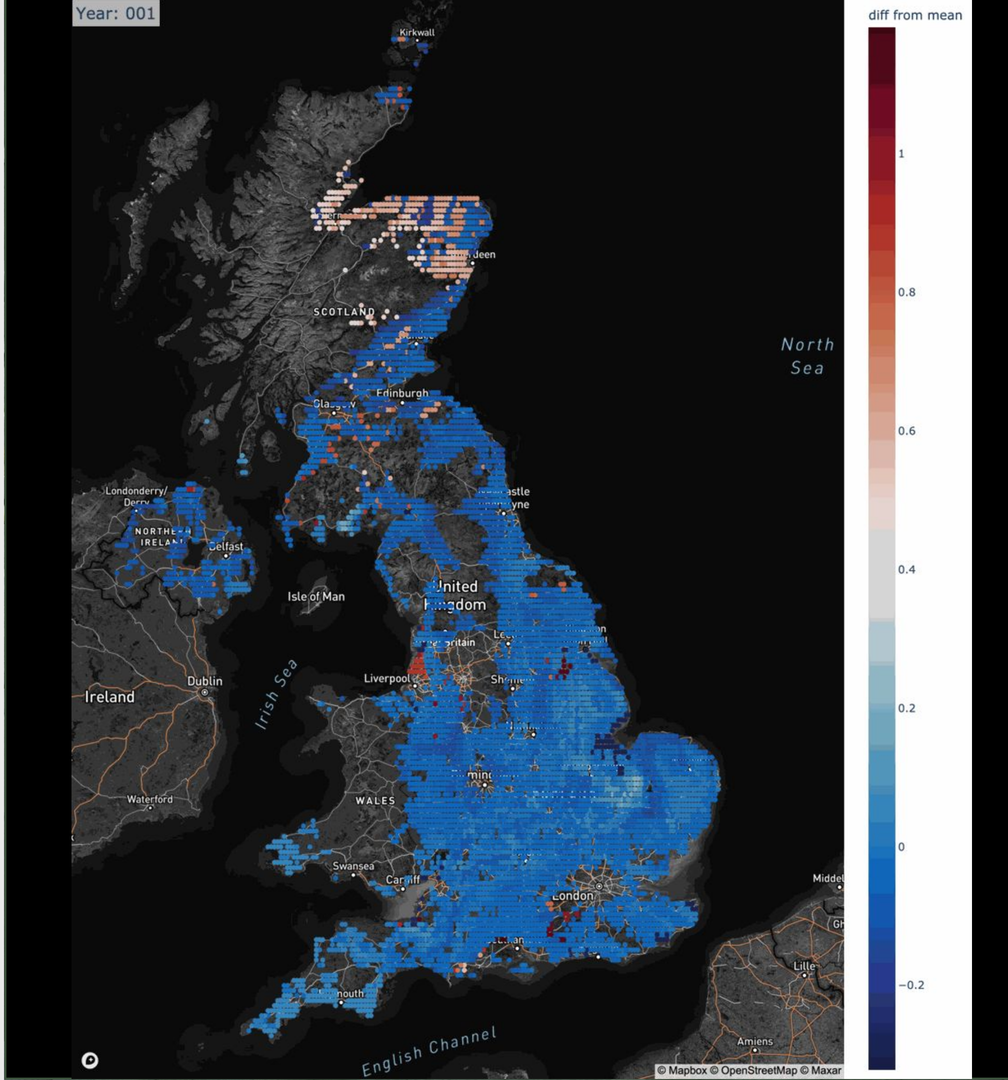


HEATMAP OF CUMULATIVE CDR ANIMATED OVER TIME

This graphic shows CDR at the end of each year for each spatial point.

The colour denotes the difference (in tCO_2) from that point CDR value to the project wide mean CDR value at that time step.

Towards the end of the animation the colour scale is quite narrow (-0.3-0.1 tCO_2 ha^{-1}) so the variation is not as large as the colour differences seem.



ALL CDR CURVES OVERLAID ON TOP OF EACH OTHER TO PRODUCE A 2D-HISTOGRAM.

If you take the CDR curve produced from every spatial point and overlay them on top of each other to form a 2D histogram, you can clearly see the regions of most probable modelling output as well as the bands above and below.

This predicts that cumulative CDR is mostly the same throughout the project area, particularly in the initial 10 years and by year 50.