CDR Measurement for ERW via Alkalinity in Leachate (With Actual Data From Our Greenhouse Experiment)

Blog article - Dirk Paessler, Jens Hammes, Ralf Steffens, Ingrid Smet - ~~30.11.2023 - V1.0~~18.12.2023 - V1.1

UPDATED V1.1 - Dec 2023

The history of this document

- V1.0 (Nov 30 2023): Initial release
- V1.1 (Dec 18 2023): Update
  - Added newly measured December data.
  - Changed uncertainty calculations and added a detailed description of our approach of assessing uncertainty (this change has very little consequence on the practical results).
  - Fixed a bug in our code that converts the results of the accumulated alkalinity measurements (in mmol over time) into the related CO_2 equivalent in tCO_2/ha over time. The initial version showed values about x10 too high. The relationship between experiments did not change, but the absolute numbers of captured carbon are considerably lower now.
  - No one of us nor anyone who read version 1.0 and gave feedback realized that the captured CO_2 calculations were an order of magnitude off. This highlights how uncertain we all are regarding the actual numbers of observable CDR effects over short time periods (here 11 months) we can expect - and confirms the importance of this work.
  - No substantial changes were made to the other theoretical and practical parts of the document.

Introduction

Join us on our endeavor to reliably measure the climate-positive effect of enhanced rock weathering (ERW) in agricultural settings by analyzing leachate waters! In this blogpost we explain how the carbon dioxide removal (CDR) effects of weathering rock can be estimated using alkalinity measurements and what early results we see in [our greenhouse experiment](#).

In the first 10 months of our experiment we found that:

1. There is no published standard in the context of CDR on how to do this and so we had to ~~build a process~~design processes and calculations ourselves.
2. It is much harder to obtain a reliable CDR signal from leachate alkalinity than we expected, even in a greenhouse experiment.
3. The weathering rates vary extensively, depending on both soils and rocks and the variability is much bigger than we anticipated.

Well, welcome to real, set-back-riddled science! Let's dive in…

Notes

- Note 1: This article tries to explain the process of alkalinity measurements in the monitoring, reporting and verification (MRV) context to a general audience. For the experts we have added "Nerd-Notes" and an appendix with in-depth details of our work and reasoning.
- Note 2: The following data are obviously limited to [our choices of soils, rocks](#) and [greenhouse ambience](#) as well as the short duration (6-~~10~~11 months). Even though our rock/soil combinations are diverse and should give us a first order of understanding, the absolute numbers may or may not be applicable in other situations or in outdoor settings.
- Note 3: Several scientists as well as practitioners (from rock weathering companies we work with) have reviewed this blog post before publishing, but this document has not been formally peer-reviewed. We decided to go for direct publishing on our blog because a formal scientific publishing process with proper peer-review would take at least several months and the climate does not have this time. We need to move faster!

Why do we need a reliable MRV for ERW?

A commonly accepted, reliable, highly scalable approach for MRV is the major hurdle that needs to be overcome before ERW can become one of the main pillars of CDR by 2050 (i.e. removing hundreds of megatons of CO_2 per year, see Beerling, et al. 2020).

Most of what we think we know about the processes involved in CDR through enhanced weathering comes from laboratory studies and theoretical models. The reason why we use models and lab data is that we do not fully understand all aspects and we cannot properly measure or monitor ERW in the field at commercial scale yet. As there are to date only a few weathering datasets from actual field experiments, we do not know how good the current models are. However, we do know that the processes in the soil are very complex (an interplay of chemistry, geology, hydrology, biology, physics, etc.) and their effects on ERW vary greatly in different environments, making it challenging to predict or model resulting CDR.

If ERW is deployed at full scale in the next decades we will probably rely on such models for day-to-day MRV as it seems unlikely that we will be able to measure ERW on millions of hectares. So, to train and verify the ERW models that will be necessary in the future, real-life weathering data from many thousands of geographically diverse locations will be required over the next decade. Today, one of the main challenges for MRV is the ability to measure the capture and storage of carbon dioxide by ERW in a fast and reliable manner for many variations. In our extensive greenhouse experiment (400 pots, 16 soils, 11 amendments) we are trying to find ways to measure the CDR effects caused by adding rock dust to agricultural soils on short timescales (months to years).

In our thinking the ERW process consists of four stages (see our blog article) with each further step being harder to measure, but also being more accurate in their assessment of the achieved CDR. A "rock solid" method (pun intended) to assess the climate positivity of rock weathering in agricultural settings is done in stage 3 by measuring the so-called "titration alkalinity" in the leachate waters that come out at the bottom of the soil.
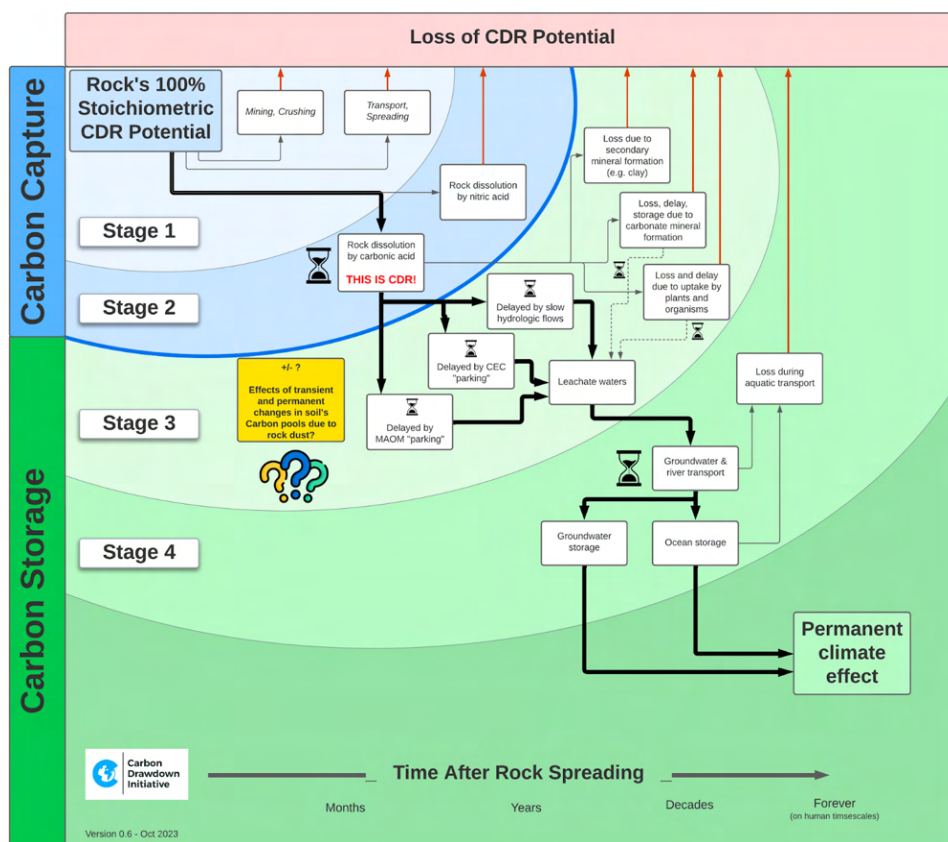
Why could measuring alkalinity be a good way to assess CDR?

When rock dust weathers, the CO_2 molecules are captured and transformed into negatively charged bicarbonate ions (HCO_3^-) (and to a lesser extent carbonate ions CO_3^{2-}, depending on the pH). Weathering also releases positively charged ions from the rock which are balancing these negatively charged bicarbonate ions in the water. ~~They~~These cations are effectively "trapping" the bicarbonate ions so that the water flow takes both ~~ions~~ from the soil into rivers and eventually the ocean.

Bicarbonate ions represent the majority of the so-called 'alkalinity' of a solution. It is a parameter that can be measured in situ by titration (explained in detail further down). So we are measuring alkalinity as a proxy for bicarbonate concentration. We expect the alkalinity of rock dust amended experiments to be higher than their respective controls, reflecting that they transport more carbon (ex-CO_2 that has become bicarbonate) from the atmosphere into the ground (-water). This would be the desired CDR effect!

Eventually the bicarbonate is stored in groundwater, rivers and oceans for thousands of years, even longer if it precipitates as carbonate minerals on the ocean floor, keeping the carbon out of the atmosphere. There may ~~still~~ be some loss along this journey ~~(this is in stage 4). Modeling indicates~~as bicarbonates are again released as CO_2 from rivers (in stage 4) or ocean, with models indicating long term loss rates in the ocean ~~to be in the range of only~~up to 10% (Kanzaki et al. 2023). ~~This likely makes~~Despite these small potential losses along the way, field/experiment-based alkalinity measurements are likely the most accurate means of assessing CDR~~.~~ - at least for now.

Fine, then why not use this measurement for field-based MRV, too?

This approach works fine for weathering experiments in pots, soil columns or lysimeters. Unfortunately, measuring alkalinity does not look like the perfect option for MRV ~~for~~of open field applications, especially at scale (megatons) as this will involve hundreds of thousands of hectares:

- You need to have reliable access to the leachate waters, in a statistically relevant number of locations in the field. But one can't simply litter ERW fields with lysimeters or water samplers, because the field would become unusable for the farmer.
- Taking the samples and measuring them in-situ takes a lot of time~~.~~. For instance, two people need almost 5 workdays to sample and measure one full data set for our greenhouse experiment of 400 pots.
- You need to assess the full leachate volume per surface area so you can calculate the alkalinity flux from alkalinity concentrations. This will be quite challenging to do in an open field with unconstrained water discharge in multiple directions.

Even if models are eventually used at full ERW deployment scale, we will need extensive measurement data just to train/verify such ERW models. These are the reasons why we need to find easier/simpler proxies to the alkalinity measurements, but that's already the topic for one of the next blog articles. For now, let's go back to the actual alkalinity data.

How are we measuring titration alkalinity in our greenhouse?

We are measuring alkalinity and other leachate parameters for each experiment once per month. In every monthly cycle we empty the lysimeter tanks completely, so last month's data does not skew the following month's data. We record the water volume. Directly after taking a water sample the ~~titrated~~titration alkalinity is measured on-site using a mobile titrator, giving us an alkalinity concentration in micromol/liter.

Nerd-Note: Before every leachate analysis we ~~flush~~rinse the two containers involved (Erlenmeyer flask and measuring cylinder) three times with the leachate sample. This prevents contamination by the previously measured samples. Then 100 ml leachate is measured with the cylinder and poured into the Erlenmeyer flask. For the titration with the HACH digital titrator kit (Digital Titrator Model 16900) we are adding Bromcresol Green-Methyl Red indicator powder. With the titrator, sulfuric acid (1.6 N) is added in tiny drops to the sample until the indicators change colors at around pH 4.3. According to the HACH titrator instructions, this amount of added acid can be expressed as $CaCO_3$ mg/l. This result is converted into mg/l HCO_3^- by multiplying with a factor of 1.22 for conversion from $CaCO_3$ to HCO_3^-. In order to convert this number to micromol we divide by 61, the molar weight of HCO_3^-. Note that other species may contribute to alkalinity (i.e. the acid buffering capacity) but in most solutions we deal with it is a safe assumption that HCO_3^- is the major acid buffer.

As we are not aware of an "officially approved" best practice to analyze alkalinity in soil water from greenhouse/field experiments in the ERW context to calculate the amount of CDR, this is the method we used after consulting several advisors. The USGS has a deep dive document on alkalinity measurements, but this does not cover CDR calculations. USGS requires filtering of samples with a 0.45 μm filter before titration to achieve an "alkalinity measurement". They refer to an unfiltered titration measurement as "ANC measurement" (Acid Neutralizing Capacity). However, repeated tests have shown that in our setting it makes no significant difference whether a water sample is filtered first or titrated unfiltered. This could possibly be due to the installation of a filter sand layer and a root fleece at the bottom of every soil pot. As filtration did not lead to any other significant measurement results, the sample filtration step was omitted for our measurements. This decision allowed us with our resources to get more data points at shorter intervals (monthly) for hundreds of pots which we think is particularly important for our work. A standard method for alkalinity measurements for ERW, however, is something that should be agreed on by industry and science and should be published soon. Consider the oceanic scientific community, where such a standard already exists (Dickson et al. 2007, see SOP3a and 3b)!

Each of our variations has 4 replicas. We calculate the median of these 4 to get a value per variation. We use the median because nature's heterogeneity and practical limitations/issues inside the greenhouse create situations where not too seldom one of the four pots is obviously "far off" from the other three. Statistically, such heterogeneity is better covered by using medians than averages, and is preferred to altogether eliminate the outlier pots from the analysis.

To make this text better readable we will from now on use the word "alkalinity" for "titration alkalinity" as explained above.

For our work we need the monthly alkalinity flux in micromol, so for every month we multiply the monthly volume (in l) with the concentration (in micromol/l) of that month's sample:

$$\sout{alkalinity\ flux_{month} = alkalinity\ concentration_{month} * volume_{month} \qquad [in\ micromol\ per\ month]}$$

$$alkalinity\ flux_{month} = alkalinity\ concentration_{month} * volume_{month} \qquad [in\ millimol\ per\ month]$$

This gives us the alkalinity flux for each experiment (=pot) in micromol HCO_3^-/month.

Here is figure 1 for the 4 control experiments of our 4 main soils, showing the monthly water volumes, the alkalinity concentration as well as the accumulated water volume and accumulated alkalinity:
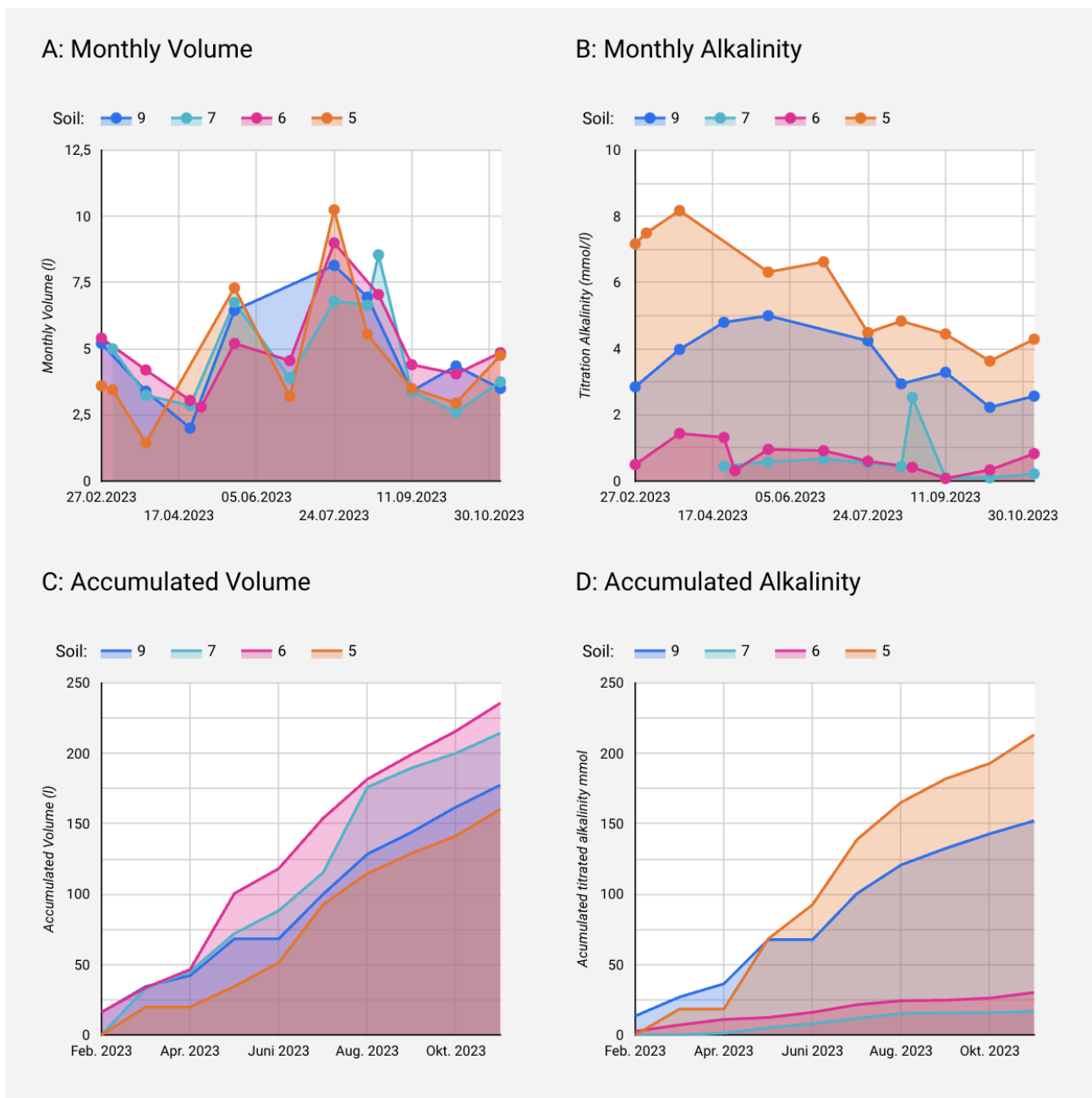
Nerd-Note: There is a pH dependent aspect of the bicarbonate concentration in the leachate water that needs to be taken into account in certain situations. Dissolved inorganic carbon (DIC) in water consists of dissolved CO_2, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) whose relative proportions change with pH according to the Bjerrum plot (Figure 2). Below pH 9 almost all DIC is either dissolved CO_2 or bicarbonate (HCO_3^-), so there is virtually no CO_3^{2-} which would affect our interpretation of the titration measurements. Figure 3 shows the pH range of our experiments for all data points in 2023 (colors symbolize soils). As we were never even close to pH 9, we can disregard the presence of any carbonate ions for our experiments.
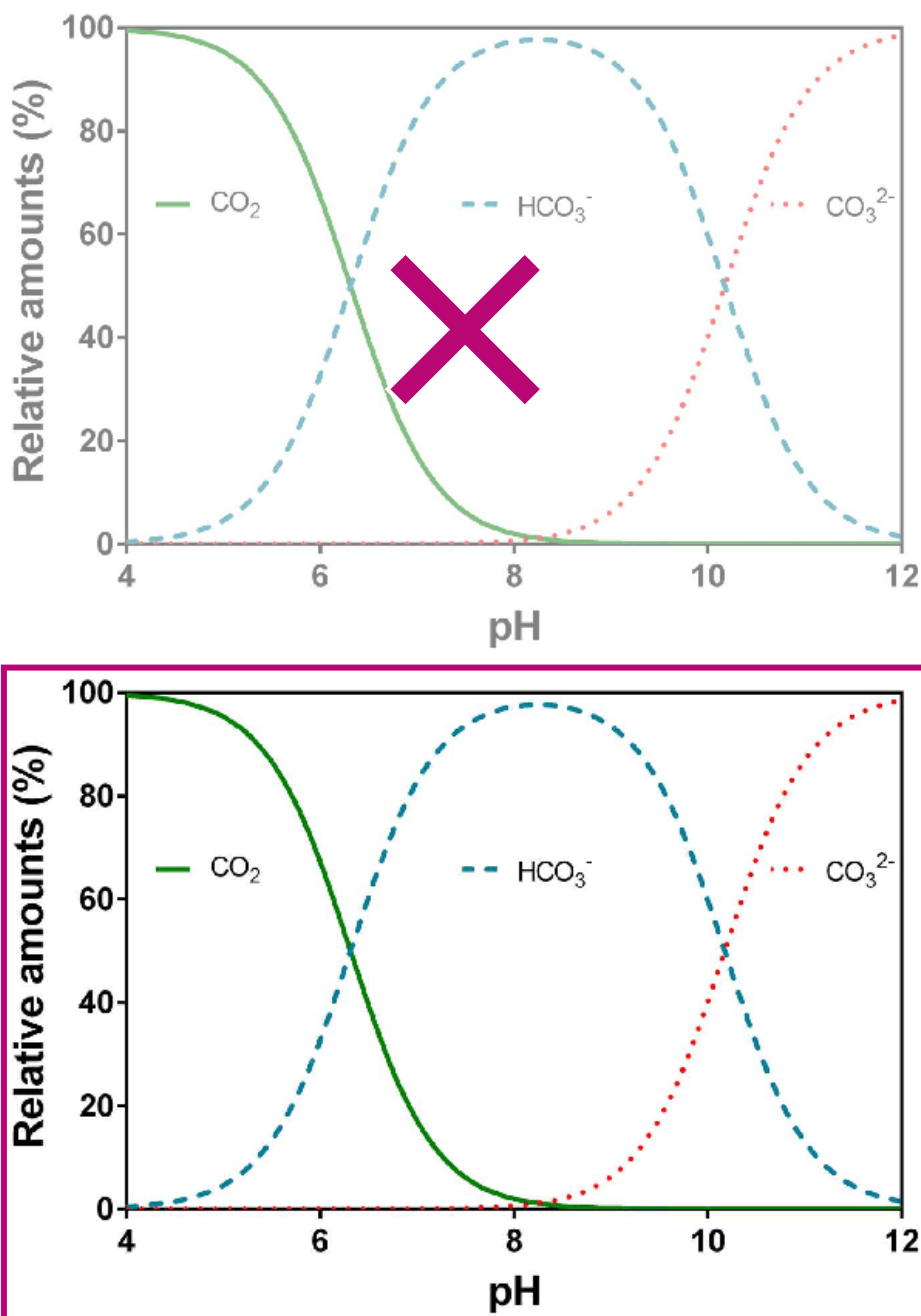

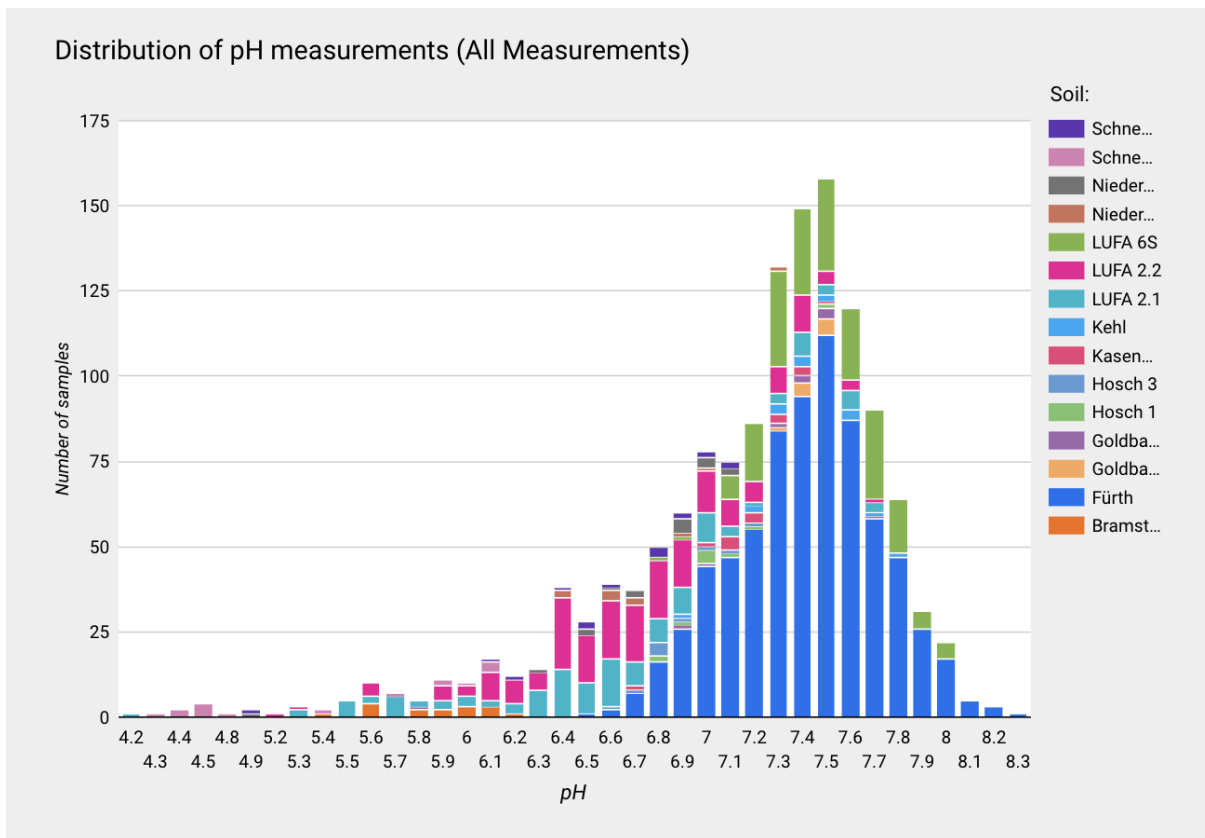Figure 2: Bjerrum Plot, Source: Pedersen et al. (2013)

Figure 3: Number of occurrences of pH values in 2023, colors symbolize soils

The alkalinity flux as a cumulative metric over time

We think of the monthly alkalinity concentration multiplied with the leachate volume as a so-called *"alkalinity flux"* expressed in mol per month. The "accumulated alkalinity" is the cumulative summation of this metric where we are adding up the monthly values to a total lifetime alkalinity flux value for each experiment (Figure 1D), effectively ignoring when exactly the cation-bicarbonate couples have reached the leachate since being produced in the pots. This cancels out potential variations such as water runtime differences or temporary drought issues inside the pots.

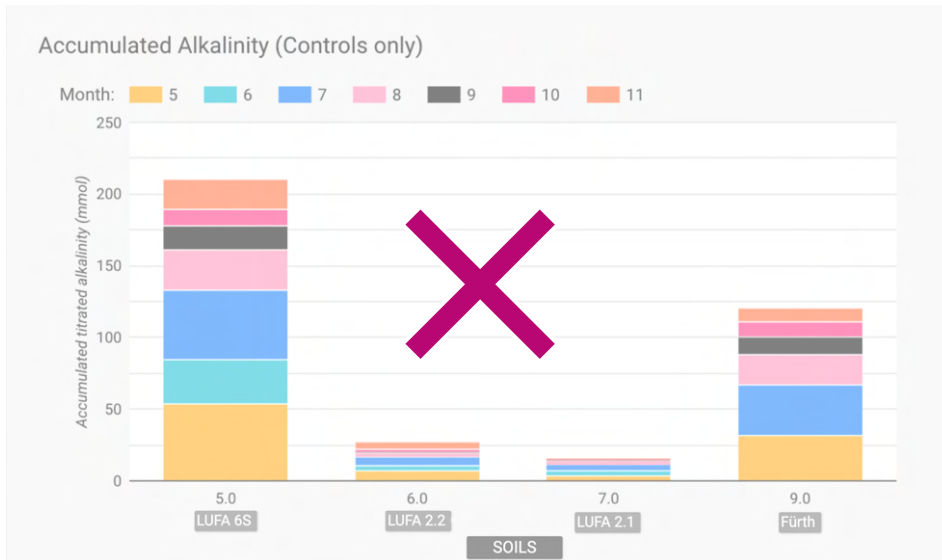$$\text{Accumulated Alkalinity} = \sum_{t=experiment\ time} \text{Alkalinity Flux}(t) \quad [\text{in mol over time}]$$

$$\text{Accumulated Alkalinity} = \sum_{t=experiment\ time} \text{Alkalinity Flux}(t) \quad [\text{in millimol over time}]$$

In fact a few times we did not get water in the tanks due to extreme evaporation and/or too little irrigation (e.g. in June for some pots). Since the alkalinity of this month had no other way to escape from the pot it was washed out later with the next leachate waters. If we accumulate the monthly values we still cover the whole alkalinity signal and can ignore no-water-months.
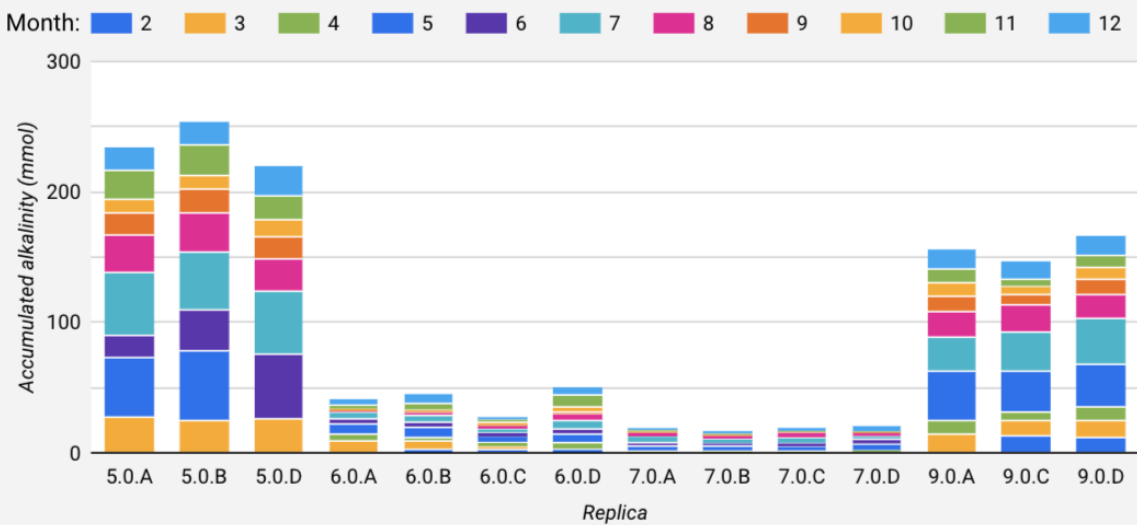
Another cause for a lack of consistent monthly data for some pots is dirty water due to a suspended load of fine floating particles. This makes it difficult to see the indicator color during the titration. In this case we can't just skip this month's titration data as unaccounted-for alkalinity has left the system. Fortunately this only happened in the first 3 months on some experiments/soils.

The alkalinity data of our control experiments

Figure 4 shows what the accumulated alkalinity looks like for the four soil control experiments ~~(each month's bar shows the median of 4 replicas, monthly data stacked for total) between May and October 2023.~~ from February through to December 2023. The upper chart shows the accumulation of the alkalinity for each replica/pot based on the monthly measurements. The lower charts show the medians of each experiments' replicas (left) as well as the standard deviations (in % of the medians, right). Note that we have removed 5.0.C and 9.0.B before this analysis as they were obvious outliers (>40% off) within their respective replica set.
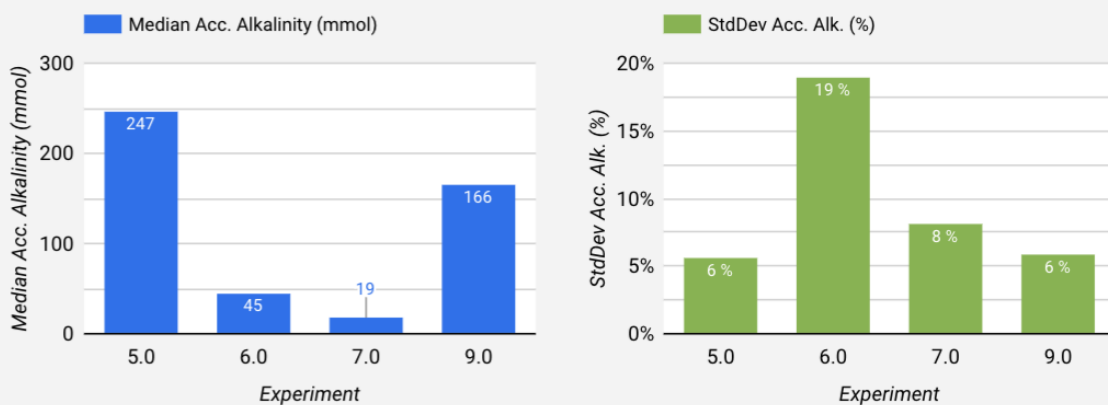
Figure 4: Untreated controls only; Colors=months;
Replicas' Standard Deviations ca. 5-10% of total (mmol): 5.0=13.2, 6.0=2.3, 7.0=1.3, 9.0=9.7 Soils: 5.0 = LUFA 6S, 6.0 = LUFA 2.2, 7.0 = LUFA 2.0 and 9.0 = Fürth

Nerd-Note: Here is how we came up with the graphs in the above figure. Every month we did one sweep of alkalinity measurements through the greenhouse (350-400 pots). For each replica we accumulate alkalinity measurements of each month over time to get the accumulated alkalinity in the first step. Then we calculate the medians and standard deviations for each experiment (=rock/soil combination) based on these accumulated values.

We noted that the standard deviations of the replicas' alkalinity per month was often higher than for the total which might indicate that the alkalinity does not leave each replica at the same time. Which underscores the thesis of alkalinity being an accumulated metric in this context. We found that our data gets better (i.e. standard deviations going down) the longer the analysis' time window was. This might also imply that one needs all of the leachate for an accurate measurement and/or a high measurement frequency. Only looking at a few samples e.g. every x months will likely miss parts of the signal. Consider these two examples of controls 7.0 and 9.0 which we show above with an error bar of 8% and 6% for the accumulated alkalinity over 11 months: If we only had an unfortunate subset of the 11 monthly leachate samples per replica these error rates would be much higher and could potentially "hide" the CDR signal that we look for.
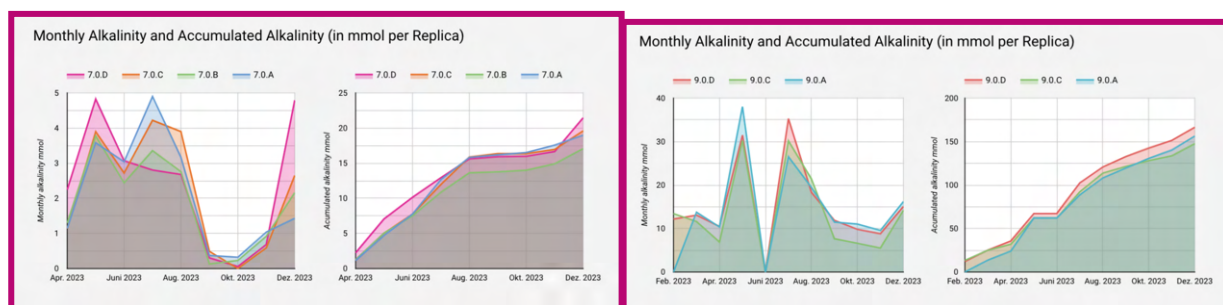
In this context it is important to distinguish between not having any leachate in one month (means no alkalinity has been transported out, so no part of the signal was lost) and having leachate but not being able to measure the alkalinity for whatever reason. In the latter case we are losing a part of the signal.

One soil is from our experimental field in Fürth and three soils (2.1, 2.2 and 6S) are from LUFA. There is a detailed data sheet for the LUFA soils. Here is the preliminary soil data.

	Experiment 5.x	Experiment 6.x	Experiment 7.x	Experiment 9.x
	LUFA 6S	LUFA 2.2	LUFA 2.1	Fürth
Soil Type	clayey loam	loamy sand	sand	silty loam
pH	7.3	5.5	4.6	>7
organic carbon % C	1.50	1.66	0.55	1.39
Nitrogen % N	0.17	0.19	0.06	t.b.d.
CEC meq/100g	18.7	8.5	2.9	6

Why are there such big differences in the background alkalinity leaching out of these 4 soils?

Our data show that the accumulated alkalinity is vastly different from one soil to another. For example, in our experiment the LUFA 6S leachate of the 5.0 control experiment has over ten times the accumulated alkalinity of the LUFA 2.1 leachate of the 7.0 control experiment.

We think the following three soil parameters are governing the alkalinity of the soil leachates, with their relative importance varying between different soil types:

- First, the pH is quite different and hence the relative contributions of DIC will vary according to the Bjerrum plot. Two soils are rather acidic (LUFA 2.1, experiments 7.x, pH=4.6, and LUFA 2.2, experiments 6.x, pH=5.5) whereas two others are neutral to slightly alkaline (LUFA 6S, experiments 5.x, pH=7.3, and the Fürth soil, experiments 9.x, pH>7).
- Second, the soils come from different backgrounds and have different composition (e.g. LUFA 6S soil formed from a type of rock that contains carbonate minerals which adds to the alkalinity).
- Third, besides a background level of natural inorganic alkalinity, soils also have organic carbon (OC), i.e. particulate organic carbon (POC) and dissolved organic carbon (DOC). Both of them leach out naturally and so both can be part of our titration alkalinity measurements (charged functional groups like $COOH^-$ or OH^-).

All these aspects should not affect our measurement of CDR notably because in the next step we subtract the control's alkalinity from the alkalinity of the amended pots.

Accumulated Alkalinity of amended pots vs. controls

The following graph shows the accumulated alkalinity in the leachate between ~~May and November~~January and December 2023 for our experiments with basalt and dunite and their respective controls.
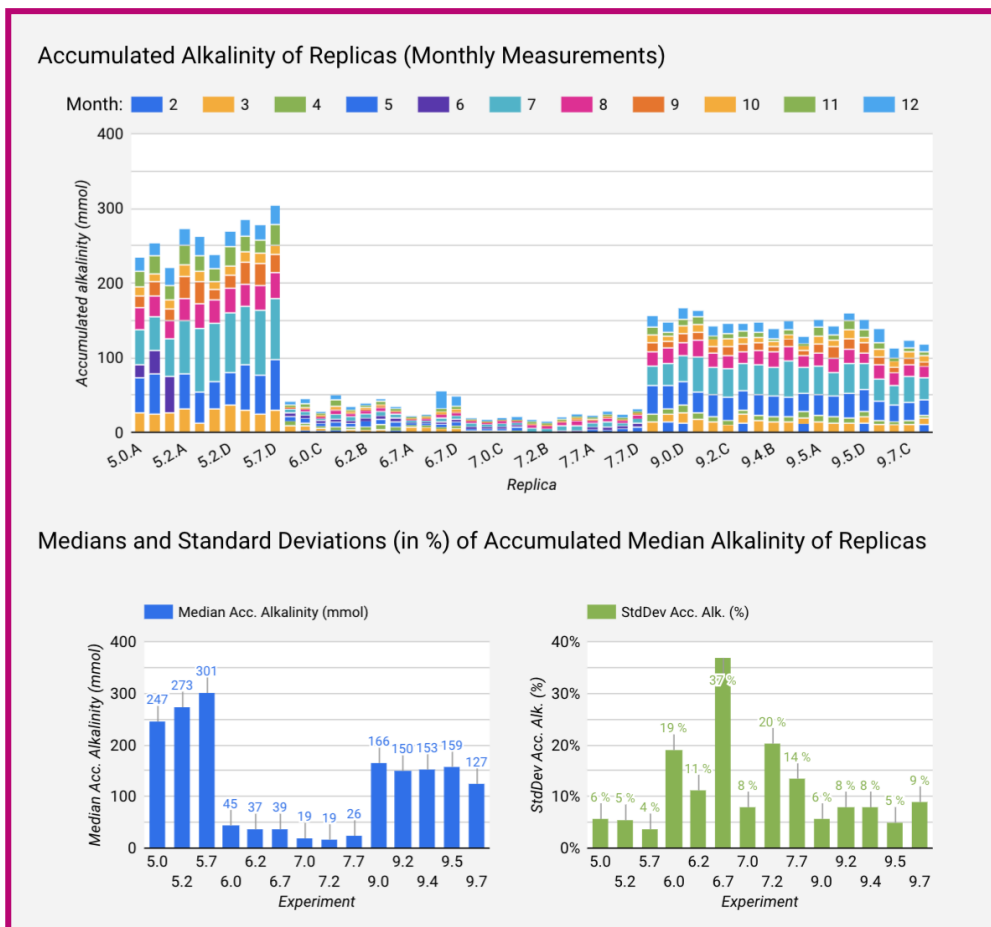

Figure 5: Treated experiments and their controls; Colors=months;
Rocks: x.0=Control, x.2=Basalt 40 t/ha, x.4=Basalt 200 t/ha,
x.5=Basalt 400 t/ha, x.7=Dunite 40 t/ha;
~~Replicas' Standard Deviations ca. 5-10% of total (mmol)~~*Soils: 5.x=~~20.5~~LUFA 6S, 6.x=~~2.0~~LUFA 2.2, 7.x=~~1.9~~LUFA*
2.1, 9.x=~~11.2~~Fürth

We have achieved the desired carbon capture if the amendment's bar is longer than the control's. A shorter bar shows less accumulated alkalinity in the leachate, not good.

The rocks that were used can be characterized as follows (more data in the appendix):

	Experiments x.2, x.4, x.5	Experiments x.7
	Eifelgold Basalt (RPBL, Germany)	Dunite (Sibelco Olivine, Norway)
Main Minerals (XRD)	49% Clinopyroxene, 13% Leucite, 11% Olivine, 9% Nepheline	79% Olivine, 10% Serpentine
Main chemical components (XRF)	43.3% SiO_2, 12.7% CaO, 9.8% MgO, 3.6% K_2O, 2.6% Na_2O	48% MgO, 41% SiO_2
Grain size distribution	65% under 100 μm, 90% under 500 μm	99% under 300 μm

How do we convert alkalinity data to CO_2 to assess CDR in tons of CO_2 per hectare?

As a first step we calculate the difference of the accumulated alkalinity between an amended variation and their respective control variation so we get how much ADDITIONAL alkalinity the rock amendment has produced. The "additional" is the decisive factor: What has changed BECAUSE we added the rock?

$$\textit{Additional Alkalinity} = \textit{Accumulated Alkalinity}_{Amendment} - \textit{Accumulated Alkalinity}_{Control}$$

$$\textit{Additional Alkalinity} = \textit{Accumulated Alkalinity}_{Amendment} - \textit{Accumulated Alkalinity}_{Control} \quad [\textit{in mmol}]$$

We assume that one mol of this additional alkalinity (compared to control) corresponds to one mol of bicarbonate (HCO_3^-) which was formed during the weathering process and which was formerly one mol of CO_2 taken from the atmosphere some time earlier. This reasoning includes the assumption that all alkalinity resulting from natural soil background (organic alkalinity, pH, carbonate minerals) is canceled out by the subtraction of the control.

In step 2 we can easily calculate how much additional CO_2 the leachate carried away over the past 7 months from the additional alkalinity in ~~mol. Multiply~~ mmol. Divide it by 1000 mmol/mol, multiply by 44.01 g/mol for CO_2 and we have the amount of CO_2 in grams, divided by 1,000,000 grams we then have the weight of removed CO_2 expressed as tons. Dividing this weight by the surface area of the experiment-pot (0.05 m^2) and multiplying by 10,000 m^2 (=1 ha) eventually expresses the amount of CO_2 removed over the past ~~7~~11 months in t/ha.

$$\textit{CDR Effect} = \textit{Additional Alkalinity} \times \frac{44.01 \frac{g}{mol} \times 10,000 \frac{m^2}{ha}}{1,000,000 \frac{g}{t} \times 0.05 \, m^2} \quad \left[in \, \frac{t \, CO_2}{ha} \, over \, experiment \, time \right]$$

$$\textit{CDR Effect} = \frac{\textit{Additional Alkalinity mmol}}{1000 \frac{mmol}{mol}} \times \frac{44.01 \frac{g}{mol} \times 10,000 \frac{m^2}{ha}}{1,000,000 \frac{g}{t} \times 0.05 \, m^2} \quad \left[in \, \frac{t \, CO_2}{ha} \, over \, experiment \, time \right]$$

To get the full annual CDR effect with this approach we will need data from 12 months (which we ~~do not have yet~~almost have). To put our data into context we need a reference: we optimistically expect the actual CDR effect for a successful carbon removal ERW project to be in the order of 1-8 tons of CO_2 per hectare per year (assuming an application dose of 50 t/ha of rock annually). This estimation is based on recent studies from Beerling et al. (2023) and can be found in their pre-prints [here](#) and [here](#).

Keep in mind: If for a certain set-up the CDR effect signal is much smaller than just a few tons per ha per year, it seems unlikely that this ERW project by itself (without other potential benefits aside from CDR) will be economically viable.

Finally, figure 6 shows the additional alkalinity, i.e. the cumulated alkalinity data shown as differences between the amended experiments and their respective controls, plotted with error bars (~~plus/minus 1 standard deviation~~using the absolute standard deviation of either control or treatment, whichever is bigger) converted to tCO_2/ha. In other words, this figure 6 shows the CDR effect:

CDR Effect in t/ha of CO₂ in 7 months (above zero is desired range)

Rock dusts at 40 t/ha: x.2/4/5=Basalt (yellow), x.7=Dunite (red) -- Soils: 5.x=LUFA 6S, 6.x=LUFA 2.2, 7.x=LUFA 2.1, 9.x=Fürth soil
Derived from accumulated alkalinity May-Nov 2023 (=4-10 months after amendment)
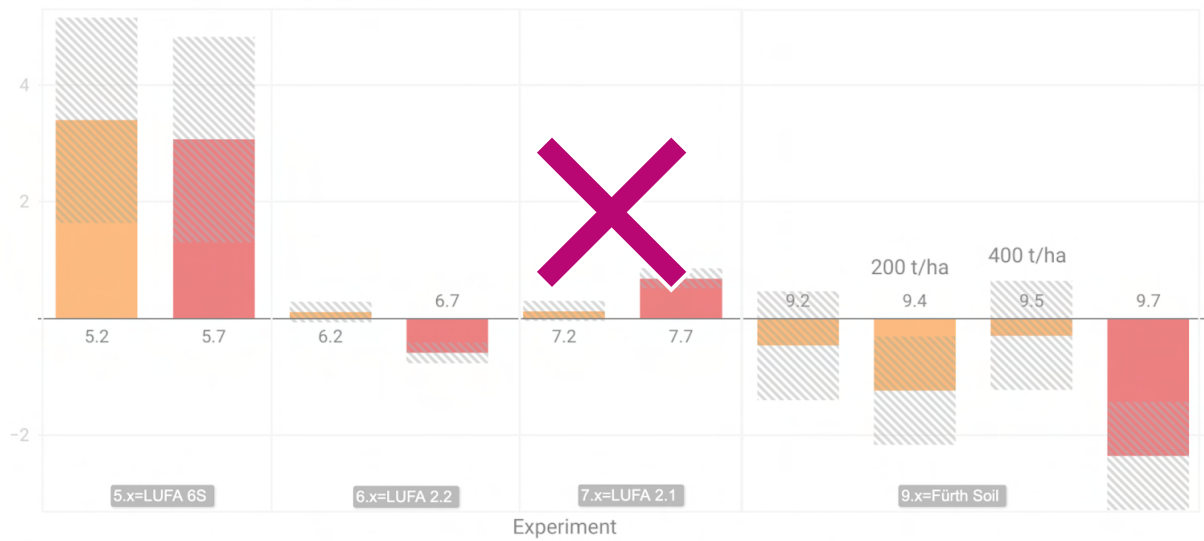Shaded areas show plus/minus 1 standard deviation

CDR Effect in t/ha of CO₂ in 11 months (above zero is desired for CDR)

Rock dusts at 40 t/ha: x.2/4/5=Basalt (yellow), x.7=Dunite (red) -- Soils: 5.x=LUFA 6S, 6.x=LUFA 2.2, 7.x=LUFA 2.1, 9.x=Fürth soil
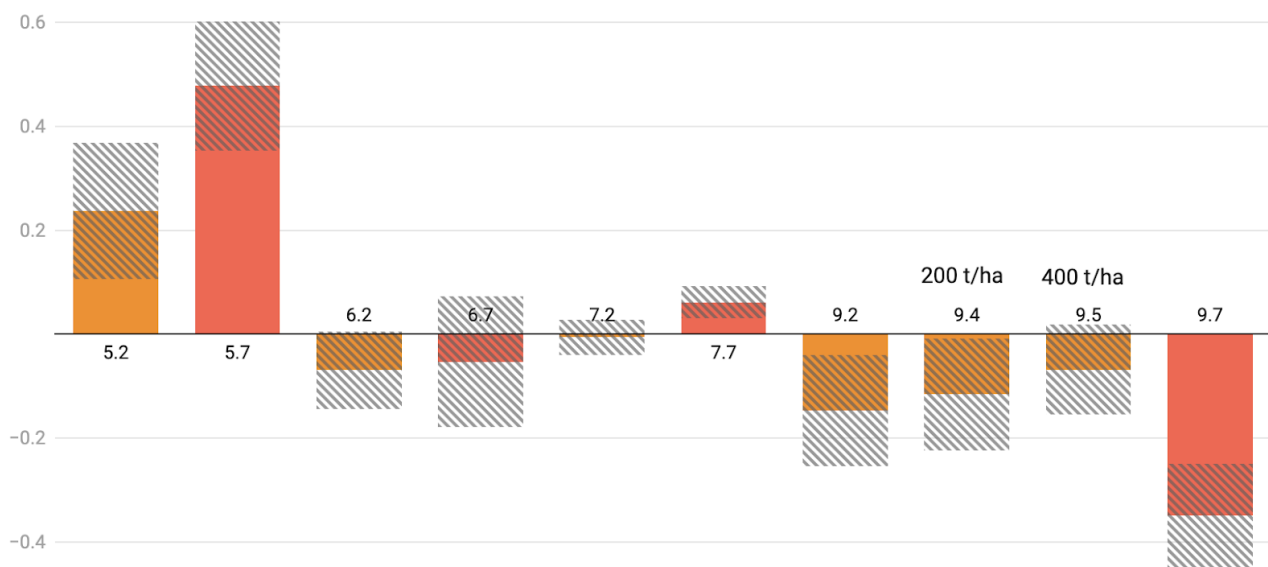Derived from accumulated alkalinity Feb-Dec 2023 -- Shaded areas show error bars, refer to description

Chart: Carbon Drawdown Initiative - www.carbon-drawdown.de • Source: Carbdown Greenhouse Experiment 2023 • Created with Datawrapper

Figure 6: CDR Effect of treated experiments in t/ha CO₂ in 7 11 months;
Rocks: x.0=Control, x.2=Basalt 40 t/ha, x.4=Basalt 200 t/ha,
x.5=Basalt 400 t/ha, x.7=Dunite 40 t/ha; (red);

These numbers, ca. 0,5 t/ha in 11 months in the best case, are obviously disappointing compared to the desired range of 1-8 t/ha/year. But it is likely that we are not seeing the full signal yet: There are several mechanisms in the soil that delay the arrival of the actual weathering signal in the leachate soil water, see

our article about the "Cartion Park". Dissolution measurements and other proxy measurements will help to understand this better (planned for early 2024).

We can see that in our experiments

- The additional alkalinity is to a large extent a function of the soil.
- On soils with high default alkalinity flux the ~~actual,~~ possibly much smaller weathering signal can be hard to measure due to the soil's high "noise level" (compare standard deviations of soils with high natural alkalinity in experiments 5 and 9 with the standard deviations of the soils with much lower natural alkalinity in experiments 6 and 7). The smaller the application rate, the bigger challenge this background noise problem can become.
- The CDR effect, i.e. the difference in accumulated alkalinity between control and amended pots (or, in simpler words: the rock-induced additional alkalinity converted to ton CO_2/ha), varies widely depending on the rock/soil combination
- Except for the LUFA 6S soil (5.x) the two rocks, basalt and dunite, show no consistent effect yet. Some variations seem to reduce atmospheric CO_2, others not.
- On Fürth soil (9.x) with basalt there was no significant difference between the 40, 200 and 400 t/ha basalt amendments (9.2/4/5) and none of the amendments show a significant positive CDR effect.
- The dunite (x.7) until now shows the desired positive CDR effect on two soils, and a negative on ~~the other two~~one.

Although it was quite disappointing for us to learn that our own Fürth soil seems so exceptionally bad for CDR with some rocks, this discovery is still valuable. Having total-failure-soil/rock combinations might help us understand aspects we need to avoid when throwing rocks on fields. Because the first goal of ERW rock applications must always be to not make things worse.

At least now we have proof that our observations of "there is no leachate-based measurable CDR" in our previous XXL Lysimeter experiment (which uses the same Fürth soil, see our working paper from March 2023) were accurate (after 8 months we could not measure alkalinity increase in leachate of large lysimeters in open field, even with 100/200/400 t/ha basalt application). Both experiments produce the same results.

Wait, it gets even more diverse with more data

We have seen that the CDR results of different rock/soil combinations can vary widely. To make things even more interesting, figure 7 shows the data of our side experiment with material from 7 ERW companies on the Fürth soil (the latter being the total loser in the graphs above). As these experiments were set up a little later, in April 2023, we collected new Fürth soil at this time and hence we regard this as its own soil type, Fürth II.
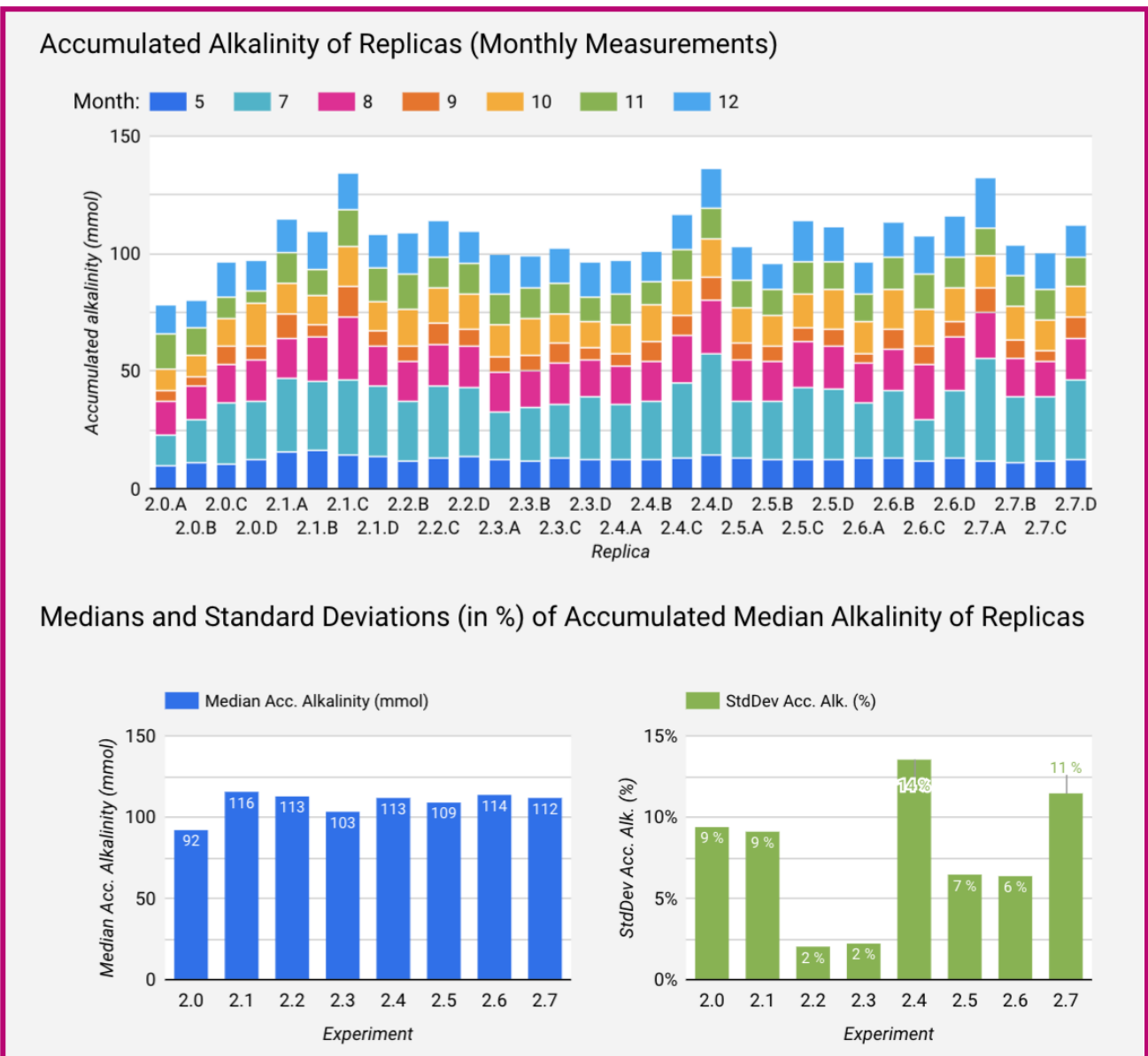
Figure 7: Treated experiments (ERW company rocks) and their controls; Colors=months;
Soils: 2.x=Fürth II soil; Rocks: Rock dusts from 7 ERW companies (40 t/ha).
Replicas' Standard Deviations: ca. 6% of total (7,6 mmol)¶

Compared to the control, all rock dusts have already generated an increased accumulated alkalinity over only the first ~~6~~7 months (all bars are higher). For all amendments the accumulated alkalinity in the leachate was higher than for the control. Good!

Again we subtract the control's accumulated alkalinity from the amendments', convert it into ~~t~~tCO$_2$/ha and we get the CDR effect in figure 7: On the same soil the type of rock ~~makes~~does not make a notable difference yet, CDR effect values ~~range from 0.8 to 2.3 t~~differ non significantly in a range from 0.1 to 0.2 tCO$_2$/ha in ~~6~~8 months~~, thus a factor 3 difference between fastest and slowest~~.

Although there are rather low total numbers, let's keep in mind that…

1. … part of the weathering signal is likely delayed by temporary storage in the soil - the "Cartion Park".
2. … the Fürth soil exhibited the lowest CDR potential in the previously discussed experiments when combined with other rocks.

Both aspects suggest that the absolute values shown in the following graph have limited practical relevance for the CDR projects of the ERW companies who added these rock dusts to different soils.

CDR Effect in t/ha of CO$_2$ in 7 months (above zero is desired range)

Rock dusts from 7 ERW companies at 40 t/ha on Fürth II soil
Derived from cumulated alkalinity flux May-Nov 2023 (=first 7 months after amendment)
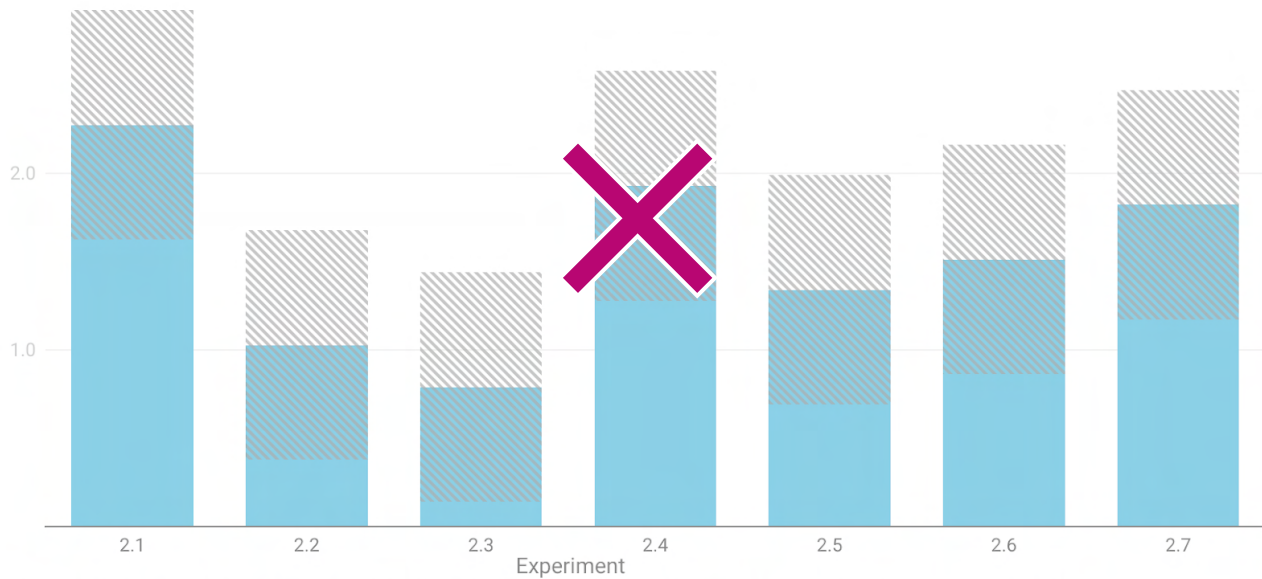Shaded areas show plus/minus 1 standard deviation

Chart: Carbon Drawdown Initiative - www.carbon-drawdown.de · Source: Carbdown Greenhouse Experiment 2023 · Created with Datawrapper

CDR Effect in t/ha of CO$_2$ in 8 months (above zero is desired range)

Rock dusts from 7 ERW companies at 40 t/ha on Fürth II soil
Derived from cumulated alkalinity flux May-Dec 2023 (=first 8 months after amendment)
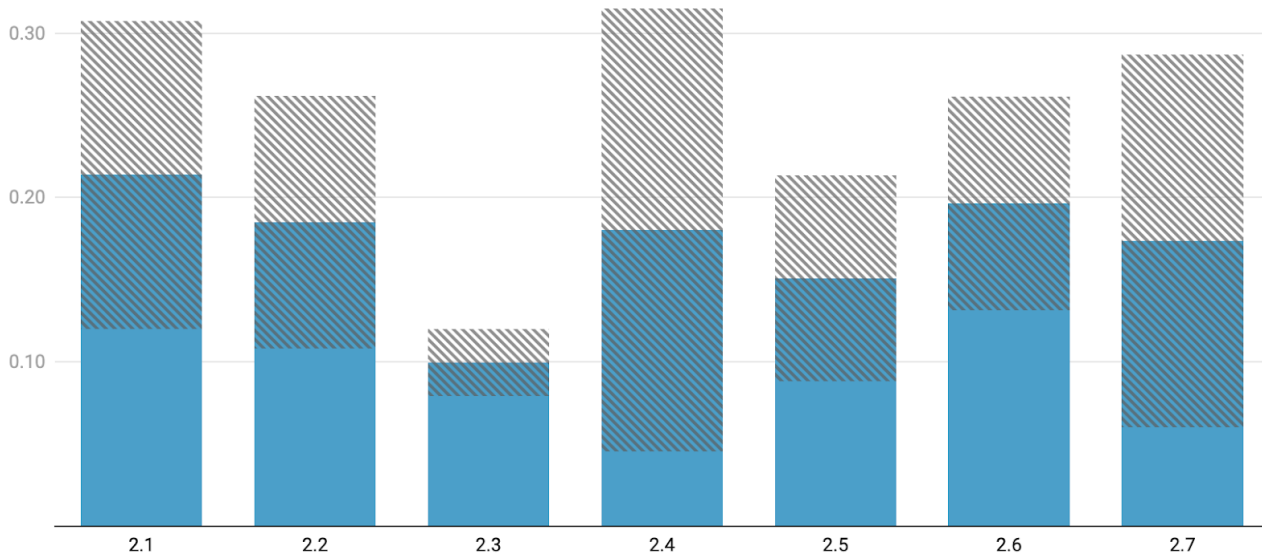Shaded areas show uncertainty, see description

Chart: Carbon Drawdown Initiative - www.carbon-drawdown.de · Source: Carbdown Greenhouse Experiment 2023 · Created with Datawrapper

Figure 7: CDR ~~Effect~~effect in t/ha CO₂ in ~~7~~8 months of treated experiments; ~~Soils~~Soil: 2.x=Fürth II ~~soil~~; Rocks: Rock dusts from 7 ERW companies (40 t/ha).

A sign of relief for us: even our Fürth soil can be useful for CDR, you just need the right rock dust.

Nerd-Note: The rock in experiment 2.1 is crushed concrete which contains cement and carbonate minerals. Their quick dissolution likely explains a part of the elevated level of alkalinity in the leachate. However, carbonate weathering has only

50% of the CDR efficiency of silicate weathering as half of the resulting bicarbonates form from the dissolution of the carbonate mineral itself and not from capture of CO_2. So although we do not know the relative contribution of the weathering of the rock's carbonate in this experiment, it is likely that the actual CDR effect for 2.1 is smaller than shown above.

However, this data set also brings another question to light. Control experiments 9.0 and 2.0 are both built using Fürth soil that was collected from the same location and depth, treated the same away, with the only difference that the soil in 2.0 was harvested 3 months later. The 9.0 experiment shows a massively different alkalinity curve (figure 8 B, an initial peak for 5 months) until both controls show similar values (August and later, left graph) and this happens uniformly in all 4 replicas (figure 8 A). We can not explain yet why this happens. Did the rainy spring time leach alkalinity out of the soil in the field? Did biology play a dominant role in seasonally changing soil-biological activities? Does this affect the CDR calculations? It is at least one more indication that measuring CDR effects in soils remains complicated, even in highly controlled greenhouse experiments.
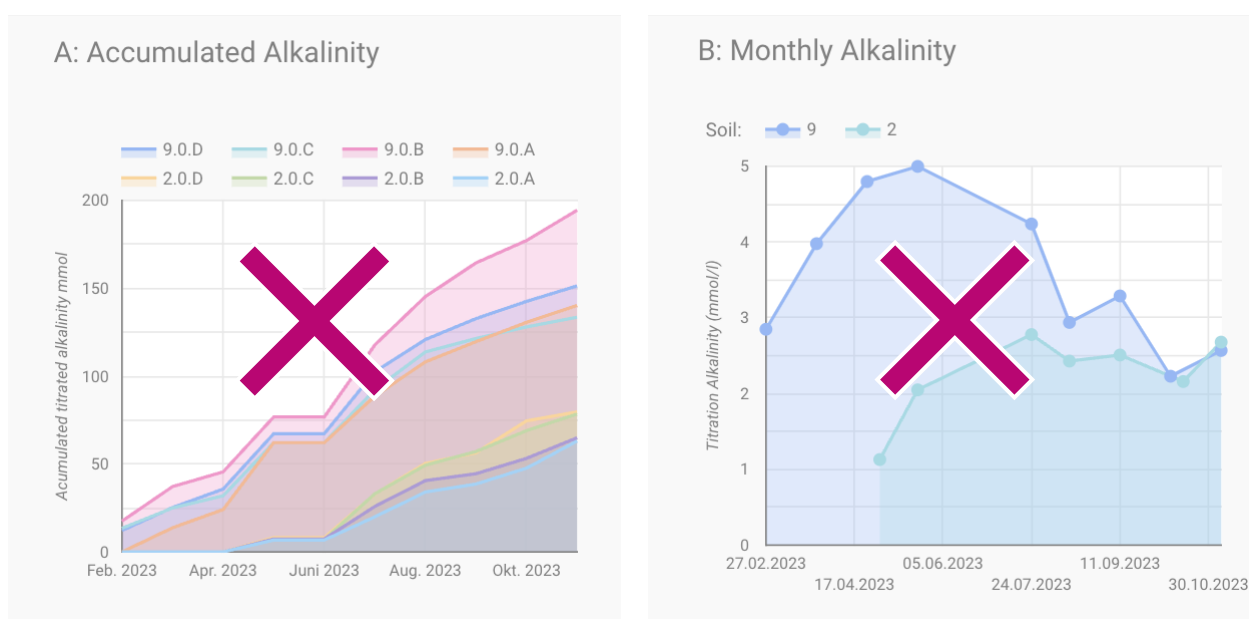
Figure 8: Titration alkalinity of two Fürth soils (controls only);
A: Accumulated alkalinity by control experiment replica A-D; B: Monthly medians

Between the two soil-harvest events we had above-average, but no extreme monthly rain totals in Fürth (Figure 9), while the time before the first harvest was drier. Could this have changed the soil's natural alkalinity background so much? If you can help finding the reason, please write to info@carbon-drawdown.de.
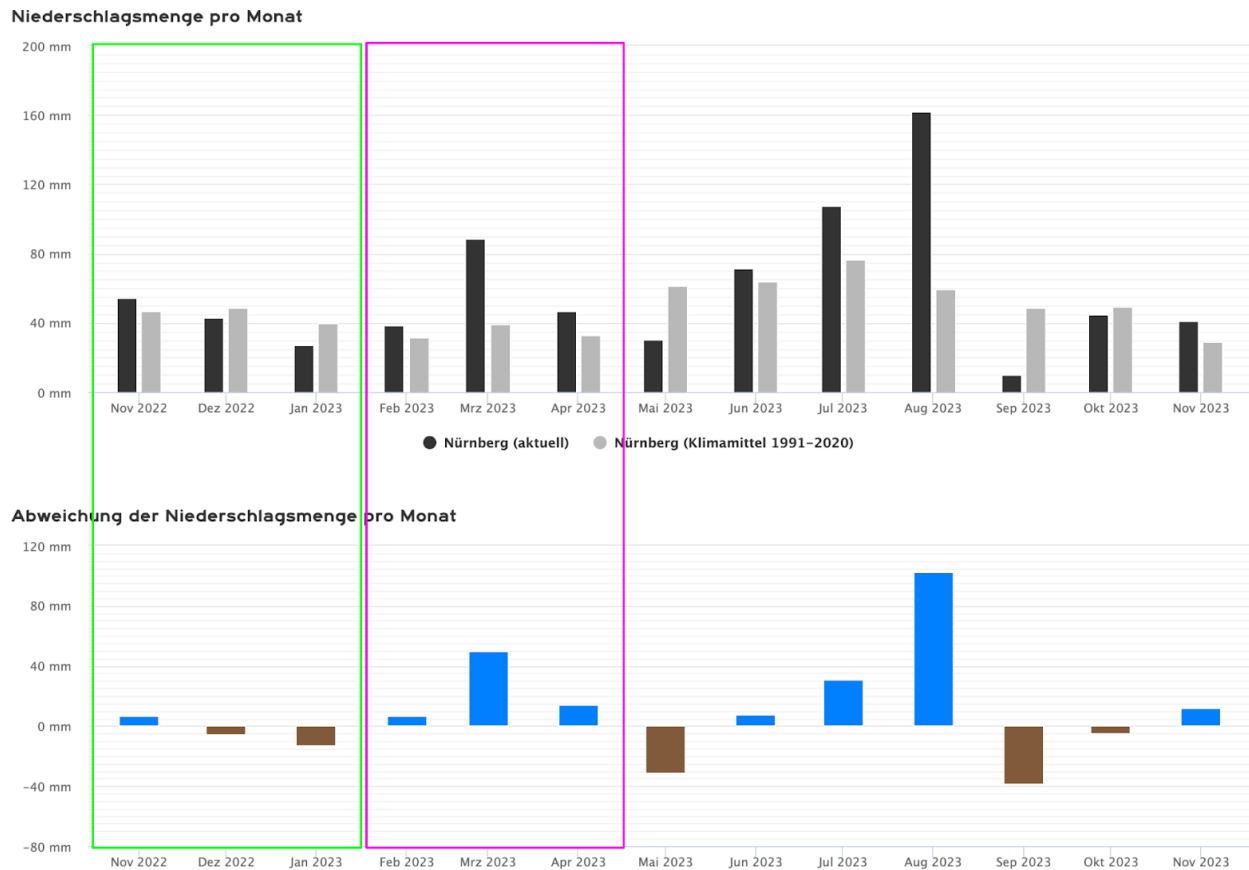
Figure 9: Rain data for Fürth (Source: Kachelmannwetter.com)

Summary

The learnings from our greenhouse experiment leachates' titration alkalinity data so far are:

- We seem to be able to estimate CDR. Which is the primary objective of our whole endeavor! Great!
- We had to come up with our own way of calculating this, there is no standard. Not Good!
- No rock and no soil was a simple safe bet for CDR, there are always combinations that did not show a significant CDR effect - at least over ~~6~~8-11 months.
- For the experiments that actually were climate positive we measured CDR effects in the ranges of up to ~~3~~0.5 tons per hectare in ~~6~~11 months, which is ~~in~~below the ranges of other publications that show CDR effects of 1-8 t/ha of CO_2 per year for ERW field experiments (links mentioned above).
- Even small changes between experiments (Fürth Soil I and II) seem to be able to massively change the outcome - at least at our time scale of 6-10 months.

There are still a lot of questions. Why is soil x not working well together with rock y? What's wrong with Fürth soil and basalt? Why does dunite not seem to work as intended on ~~only half~~all the soils?

Our main take-away-messages:

- **These early, but carefully crafted results observed with high density-measurements in a highly controlled greenhouse experiment might indicate that you can't just throw any rock on any field and simply hope for a climate-positive outcome - you need to measure your CDR, always! At least for now, until we have data-truthed models.**

- **In our experiments we found no single soil or rock that is a "safe bet". Even the rule-of-thumb "don't use high pH or clayey soil" was wrong (LUFA 6S looks like the best soil in this data). This will require many more experiments to ~~verify~~produce the real life data needed to verify future ERW models.**
- **We were actually surprised by the huge variability of the results.**
- **Even with a conservative and high-effort measurement approach (leachate alkalinity) in a highly controlled environment it is hard to get consistent data.**

We may soon need to update our climate hacker's cheat sheet for ERW.

It looks like this will keep us busy for some time. More to come… In the upcoming articles about our experiment data. Subscribe to our newsletter to get the next issues, too!

If you have comments or feedback, please write to info@carbon-drawdown.de.

Appendix: Rock data

The rock dusts have undergone chemical, mineralogical and grain size distribution analyses by QMineral.

Table 6: Results of the XRF analyses. The Loss on Ignition (LOI) was determined on the fused samples.

Element	Unit	Detection limit	Steelslag	Basalt Eifelgold <2mm 2022	"Olivine" Sibelco (NO)	Diabase Schicker
SiO_2	%	0.01	10,79	43,3	41,08	34,7
Al_2O_3	%	0.01	2,85	13,4	0,53	11,52
Fe_2O_3	%	0.01	23,85	10,95	7,15	11,12
MnO	%	0.01	1,62	0,185	0,102	0,148
MgO	%	0.01	4,85	9,8	47,27	5,09
CaO	%	0.01	43,12	12,7	0,24	16,09
Na_2O	%	0.01	0,03	2,63	0,03	1,96
K_2O	%	0.01	< 0.01	3,08	0,03	2,03
TiO_2	%	0.01	0,53	2,73	0,01	3,54
P_2O_5	%	0.01	1,42	0,55	0,01	0,48
LOI	%		10,68	0,6	1,57	13,21
TOTAL	%		100,3	100	98,64	99,96
Cr	ppm	68	1300	205	1778	68
V	ppm	17	1703	286	<17	129
Co	ppm	37	<37	51	110	59
Cu	ppm	40	<40	80	<40	48
Ni	ppm	24	<24	118	2687	110

Table 5: Quantitative bulk mineralogical compositions of the samples (in weight percentages of the identified crystalline components).

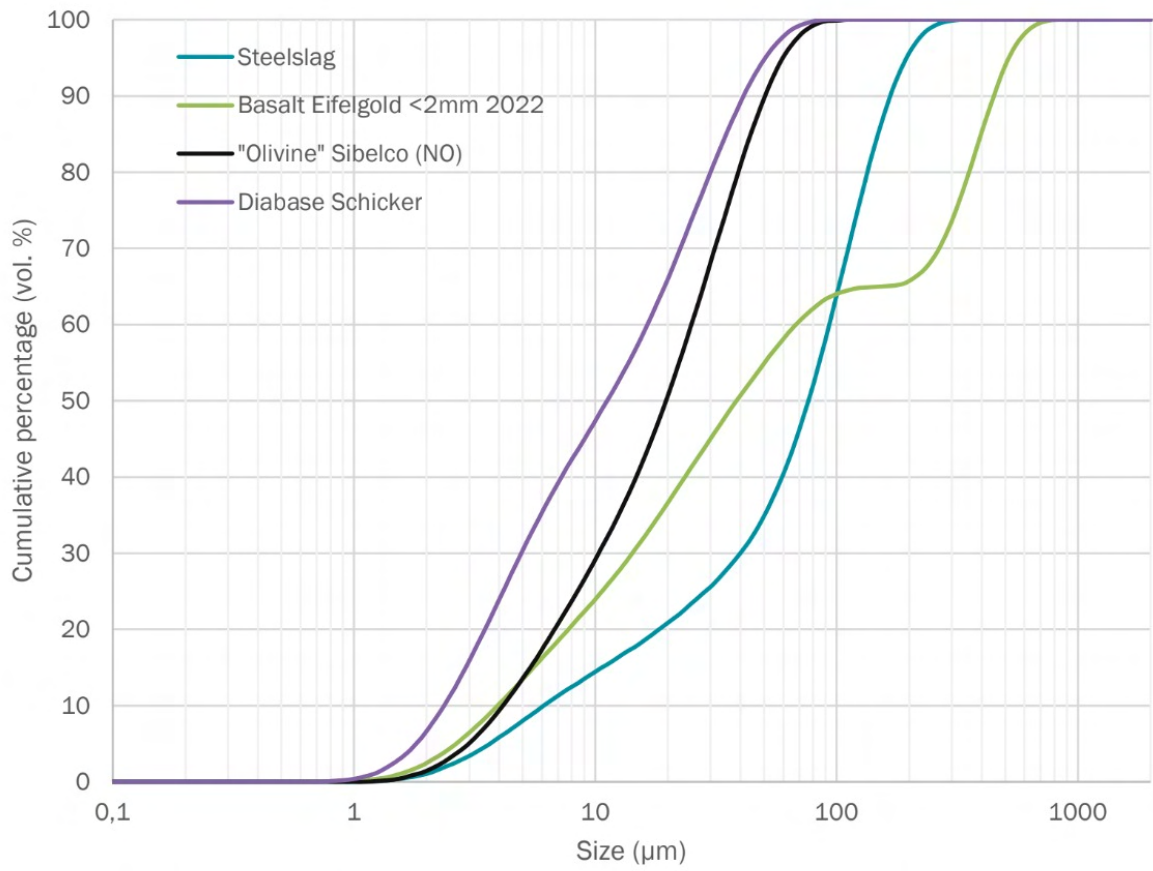| Mineral	Mineral Formula[1]	Steelslag	Basalt Eifelgold <2mm 2022	"Olivine" Sibelco (NO)	Diabase Schicker
SILICATES					
Quartz	SiO_2				4,3
K-feldspar	$KAlSi_3O_8$				10,1
Plagioclase	$(Na,Ca)(Si,Al)_4O_8$		7,7		15,5
Clinopyroxene	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$		49,4	1,6	1,8
Orthopyroxene	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$			5,0	
Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$			1,9	
Olivine	$(Mg,Fe)_2SiO_4$		11,2	79,2	3,6
Nepheline	$(Na,K)AlSiO_4$		9,3		
Sodalite	$Na_8Al_6Si_6O_{24}Cl_2$		0,5		
Leucite	$KAlSi_2O_6$		12,6	0,3	
Analcime	$NaAlSi_2O_6 \bullet (H_2O)$		1,3		
Alpha-Dicalcium Silicate hydrate	$\alpha\text{-}Ca_2(SiO_4)(H_2O)$	6,2			
Beta C2S (Larnite)	Ca_2SiO_4	8,9			
Alpha' C2S	Ca_2SiO_4	14,8			
2:1 layer silicates	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$		1,8	0,5	6,2
Chlorite	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$			1,4	22,5
Garnet	$X_3Z_2(SiO_4)_3$	4,5			
Serpentine	$(Mg,Fe,Ni,Mn,Al,Zn)_3[Si_2O_5](OH)_4$			10,3	
Titanite	$CaTiSiO_5$				6,5
CARBONATES					
Calcite	$CaCO_3$	8,3			27,2
PHOSPHATES					
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$			1,2	0,8
OXIDES/HYDROXIDES					
Anatase	TiO_2				0,8
Hematite	Fe_2O_3				0,7
Spinel-type minerals	$Fe^{2+}Fe^{3+}_2O_4$	5,9	4,8		
Wuestite	FeO	10,8			
Lime	CaO	1,9			
Portlandite	$Ca(OH)_2$	19,5			
Periclase	MgO	0,7			

Figure 5. Cumulative frequency distribution of the grain size of the samples.