Carbon
Drawdown
Initiative

Insights from monitoring leachate alkalinity, pCO_2 and CO_2 efflux of 400 weathering experiments over one year

(Data from our greenhouse, part 3)

Working paper - V1.0 - April 11th 2024 - Dirk Paessler, Ralf Steffens, Jens Hammes, Ingrid Smet

Background: We present insights we gained from CO_2 efflux, soil pCO_2 and soil water leachate alkalinity data of 400 greenhouse experiments for enhanced weathering (EW), a promising new approach to carbon dioxide removal (CDR) which uses rock dusts on agricultural soils to capture CO_2.

Methods: We monitored hundreds of soil-rock dust combinations in a controlled greenhouse setting using fluxmeters, sensors, and high frequency leachate analyses combined with data analytics to better understand change in soil carbon fluxes and pools.

Results: Our findings reveal that (1) successful CO_2 capture via enhanced weathering seems often accompanied by an initial increase in CO_2 efflux (which is likely temporary) and (2) Whereas maximum CDR potential varies greatly between rock dusts depending on their composition, the CDR that can actually be realized is heavily influenced by the soil it is added to. Further scientific research is needed to fully understand which processes are exactly responsible for these observations.

Conclusion: Based on the high variability of observations resulting from combining 16 different soils with 12 rock dusts we suggest increasing rock-soil variations in future EW studies. We also advocate incorporation of pCO_2/CO_2 efflux measurements in more EW studies as initial CO_2 efflux spikes might need to be taken into account in the LCA of future EW projects and also because CO_2-based data could provide “early signals for future success” for EW projects.

Content

Summary

In this report we present insights and data gained over 11 months through monitoring the soil CO_2 efflux, soil pCO_2 and soil water leachate alkalinity of 400 enhanced weathering (EW) experiments in a greenhouse. We found that:

(1) An increase in leachate alkalinity after amendment quite often correlates with an increase in the CO_2 efflux. Within the context of carbon dioxide removal (CDR) the CO_2 efflux increase could be interpreted in several ways: The more optimistic assumption would be that an increase in CO_2 efflux is an indicator of a desired increased weathering as suggested by the increase in alkalinity. The more pessimistic assumption would be that the amendment-stimulated biotic processes consume old, stored organic carbon from the soil and transport it back to the atmosphere, creating a carbon source instead of the intended carbon sink. Either way, it is possible that the increase in CO_2 efflux observed in the first year of our greenhouse experiment is only a temporary effect. Since we do not have measurements of all carbon pools yet, we cannot distinguish between these two assumptions, nor can we make projections on future effluxes. Important questions still need to be answered: How can this CO_2 efflux increase be predicted? How can it be measured at scale? Is it a temporary effect? And if so, how long does it last and do we need to take it into account for the life cycle assessment (LCA) of EW projects? More CO_2 measurements are urgently needed.

(2) We also observed that changes in CO_2 efflux and leachate alkalinity of treated pots vary widely with soil and rock combination. We already reported this in our observations of varying alkalinity increases after rock amendment. In short: The same amendment on different soils and also different amendments on the same soil can cause surprisingly different results. We have the impression that the influence of an amendment's characteristics is already taken into account in most EW projects, but that the effects on weathering resulting from the soil and a particular soil-rock dust combination have been very much underestimated in the EW industry. We see that even soils collected from nearby fields can react quite differently to the same amendment. So far, this equally important influence of the soil seems to have gone somewhat unrecognized as most experiments test a particular rock dust on only one or few soil types. But the effect of the soil on CDR efficiency will likely play an important role, given that in almost any EW project the number of soils or fields outnumbers the number of amendments by orders of magnitude.

(3) We think that CO_2 measurements (as efflux or in the soil gas), carried out with cheap yet precise electronic sensors at high resolutions (every x minutes), might potentially give us "early indicators of future success" for CDR projects. If a correlation between CDR effects and CO_2 data can be shown, such measurements could help categorize a proposed EW setup as successful (measurable CDR) or failed (no/little changes in the carbon cycle or even an increase of C released to the atmosphere) very early on. Based on the fast weathering of ultra-fine fractions of the rock dust, this could give us insights into CDR efficiency at a time when more common measurement approaches such as changes in solid phase composition or increase in leachate alkalinity will not yet be able to show a signal as both need certain amounts of dissolved rock and time before their CDR signal can be distinguished from the natural background. An extra advantage of this

approach is that it also reflects any rock-induced changes to the C cycle linked to biotic processes, which might be important for full LCA of CDR projects. Such a super early signal could speed up the learning in EW science even if it may only be part of a robust MRV solution.

If you want to work with us on solving these questions, please contact info@carbon-drawdown.de, we gladly accept any help with this complex challenge.

Our data can be downloaded, links in the appendix at the end of this document.

Thank Yous

The following people (in alphabetical order) have helped us during the creation of this paper (which doesn't necessarily mean they endorse it): Thanks to Jelle Bijma, Mathilde Hagens, Jens Hartmann, Anna Anke Stöckel, Philip Pogge von Strandmann, Philip Tillmanns and Tanja Wartenberg.

This is intentionally not a formal peer-reviewed publication

Several scientists as well as practitioners have reviewed this paper before publishing. So although a lot of expertise has been poured into this document, it has not undergone a formal scientific peer-review. We decided to go for direct publishing on our blog and as pre-print 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!

Introduction

The principal idea of enhanced weathering (EW) as a climate solution is to mix rock dusts into the soil to reroute a fraction of the natural carbon cycle through trapping CO_2 into the leachate water in the form of bicarbonates which are ultimately stored in the oceans. It is a nature-based method that effectively copies Earth's time-tested natural method to control its atmospheric CO_2 concentration through natural rock weathering.

However, weathering of added rock dusts in the complex soil environment needs more time and research to be fully understood. This could delay the required large-scale deployment of EW as a climate solution. In an effort to circumvent the vast complexities of the interactions in the soil, we came up with the hypothesis that the CDR-relevant changes in the carbon cycle could potentially be monitored in a simplified way by looking at the soil "CO_2 efflux" (=CO_2 gas fluxes out of the soil) and the CO_2 concentration of soil gas (soil pCO_2). We thereby expect to see EW signals more quickly when monitoring CO_2 (gasses move fast and CO_2 sensors are very sensitive) than other, slower monitoring approaches such as solid-phase dissolution measurements or aqueous alkalinity measurements as both need certain amounts of rock dissolution and more time before their CDR signal can be distinguished from the natural background noise.

If we succeed in picking up a weathering signal from CO_2 measurements, this could potentially become an early indicator for CDR, e.g. in large-scale experiments with lots of rock/soil combinations. And it might even be a basic component of monitoring, reporting and verification (MRV) of carbon dioxide removal (CDR) in the future. As the total amount of EW captured and stored carbon of 0.1-8 tCO_2 per ha per year (Welbel et al. 2023, table 9) is expected to be in the order of 1-10% of all the carbon annually cycled through the soil of 10 to 80 tCO_2 per ha per year (Weil & Brady 2016, Box 12.4; Lee at al. 2018), it might be hard to pick up a signal against nature's noisy background signal. We will show you, however, that we observe a large range of changes in carbon fluxes after rock treatments (-15% to +60% change in CO_2 efflux, and -20% to +600% change in bicarbonate flux in leachate water, compared to controls without rock treatments) at least in year 1, and that these changes are not easy to interpret.

Even if our hypothesis of tracing CDR through EW by monitoring CO_2 effluxes proves to be too naïve and simplified, it is still worth a try. Our greenhouse EW experiment is the ideal testing ground for this as we can cross-check results from CO_2 efflux measurements with the other MRV approaches that we are also testing.

Our experiment and our early observations

Since January 2023 we have been running a large enhanced weathering experiment in a greenhouse where we use several measurement approaches to track the resulting CDR. We have been monitoring CO_2 effluxes of several hundred lysimeters/mesocosms fully automated for over 6 months and have found that many variants with a significant alkalinity increase in the leachate water after the rock amendment also had a significant increase in CO_2 efflux.

In year one, out of 36 soil-rock dust variations, 16 show a significant increase in leachate alkalinity. Eight out of these 16 also show a significant increase in CO_2 efflux, which means that they are exporting carbon simultaneously from the bottom and the top as both their CO_2 efflux and leachate alkalinity are higher in comparison to their respective controls. None of the 16 has a significantly decreased efflux.

This poses a number of questions:

- What causes this increase in CO_2 efflux together with increased leachate alkalinity?
- How long will this correlation be sustained?
- What is the source of the CO_2 efflux increase? The changes in aboveground biomass alone do not seem to explain this. We observed weathering induced pH increases that will have an effect on the biotic processes which in turn could change organic carbon dynamics within the soil. Similar temporal effects are known from research on the addition of lime to agricultural soils (Paradelo et al. 2015).
- Are we in the worst case depleting soil organic carbon (SOC) by adding rock dust? And if so, how long can this go on? It is also possible that next to this so-called "priming" effect, the residence time of the residual soil organic matter is extended by the complexation with cations liberated from the rock dust, resulting in the formation of MAOM ("mineral associated organic matter"), see Liang et al. 2017 and Cotrufo et al. 2015?
- Do we need to include such CO_2 efflux increases in life cycle assessments of EW projects?
- Would sustainable farming practices, like adding biochar, compost or plant residues to the soil, help to mitigate this effect?

Although we do not yet have a complete picture of all carbon reservoirs and the interactions and conversions between them (for example we are still awaiting data from rock dissolution measurements and soil carbon analyses), we share our preliminary results from the first year in this working paper as they may be helpful for other researchers.

It would be inappropriate to draw conclusions about the CDR occurring in our experiments from these preliminary data as they only represent a part of the full carbon budget in our pots and barely cover one year. The C cycle is poorly understood and this report is based on time-limited (only 11 months) and incomplete (some lab analyses not yet available) data. Hence it is currently not clear whether the significantly increased CO_2 efflux is the result of desired or undesired processes regarding carbon dioxide removal. Our research efforts to understand this are ongoing.

The “Carbdown Model” of carbon fluxes and pools in the soil

Our reasoning is based on a carbon-focused thought-model of the processes that occur in the soil after adding rock amendments for EW. Figure 1 shows a representation of the carbon fluxes and pools in a natural plant-soil ecosystem, flanked by carbon reservoirs of the atmosphere above and the groundwater below which both have - compared to a single pot in our experiment - unlimited storage and/or supply capacity for carbon. Through photosynthesis plants absorb atmospheric CO_2 to form their aboveground biomass and their subsurface roots. A plant’s metabolism also produces CO_2 which is partly respired by its roots into the soil air. When (parts of) the plants die they become part of the dead organic carbon pool within the soil that upon decay is once again transformed into CO_2. This CO_2 released into the soil by root respiration and organic material decay enters the atmosphere as soil CO_2 efflux or dissolves in soil pore water and becomes dissolved inorganic carbon (DIC) that leaches into the groundwater.

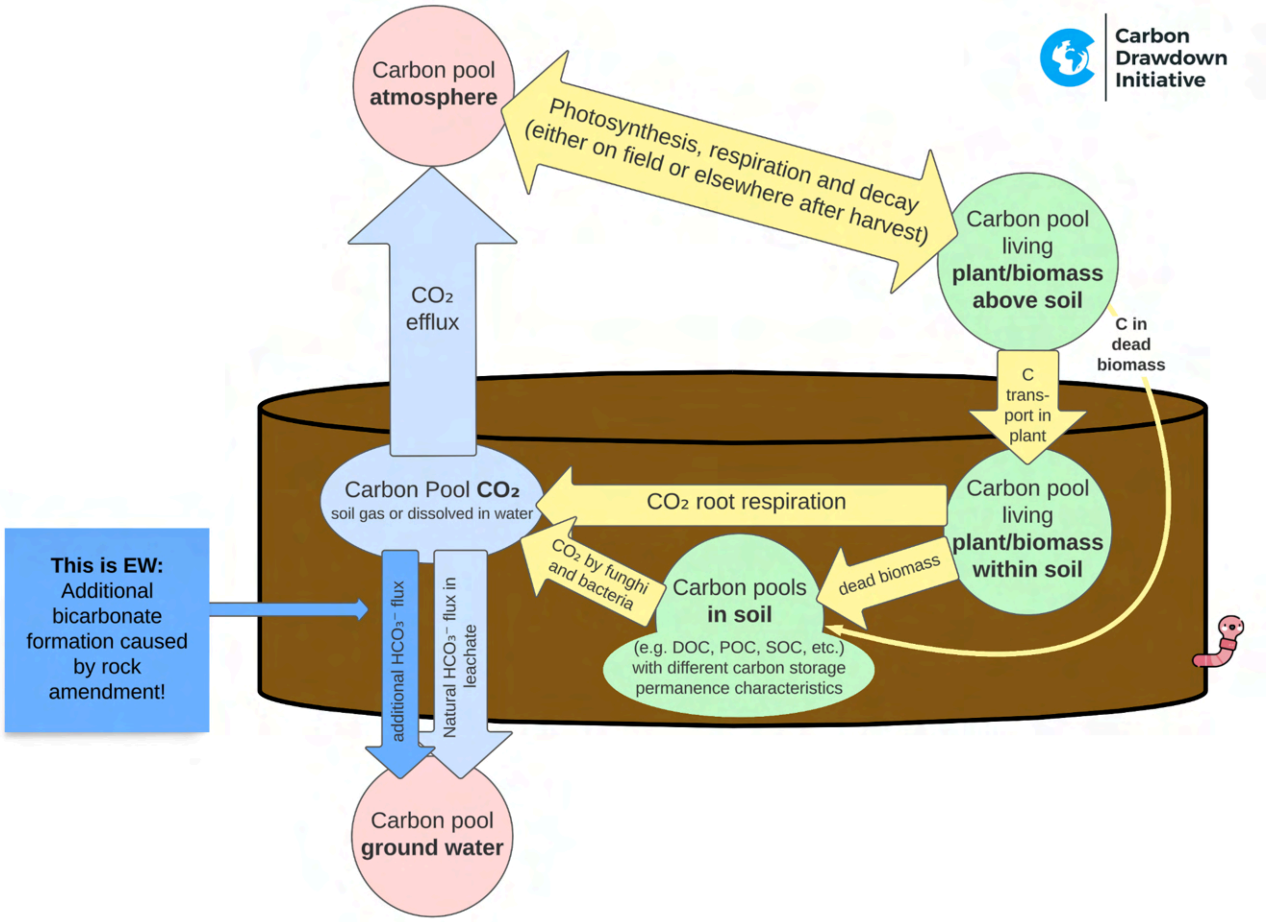


Figure 1: Illustration of carbon fluxes and pools in a soil with actively growing plants

By adding rock dust to the soil we want to enhance the formation of bicarbonate in the leachate water (dark blue arrow) which pulls carbon from the shown carbon cycle down into the ground, thus lowering the available carbon for the rest of the cycle and effectively moving it away from the atmosphere.

Our idea is that we should be able to get a basic understanding of the carbon-related effects of adding rock dust to a soil if we successfully monitor the changes (compared to the respective control which is the same soil without rock dust amendment) in CO_2 efflux, alkalinity flux in the leachate (blue arrows), soil gas pCO_2, soil carbon pools and biomass whilst most other parameters remain the same for both treatment and control - as is the case in our greenhouse. Ideally a set of metrics will emerge from CO_2 measurements which can give an early indication of successful, delayed, non existent or even failed CDR (=a carbon source was created instead of a carbon sink) through enhanced weathering before slower signals such as leachate alkalinity or rock dissolution will show this.

Our elaborate greenhouse experiment setup and sampling strategy should allow us to track changes in carbon cycling over short time scales (weeks/months) in hundreds of experiments. We combine 24/7 monitoring of both soil pCO_2 and CO_2 efflux using electronic sensors with high frequency lab data of leachate water, biomass and various soil derived data.

In the first instance, we are mainly interested in the carbon fluxes into and out of the soil column (blue arrows). Because in a simplistic view one would expect that the CO_2 efflux goes down after treatment (less CO_2 emitted to the atmosphere) whilst the carbon transport as bicarbonates in the leachate goes up. Of course, it turns out to be more complicated than that, as we will see.

A closer look at the carbon fluxes in soil with and without rock dust

The main process pumping carbon into the soil is plants taking up CO_2 from the atmosphere for photosynthesis. Carbon then enters the soil mainly via two pathways:

1. Through the plant's internal carbon transport downward where it is used to grow roots and it is respired as CO_2 into the soil (this produces carbonic acid after dissolving in water ($H_2O+CO_2 \leftrightarrows H_2CO_3$), which weathers the soil’s mineral components and releases nutrients for the plant to take up).

2. Through dead organic material (e.g. biomass from old roots, leaves, plant residues and other dead organisms) which contributes to the soil's solid carbon storage pools.

Both paths already carry carbon away from the atmosphere (good!), but the storage is not permanent (less than centuries). The dead biomass is decomposed by microbes, a process which releases CO_2 into the soil (mineralisation of organic carbon). Together with the roots’ CO_2 respiration, this increases the soil's CO_2 gas pool which is ultimately released upwards to the atmosphere as a soil CO_2 efflux (driven by Fick’s 1st law).

The desired carbon capture driven by rock dust amendment mainly happens in the form of bicarbonate ions in leachate water (i.e. downward carbon export from the soil, potentially accompanied by DOC and POC which are less relevant for the intended permanent carbon storage effect due to low storage permanence between decades to a century). These bicarbonate ions are the products of the chemical reactions that occur when added rock dust minerals are dissolved by carbonic acid.

In natural ecosystems, the carbon cycle is largely carbon-neutral in a climate sense (a steady-state apart from annual/seasonal changes when undisturbed), circulating carbon between soil and atmosphere whilst only some of it is lost as dissolved species in leachate. This natural cycle serves as our benchmark and is represented by what we measure in our untreated control experiments.

Introducing rock dusts as a CDR technology will create two effects:

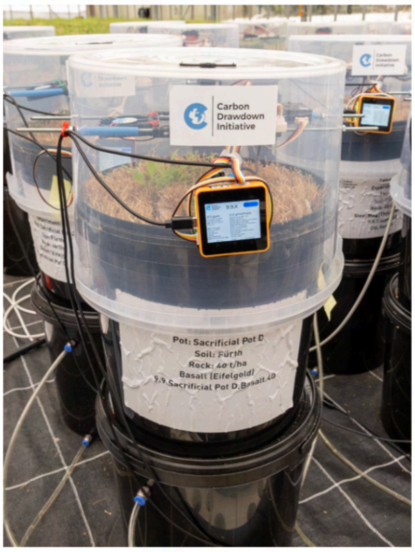
1. The rock dust is weathered by carbonic acid (=formed through the combination of water and CO_2 from air and soil gas) which produces cations that will eventually end up in the leachate, leaving the soil system together with the bicarbonate ions they counterbalance (= the desired effect). This might take a while (months-years-decades?) to fully materialize due to temporary immobilization of cations (and anions) as they move down in the soil column, see cartion park model. The bicarbonate/alkalinity signal is a slow CDR signature that lags behind the rock dust dissolution, but it is a rather reliable one as it directly measures the CO_2 that leaves the soil system captured as bicarbonates.

2. The cations released by the rock weathering reactions may also act as fertilizer for plant growth, change the soil pH and impact soil biotic processes. This effect of cation release due to rock dust dissolution could lead to increased yields (Beerling et al. 2024) and may occur faster than the increase of cation content in the leachate water.

From our initial observations it appears that rock dust amendments indeed alter multiple carbon fluxes in our pot experiments linked to leachate alkalinity and soil CO_2 gas, although not at the same rate and pace. Plant growth and biotic activity in the soil is often boosted, at least for some time after the rock dust application. We saw an increase in biomass after rock dust amendments in our experiment and similar observations have been reported in the review paper of Swoboda et al. 2022, section 4. These biological processes can both increase CO_2 respiration into the soil, which in turn likely boosts the weathering reactions due to higher availability of CO_2.

Our experiments' carbon flux data

Let us take a look at the preliminary 2023 results from our main greenhouse experiment. The data presented here are based on 36 treatments and 17 controls with 4 replicas each, i.e. in total covering 212 of our 400 lysimeters, monitored by 635,608 automated flux measurements and 3,486 manual on-site leachate titrations over a timespan of 11 months in 2023.



```
601 ppm                    0.2 umol/m2/s
Chamber CLOSED             10:23:49 Cycle #540 - 228
3.78 ppm Cdelta            10:13:18 Flux 0.1640981 umol/m2/s
960 hPa 21 °C 59 %         10:5:20 Flux -0.03467631 umol/m2/
3784 lux                   9:53:19 Flux 0.1682937 umol/m2/s
                           9:45:54 CO2 failed
9042 ms Cycle              9:45:53 I2C bus error (110)
268 ms MQTT                9:45:21 Flux 0.0006098508 umol/m
1 Errors                   9:33:24 Flux 0.0621361 umol/m2/s
-48 dB Wifi                9:23:16 Flux 0.179303 umol/m2/s
V 6.00                     9:13:20 Flux 0.1363214 umol/m2/s
MAC 215B414D               9:4:33 Starting...
2024-01-15 10:23:56 Mon    9:4:27 System setup completed
```

Because our research is focused on CDR, we work with annual carbon transport estimates expressed in tCO_2/ha/year, a common metric for people working in the CDR space (calculations explained in Appendix 5). We extrapolated the annual carbon transport after treatment in tCO_2/ha/year from our accumulated alkalinity data and our CO_2 efflux data in figure 2-A and 2-B. The green bars in figures 2-A and 2-B are controls, the untreated soils, with their respective treatments to their right.

At first glance, figure 2-A shows that many treated variations have a higher CO_2 efflux than their controls, although this difference is only statistically significant (based on 90% CI error bars) for about half of them. Taking into account that every control represents a different soil, figure 2-B shows that the leachate alkalinity is heavily dependent on the soil type.

In general the variability of accumulated alkalinity observed across the different experiments (figure 2-B) is much larger (33x, between 0.1 and 3.3 tCO_2/ha/year) than their variability in CO_2 efflux (4.5x, 18-78 tCO_2/ha/year, figure 2-A). Regardless of rock dust treatment, four soils (the farmers' soils in 3.0/1 and 4.8/9 as well as 7.x=LUFA 2.1 and 6.x=LUFA 2.2) have leachate alkalinity that is significantly lower than the other soils, while 5.x experiments (LUFA 6S) tend to have an overall higher alkalinity flux. The background level of leachate alkalinity thus clearly depends on the soil type.

When comparing the absolute values of these two carbon fluxes we find that the carbon transport in the leachate is in the order of 0.3-11% of the carbon transport in the efflux, i.e. 10-30 times more carbon leaves the soil as gas efflux than as leachate bicarbonate.

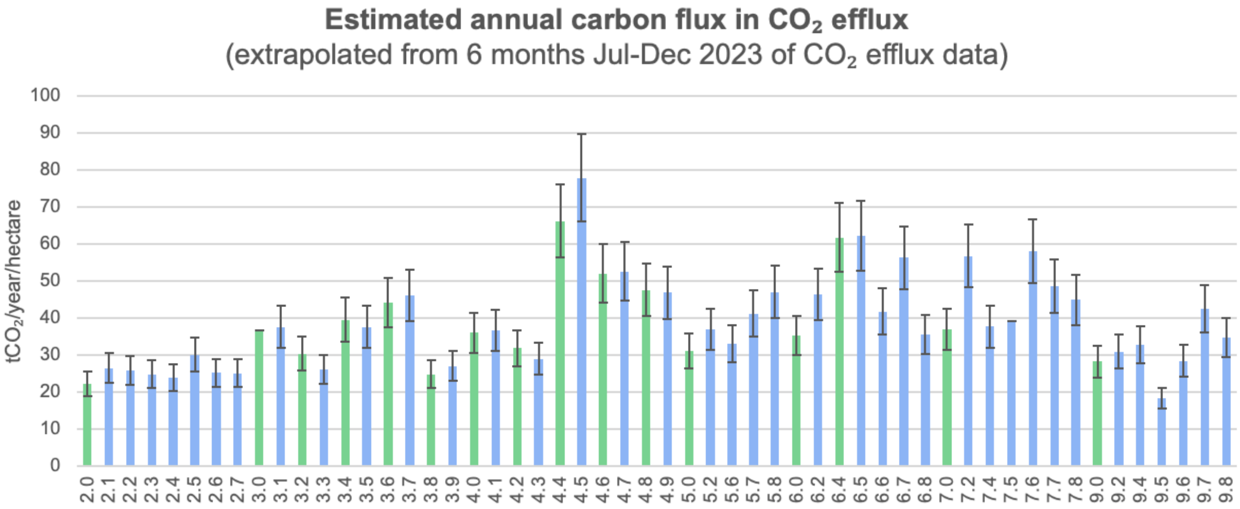


Figure 2-A: Carbon efflux (in tCO_2/ha/year) derived from CO_2 efflux monitoring, extrapolated from 6 months (July to December 2023) - green bars represent controls with their respective treatments to their right. For all bars, n=4. Refer to "appendix 3: Pot plan" for experiment details.

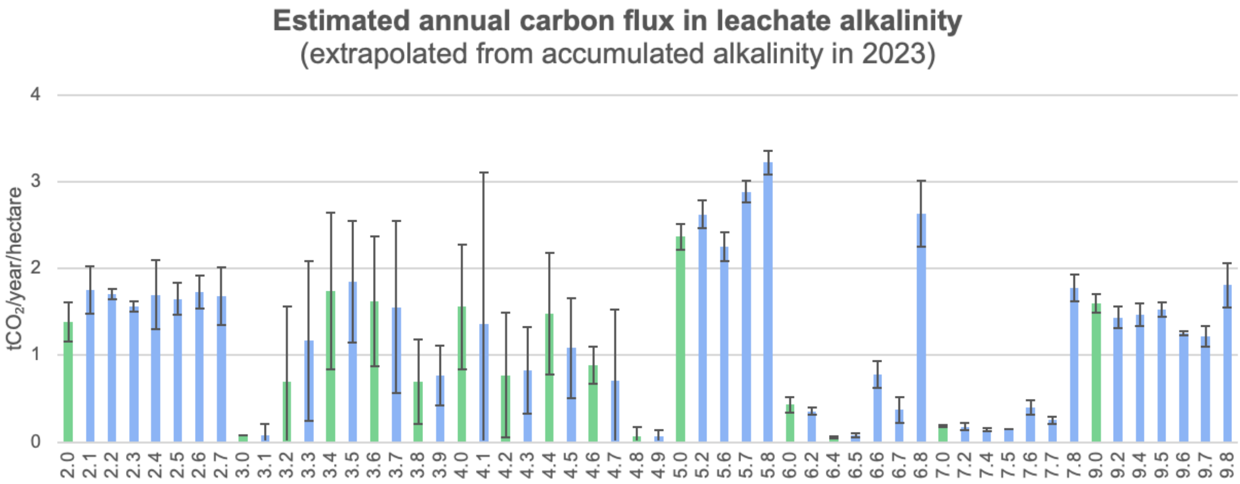


Figure 2-B: Carbon flux in leachate (in equivalent tCO_2/ha/year) derived from accumulated alkalinity, extrapolated from 11 months (7 months for table 2; 3 months for tables 3 and 4) - green bars represent controls with their respective treatments on their right. For all bars, n=4.
Refer to "appendix 3: Pot plan" for experiment details.

As a plausibility check let's get an understanding of usual orders of magnitude:

- The annual CO_2 efflux of cropland fields can be in the range from 10 to 80 tCO_2 per ha per year (Weil & Brady 2016, Box 12.4; Lee at al. 2018). We have an illustration of this in our blog.
- Various studies put the expected amount of CDR through EW (estimate from the difference in alkalinity flux between rock dust amendments and their control) in the range of 0.1-10 tCO_2 per ha per year (Welbel et al. 2023, table 9; Kukla et al. 2024).

- In our greenhouse we expect 2-3 times higher weathering rates and likely also efflux rates compared to a similar outdoor field in Germany due to the CDR optimized ambience (see: How much faster is rock weathering in our greenhouse compared to the field?).

Our data fall within these ranges and hence pass the plausibility check.

We calculated the changes caused by the rock amendments by subtracting the carbon fluxes of the controls from the carbon fluxes of their corresponding treatments. We then sorted the dataset by the resulting changes in CO_2 efflux and plotted these data for 36 treatments in figure 3. The error bars for alkalinity data are analogous to the ones in our article on alkalinity measurements showing standard deviations of accumulated sums of the replicas. Error bars for efflux data are using the 90% confidence intervals as described in the fluxmeter article.

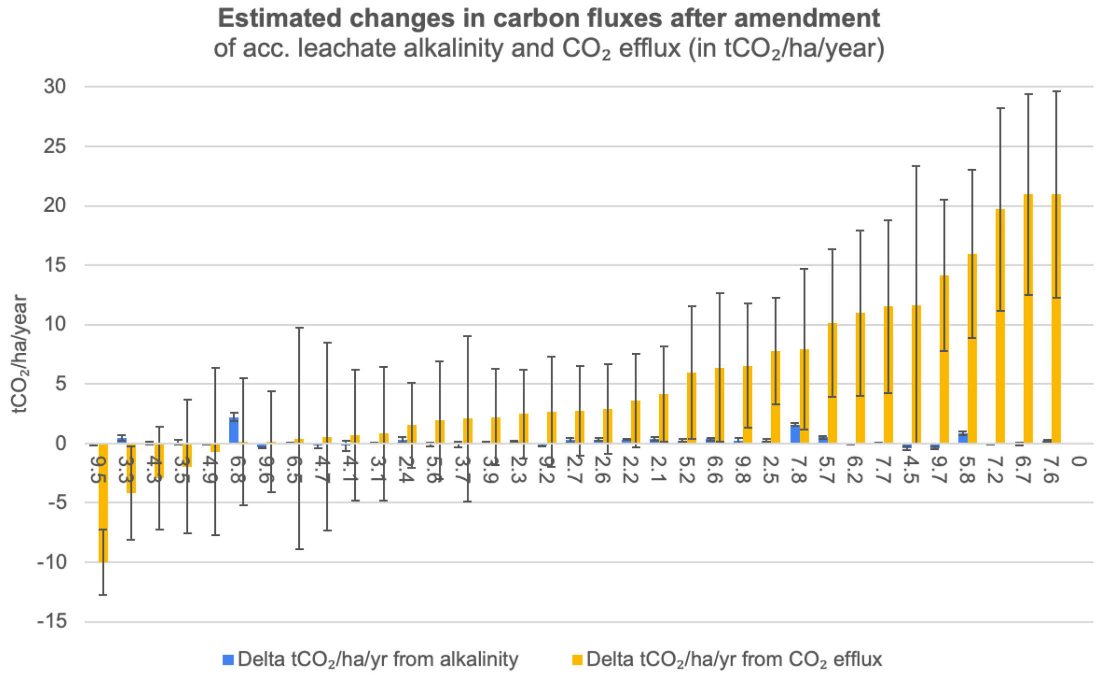
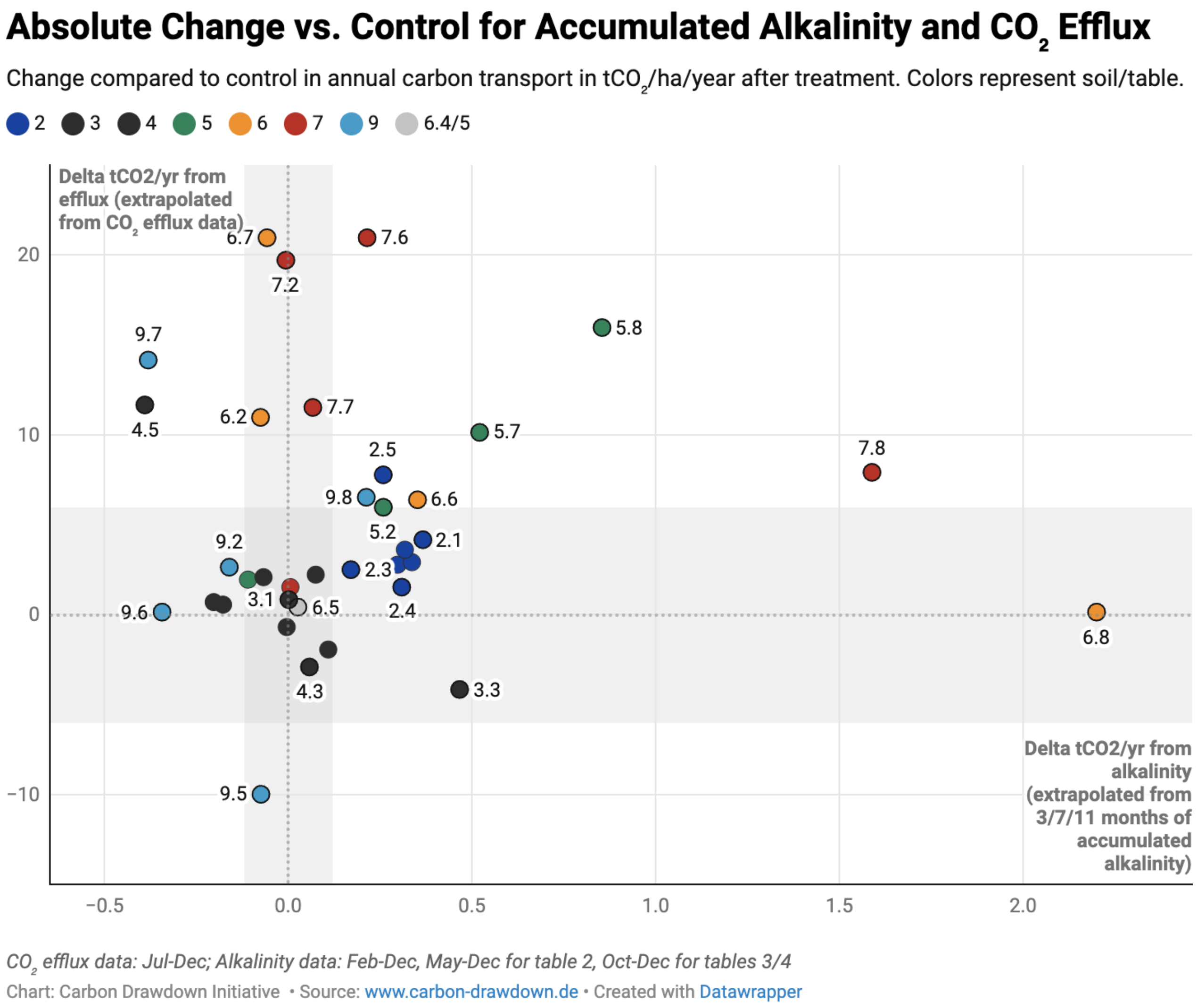


Figure 3: Differences between carbon fluxes of treatments and their respective controls. For all bars, n=4. Refer to "appendix 3: Pot plan" for experiment details.

We found that 15 of 36 treatments (42%) on 10 of 16 soils showed a significant increase in CO_2 efflux after the rock amendment (compared to their control). 20 treatments (56%) showed no significant change in CO_2 efflux and in only one case (3%) the CO_2 efflux was significantly lower than the control. On the right hand side of Figure 3 the relative CO_2 efflux increases are in the order of +60% compared to their respective control.



Absolute Change vs. Control for Accumulated Alkalinity and CO_2 Efflux

Change compared to control in annual carbon transport in tCO_2/ha/year after treatment. Colors represent soil/table.

CO_2 efflux data: Jul-Dec; Alkalinity data: Feb-Dec, May-Dec for table 2, Oct-Dec for tables 3/4

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

Figure 4-A: Scatter plot of treatment alkalinity relative to control (x-axis) and treatment CO_2 efflux relative to control (y-axis), with the gray bars around each axis representing the uncertainty on the measurement of the respective parameters. Color codes reflect soil types: red = LUFA 2.1; orange = LUFA 2.2; green = LUFA 6S; light and dark blue = soil collected from the same location in Fürth at two different times; gray/black = 11 soils from several farms. For all dots, n=4. Refer to "appendix 3: Pot plan" for experiment details.

Let's look at figure 4-A which shows the difference in alkalinity and CO_2 efflux between treatments and their controls in tCO_2/ha/year:

- Out of 36 soil-rock variations, 16 show a significant increase in alkalinity. 8 out of these 16 also show a significant increase in CO_2 efflux (referring to the dots in the upper right quadrant outside the gray uncertainty bars) while none show a significant lowering of CO_2 efflux (lower right quadrant). This suggests that for about half of the rock-soil combinations with a significant increase in leachate alkalinity there is also a significant increase in CO_2 efflux.

- 26 soil-rock variations plot in at least one of the gray bars indicating that they do not show a significant change for leachate alkalinity and/or CO_2 efflux. So a significant change in one of the metrics does not always coincide with a change in the other one as well. This might reflect that rock dust dissolution affects individual components of the carbon system to varying degrees and at different speeds depending on a soil's specific parameters. For example, 4 amendments show a significantly increased CO_2 efflux whilst their leachate alkalinity is not significantly different from their respective control (6.2, 6.7, 7.2, 7.7). This could indicate that whereas the rock dust induced pH change is observable as an increase in soil bioactivity, the simultaneously expected increase in soil water alkalinity is delayed due to soil CEC.

- There are 9 soil-rock combinations that do not show a significant change for either one of these parameters over the first year, suggesting that rock dust addition did not have much effect in these experiments. Interestingly, 7 of the 9 are part of the farmers' soils experiments on tables 3 and 4 (black dots and the gray dot in the graph) and represent 7 different soils.

- Variation 9.5 is the only treatment with a significantly lowered CO_2 efflux (bottom left). However, this soil-rock combination had "dead pot" replicas (grass died over the summer, we do not know why) which likely explain the low CO_2 efflux measurements.

- Experiments involving the Fürth 1 soil (9.x, light blue dots) are often outliers, generally showing lower leachate alkalinity for the treatments than for the control. The same soil also showed unexpected reactions to rock dust amendments in our other EW experiments. So far we do not have an explanation for its unexpected behavior but extensive sampling and analysis are underway. Only the steel slag treatment on the Fürth soil (9.8) is in the upper right quadrant together with most other steel slag experiments (x.8). Our steel slag contains $CaCO_3$ which upon dissolution releases not only cations but also carbonates, hence increasing the leachate alkalinity regardless of the soil it is mixed into.

- Table 2 (dark blue dots) has Fürth 2 soil, which was harvested right next to Fürth 1 soil, but three months later. The dark blue dots from these Fürth 2 soil combinations cluster in the upper right quadrant of Figure 4 which seems to suggest that this soil may behave more as expected after addition of rock dusts compared to table 9.

Figure 4-B is a less-easy-to-read graph of the same data as in figure 4-A, but here we plot each datapoint with its individual x/y-uncertainty bars. The yellow area highlights the quadrant that

combines both increased leachate alkalinity and increased CO_2 efflux:

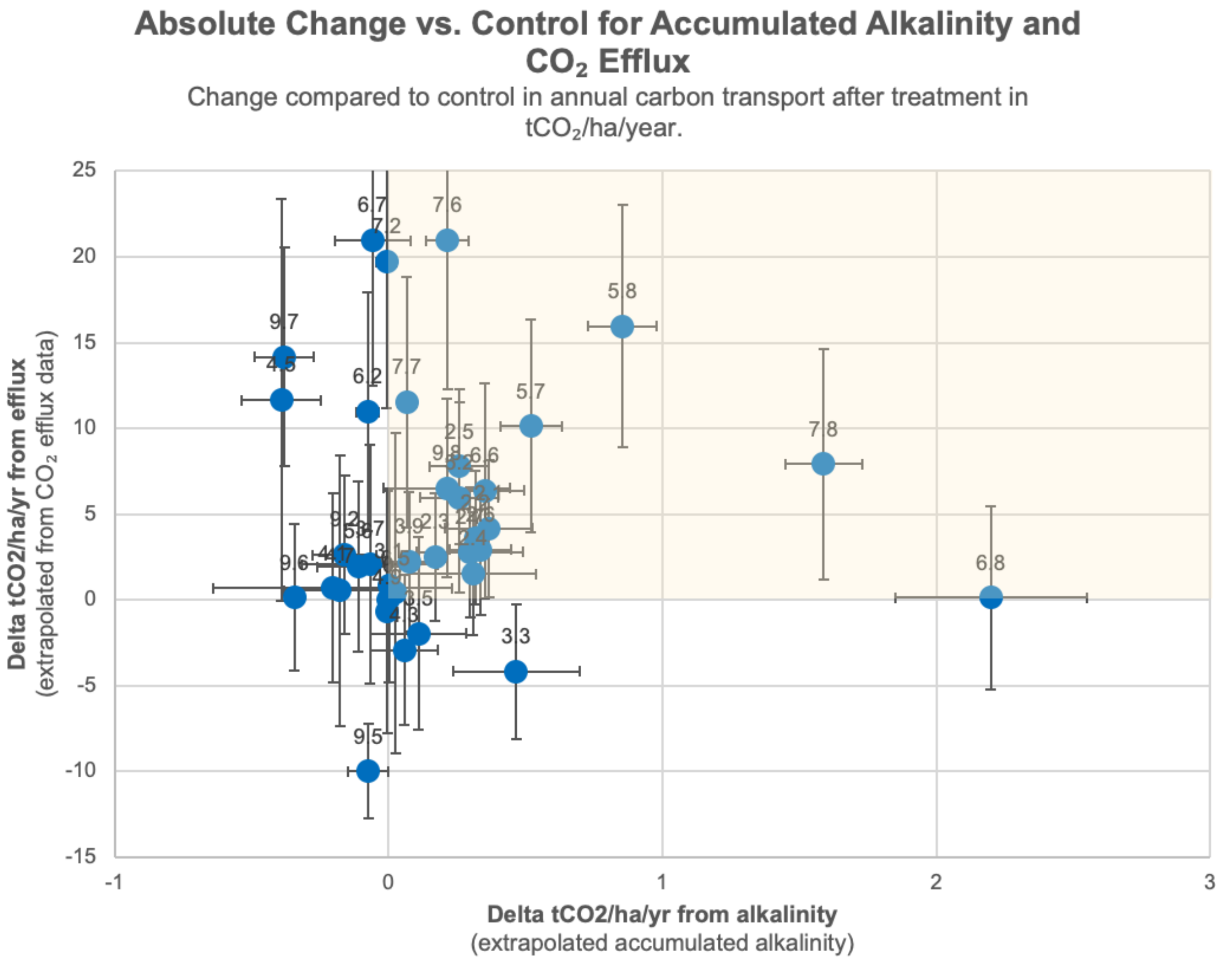


Figure 4-B: Deltas of carbon fluxes based on CO_2 efflux and accumulated alkalinity, same data as figure 4-A. For all dots, n=4. Refer to “appendix 3: Pot plan” for experiment details.

For all rock-soil combinations that plot within this yellow quadrant, carbon is leaving the experiment’s pot into both directions - upwards as CO_2 efflux and downwards as alkalinity in the leachate water. But where do the additional outflowing 0-20 t/ha/year of CO_2 come from?

Our highly variable observations of CO_2 effluxes and leachate alkalinity fluxes on almost 100 rock/soil variations are not unique to our experiment. Other EW research projects also report increased, or unchanged and even decreased CO_2 efflux and/or leachate alkalinity after rock amendments in lab and field settings.

Clarkson et al. (2023) (Preprint, Chapter 2.6) write about CO_2 effluxes: “*Varying interpretations about the effects of rock powders on gas fluxes have been obtained to date using gas flux chambers.*” Whereas some scientists report an increase in CO_2 efflux after rock amendments (e.g. Kantola et al. 2023, Schaffer et al. 2023), there are also reports of no increase in CO_2 efflux (e.g. in the pot experiments of Vienne et al. 2023).

Could EW studies be inconclusive due to unintended bias?

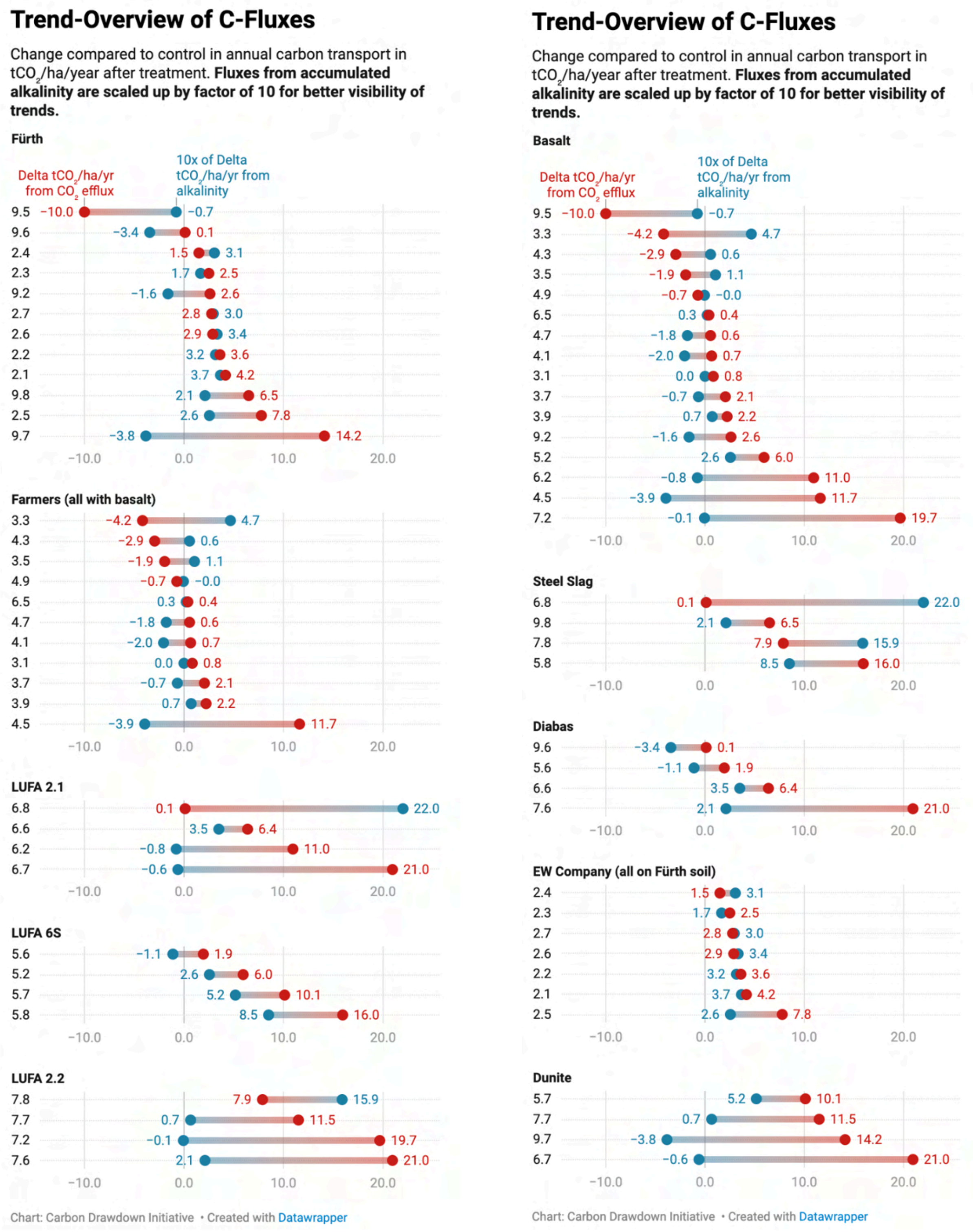
Both amendments and soils have caused high variability of the outcomes in our experiments where the only difference between the pots are the soil/amendment combinations (and to some extent the plants as we can't fully control their growth), with all other parameters being the same.

An outstanding feature of our experiment is the fact that we have a lot of different combinations of soils and rocks which may give us unique insights. In figure 5 we can see that in both graphs, grouped by soil on the left and grouped by rock on the right, the variability for alkalinity as well as efflux can be huge. This suggests that using the same rock on different soils (for example the 'basalt' group on the right) can be equally variable as using different amendments on the same soil (for example the 'Fürth' group on the left). Please note that we scaled up the fluxes derived from alkalinity by a factor of x10 to make the trends more visible in this trend-graph.

The data presented in this document may suggest three potential kinds of bias that could explain very different outcomes for studies on EW for CDR:

- Soil bias: We see a significant CO_2 efflux increase after the rock amendment only for about ⅔ of our 16 soils and a significant alkalinity increase on only about half of the soils. Our data thus indicate that the soil type can have a major influence on these effects, suggesting the need to conduct EW experiments on a set of several soils instead of just one or a few as is often the case. Eight of our soils (3.0-3.7 and 4.0-4.7) were taken from a region with a 40 km radius (Orthenau-Kreis, Germany) and show quite different results. We also have four pairs of soils where both samples were taken from fields of the same farm. Whereas two pairs show quite similar responses to the basalt amendment (4.0&4.2, 4.4&4.6 are the controls), the other two of these pairs show different outcomes (3.0&3.2 and 3.8&4.8 are the controls).
- Rock bias: When a study looks at one or only a small set of rock types the CDR results of the study will depend on the types of selected rocks and cannot be extrapolated to other rocks. For example, Figure 4 shows that among other things the presence of $CaCO_3$ in the steel slag amendment appears to result in a significantly greater increase in leachate alkalinity than any other rock dust type, regardless of the soil to which it was added.
- Bias introduced by study design due to practical/financial/time limitations: An example of this is the protocol to measure soil CO_2 efflux: Our approach to "monitor" the efflux of the control replicas in parallel with the amended replicas every 10 minutes using 50 autonomous fluxmeters 24 hours per day will give us deep insights into intra-day, between-day and seasonal changes of several hundred experiments over 2-3 years. Manual or semi-automated measurements over short time periods and with lower measurement frequency can not provide the same insights and hence understanding of the EW system (see "Why not buy off-the-shelf fluxmeters" in our fluxmeter blog article). Insights from high frequency monitoring may help design the concept of larger-scale EW experiments in the future, as we don't know yet if the overall EW rate over multiple years is mostly driven

by a few short-term events, or if a lot of the short-term events cancel each other out such that the long-term average is still well captured in the leachate.



Trend-Overview of C-Fluxes

Change compared to control in annual carbon transport in tCO_2/ha/year after treatment. **Fluxes from accumulated alkalinity are scaled up by factor of 10 for better visibility of trends.**

Chart: Carbon Drawdown Initiative • Created with Datawrapper

Trend-Overview of C-Fluxes

Change compared to control in annual carbon transport in tCO_2/ha/year after treatment. **Fluxes from accumulated alkalinity are scaled up by factor of 10 for better visibility of trends.**

Chart: Carbon Drawdown Initiative • Created with Datawrapper

Figure 5: Data from figure 4-A organized in groups of the same soil having received different amendments (left) and groups of a particular amendment on different soils (right). Blue dots show the change in leachate alkalinity (scaled up by x10), red dots show the change in CO_2 efflux (both in tCO_2/ha/year). For all dots, n=4. Refer to “appendix 3: Pot plan” for experiment details.

Hence best practice is to strive for as little bias as possible and be aware of the remaining bias and the impact it may have. Despite the large number of variations, our selection of soils and rocks remains limited compared to the total possible variability, and hence our observations are also biased. Whereas our experimental results are applicable only to a particular set of rocks and soils, our data also allow us to anticipate the potential variabilities when working with other materials.

We furthermore do not know what our experiment data will look like in years 2 and 3, whether the different rock-soil combinations will converge, or if they remain as in year 1, or if they evolve into even more different directions. Your mileage may vary. Big data to the rescue, we need much more data!

Although for commercial EW applications it should be enough to only test the relevant soils and rocks that will be used, there should still be a representative number of soils/locations for each particular project (even several from the same region/area depending on the soil variability). Experimental results from a particular project with specific location and amendment(s) cannot be directly compared or transferred to other projects/sites, but they can give guidance to make more informed decisions in planning and design of EW projects elsewhere.

We don't fully understand yet which specific soil and rock parameters are affecting the observed variabilities in CO_2 efflux and leachate alkalinity, which would make this situation much easier, especially at scale. So our next objective is to find out what causes this and how it affects CDR.

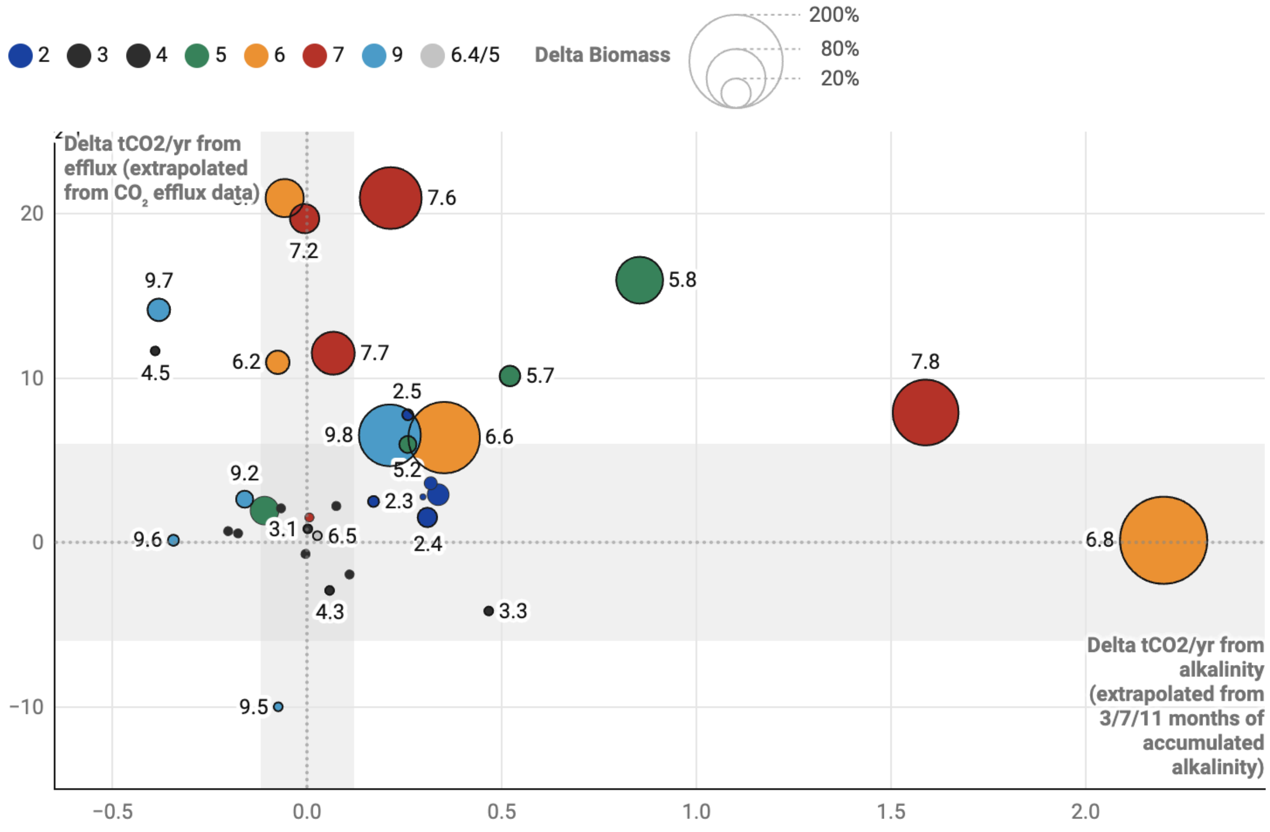
A deeper look into the data

Can we find any clues on what causes the increased CO_2 efflux within the experiment data we have? Increased plant growth and resulting root activity is a good usual suspect for an increase in CO_2 efflux. So to dig a little deeper into the data, figure 6 shows the change of accumulated alkalinity in the leachate water (x-axis), the change in CO_2 efflux (y-axis), like in figure 4-A, plus the relative change in the aboveground biomass production as the size of the dots. The colors are encoding the tables in our experiment which in turn broadly represent different soil types.

For some of the dots the increase in CO_2 efflux (higher on the vertical axis) goes hand in hand with an increase in above ground biomass (larger circles), e.g. 7.7 vs. 7.6 or 5.7 vs. 5.8. But this is not a general rule, e.g. for table 2 (dark blue dots) the biomass seems to be rather inversely correlated to the CO_2 efflux. So, although variations with more above-ground biomass often show an increase in leachate alkalinity and/or CO_2 efflux, this does not seem to be the best - or full - explanation. Please note that for 3.x and 4.x (black dots) no above ground biomass data are available.

Absolute Change vs. Control for Accumulated Alkalinity and CO_2 Efflux

Change compared to control in annual carbon transport in tCO_2/ha/year after treatment. Colors represent soil/table. Bubble sizes represent change in biomass vs. control.

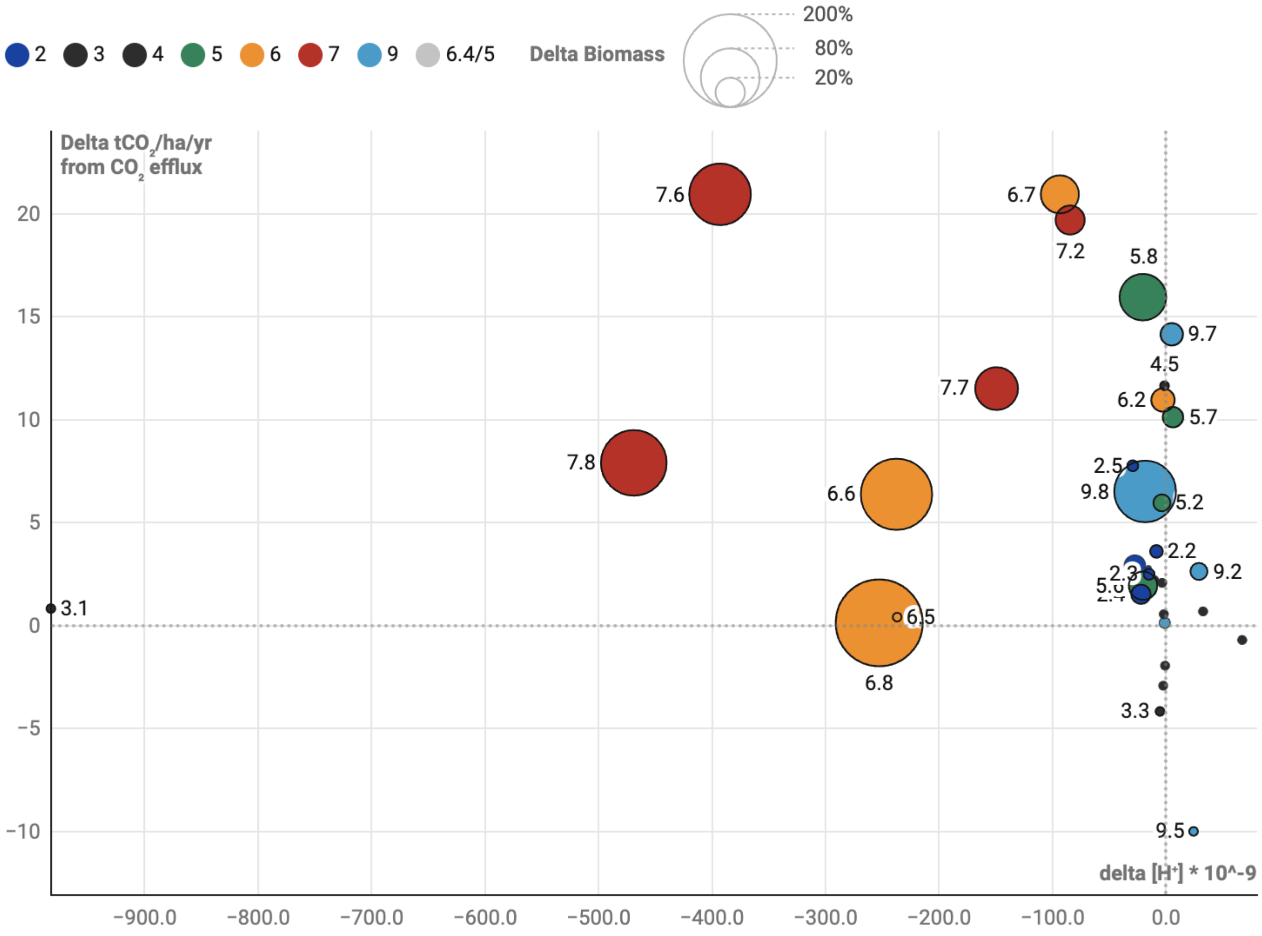


CO_2 efflux data: Jul-Dec; Alkalinity data: Feb-Dec, May-Dec for table 2, Oct-Dec for tables 3/4; Biomass data Jan-Jul 2023

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

Figure 6: Absolute change vs. control for accumulated alkalinity and CO_2 efflux (both in tCO_2/ha/year), bubble sizes represent relative change in biomass compared to control.
For all dots, n=4. Refer to "appendix 3: Pot plan" for experiment details.

What about the amendment induced change in leachate pH compared to the control, shown in figure 7 as absolute difference of $[H^+]$ (the concentration of protons, calculated from the pH) in December? As mentioned before, pH increases are known to drive up the biotic processes in the soil and with it CO_2 production, not only from plant growth but also from microbial respiration due to the decomposition of dead biomass.



Absolute Changes of CO_2 Efflux and $[H^+]$

Change compared to control in annual carbon transport in tCO_2/ha/year and H^+ concentration in leachate (de-log-ed pH) after treatment. Colors represent soil/table. Bubble sizes represent change in biomass vs. control.

CO_2 efflux data: Jul-Dec 2023; Biomass data Jan-Jul 2023; pH data for Dec 2023

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

Figure 7-A: Absolute Changes of CO_2 Efflux and $[H^+]$.
For all dots, n=4. Refer to "appendix 3: Pot plan" for experiment details.
Note: For table 3 and 4 no biomass data was available.

For figure 7 we have converted the leachate pH of controls and treatments in December 2023 to the number of hydrogen ions (hydron) $[H^+]=10^{-pH}$ and calculated the delta $[H^+]$ which means that an increase in pH becomes a negative value on the x-axis. The vertical axis shows the change in CO_2 efflux.

In the graph we have 3.1 as the outlier all the way to the left (delta $[H^+]$ of -980×10^{-9}) and also the 7.x (LUFA 2.1) and 6.x (LUFA 2.2) experiments are in a league of their own (delta $[H^+]$ between -80 to -500×10^{-9}) . In figure 7-B we show the dots for each soil/table separately:

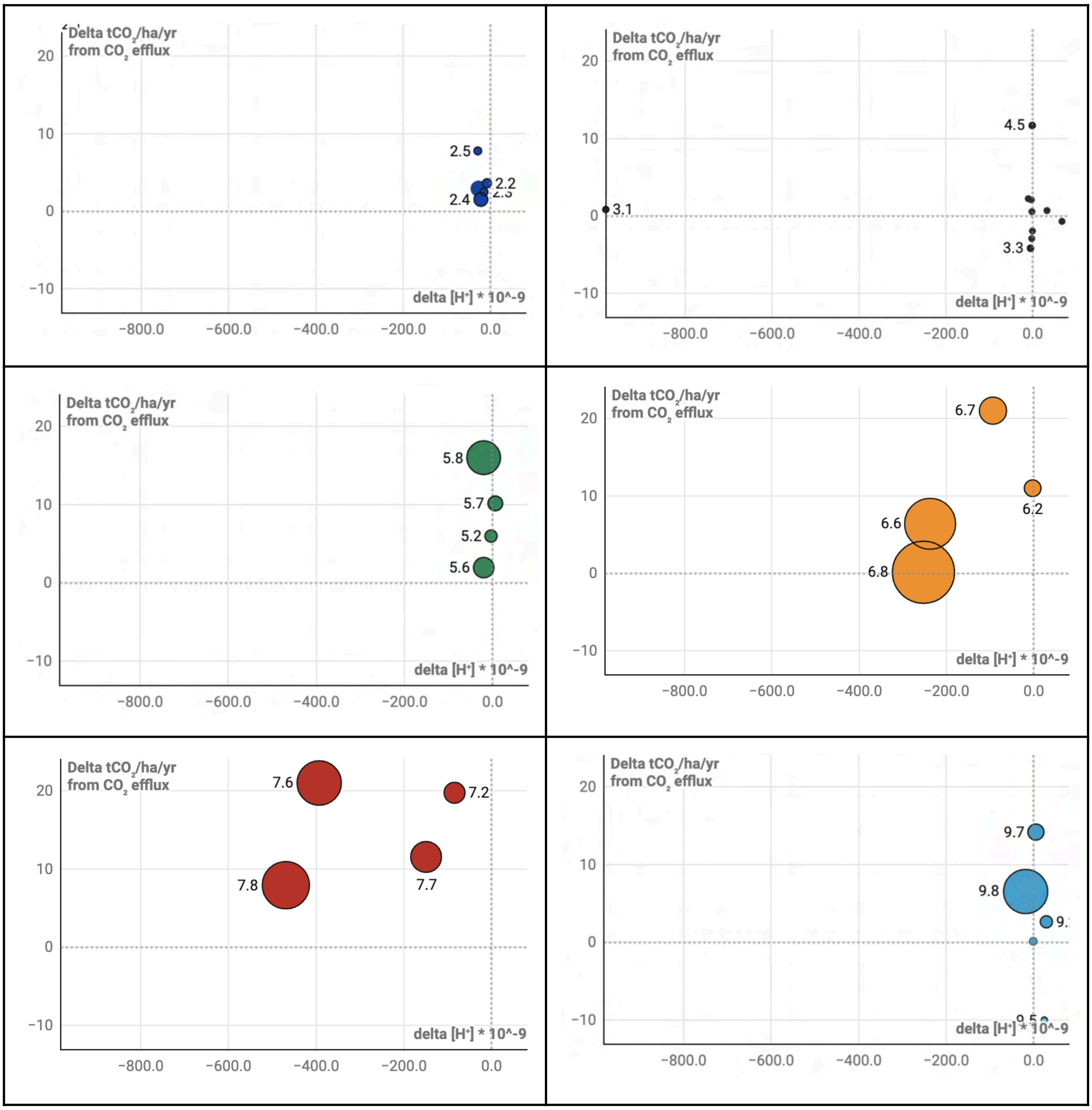
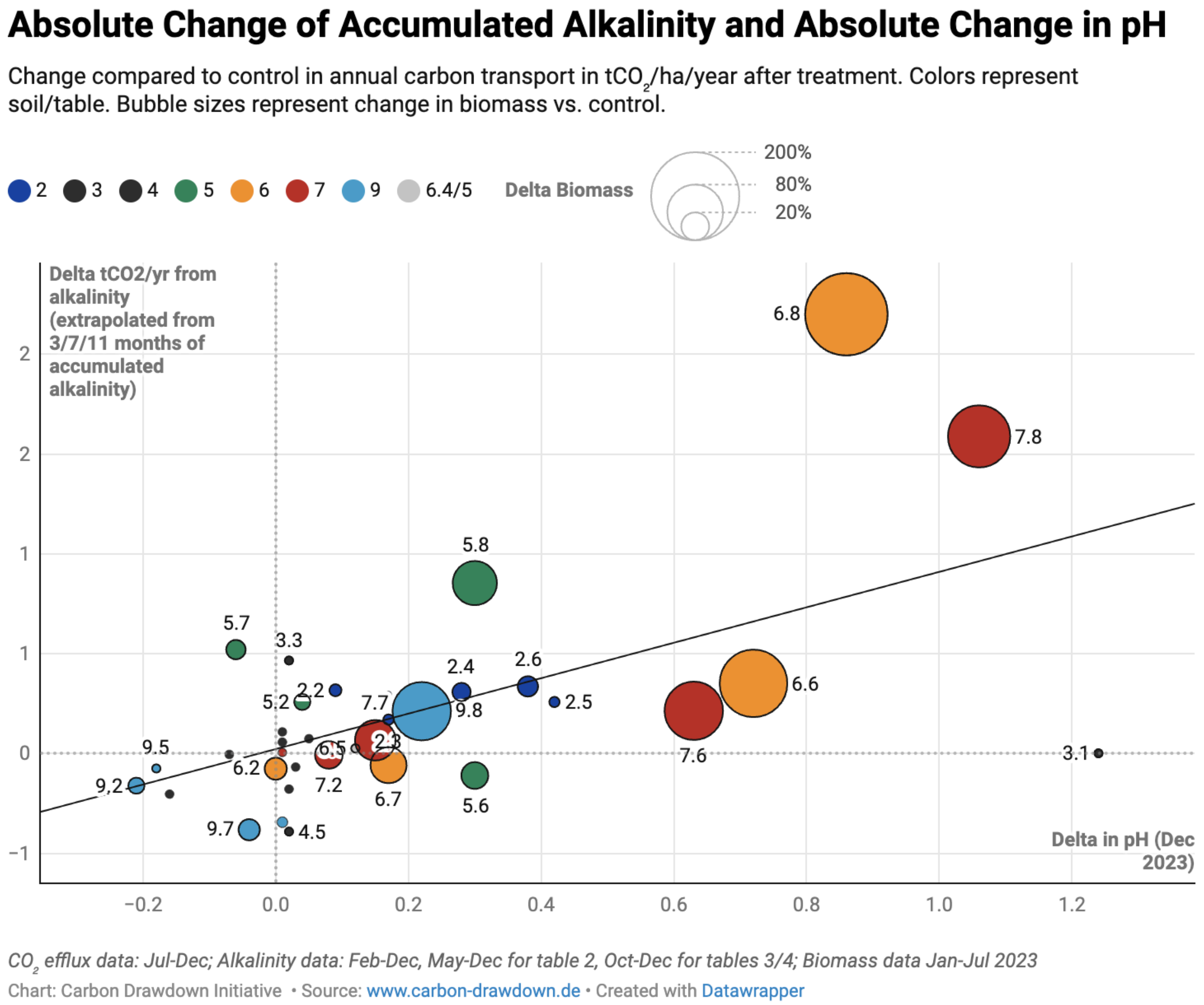


Figure 7-B: Absolute Changes of CO_2 Efflux and $[H^+]$, for each soil/table.
For all dots, n=4. Refer to "appendix 3: Pot plan" for experiment details.
Note: For table 3 and 4 no biomass data was available.

In both figures 7-A and 7-B we can see that most dots of one color (=same soil) become bigger further to the left, i.e. an increase in pH correlates with an increase in biomass on the same soil, which was to be expected. But an increase of biomass and pH does not necessarily mean a correspondingly higher CO_2 efflux (=bigger dots further to the left are not always also further up). However, as all bigger/higher dots are plotting in the upper left quadrant, our data do seem to reflect an overall tendency of an increase in CO_2 efflux coupled to increased pH after rock amendment.

It is interesting to note that our Fürth 1 soil (light blue, 9.x) which has shown unexpected EW results before, tends to lower the pH with rock amendments. The only exception is treatment 9.8 where dissolution of $Ca(OH)_2$ present in the steel slag is an obvious source of pH increase.

Figure 8 shows the expected positive correlation (correlation coefficient r=0.59) between leachate pH change and leachate alkalinity change. Please note that the x-axis in figure 8 is based on pH, not $[H^+]$ as in figures 7-A/B, and that due to the logarithmic nature of the pH scale a given delta-pH value represents different magnitudes of $[H^+]$ changes depending on the absolute pH value.



Absolute Change of Accumulated Alkalinity and Absolute Change in pH

Change compared to control in annual carbon transport in tCO_2/ha/year after treatment. Colors represent soil/table. Bubble sizes represent change in biomass vs. control.

CO_2 *efflux data: Jul-Dec; Alkalinity data: Feb-Dec, May-Dec for table 2, Oct-Dec for tables 3/4; Biomass data Jan-Jul 2023*

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

Figure 8: Absolute changes of accumulated alkalinity and leachate pH.
For all dots, n=4. Refer to "appendix 3: Pot plan" for experiment details.

As they are more closely related, leachate pH seems to be a reasonably good, easy-to-measure, rather conservative proxy for the alkalinity change in the leachate. The positive correlation between these two soil water parameters however also depends on the type of amendment and the soil.

- Amendment: Steel slag treated 5.8, 6.8 and 7.8 play in a league of their own (above the trendline defined by the basalts and olivine rich rocks) and diabase treated 5.6, 6.6 and 7.6 also plot away from everybody else (below the trendline). Steel slag contains 19.5% portlandite ($Ca(OH)_2$) and 8% calcite ($CaCO_3$), diabase holds 27% calcite - both minerals that dissolve fast and upon doing so increase alkalinity and pH more than the other rock dusts
- Soil: Let's look at experiments 3.1, 3.3 and 4.5: They all have different soils but the same amendment (Eifelgold basalt 40 t/ha). 3.1 reacts with the highest pH increase of all variants but no alkalinity increase whatsoever, while 3.3 shows a high alkalinity increase, but no pH increase and 4.1 shows a lower alkalinity measurement while pH is also unchanged.

So despite their close relationship, leachate pH can not be used as a proxy for the leachate alkalinity for a specific rock-soil combination without measurement of both parameters confirming their positive correlation in a certain setting. So once again we see the same trend: A specific amendment on different soils can cause very different results.

CO_2 efflux, microbes, soil carbon and pH: It's complicated!

Soil microbial life is affected by the rock dust addition for EW. This seems to be mainly driven by pH changes, and can lead to an increased digestion of carbon from the soil's carbon pools which could boost the CO_2 efflux even more than the plant's increased C-cycle. Grover et al. 2021 found that "*Decomposition of existent SOC was positively correlated with pH and N*" for liming projects.

So far, there is little research published on changes to soil carbon pools after rock dust amendments intended specifically for CDR. There are however some publications about these effects in relation to liming and here is a quote from the review of Paradelo et al. (2015) which could also be applicable in EW projects: "*... the effects of liming on soil organic C (SOC) stocks still remain poorly known. The net effect on SOC can be the result of several factors: first, liming increases the soil biological activity, thus favoring the mineralization of organic matter, which should result in* CO_2 *losses and a decrease of the SOC stocks. Second, liming ameliorates soil structure, increasing the stability of clay assemblages and clay-organic matter bonds, which should bring an increase in SOC physical and physicochemical protection. Finally, as liming ameliorates soil conditions to plant growth, plant productivity increases and also the return of C inputs to soil, thus potentially increasing SOC concentrations. The net effect of these processes is not well understood yet. Still, some overall trends can be deduced from data currently available in the literature. Liming does modify SOC stocks, increasing them in most cases, what seems to be caused by higher C inputs to limed soils due to increased productivity. Reductions in SOC have also been reported, probably in connection with increased mineralization, whereas the role of improved soil structure remains unclear.*"

Two posters are also notable in this context: Almaraz et al. 2023 find that "*that surface soil (0-10 cm) SOC concentrations slightly increased in all treatment plots amended with rock*". And Sokol et al. 2023 write that "*Our findings highlight that ERW field trials should incorporate measurements of SOM pools over longer timescales – especially with robust baseline data, and to balance these measurements* *against inorganic C drawdown.”* and “*Future studies should also mechanistically address the interactions between rock dust, organic matter, and soil microorganisms, to understand what can drive C gains or losses, and to determine if certain microbial taxa and organic amendments can both enhance the dissolution of rock dust and promote the formation of SOM.”*

Almaraz et al. (2022) write: “*EW of rock amendments can interact with biogeochemical conditions of the soil matrix by altering soil pH, base cation pools, and mineral mass in a different range of scales. Such micro or macro environmental changes in the soil matrix can in turn influence microbial vitality, which is a major player in processing SOM into different C pools in soil. SOM is susceptible to decomposition or microbial oxidation and loss back into the atmosphere through microbial respiration.”*

The involved biological activity does not only include bacteria, but also fungi: Medeiros et al. (2023) mention Carvalho et al. (2012, in Portuguese) as follows: *“According to Carvalho, the bioavailability of nutrients derived from rocks affects the activity of arbuscular mycorrhizal fungi (AMF) and, as a result, plant growth.”*

The possibility of more CO_2 efflux into the atmosphere does not seem to be a positive outcome…? This may be the first thing that comes to mind, but there is something called the “soil carbon dilemma”: as decomposing SOC also releases nitrogen, a plant nutrient that rock dust does not provide,plants can use this for increased growth by absorbing CO_2 (see Janzen 2006).

In summary, there is a complex interplay between soil pH, microbial activity, SOC and soil CO_2 efflux and the scientific community does not yet fully understand how these are influenced by rock dust addition. If you have further insights into the changes to soil carbon fluxes and pools after EW amendments, please get in touch with us at info@carbon-drawdown.de.

A preview of our brand new 2024 data

At the end of January 2024 we set up 80 new pots with 2 soils and 8 amendment types with the aim to better understand the reactions of various soil carbon pools and fluxes to the rock dust additions. One of the differences with our older greenhouse experiment is that this time we were able to measure both soil pCO_2 and CO_2 efflux from day one. Being able to follow the development of the pCO_2 and CO_2 efflux from the construction of the experimental pots onwards, these new data show that all amended variations quickly and in part significantly exceeded their controls’ soil pCO_2 and CO_2 efflux - with only one exception.

Figure 9-A shows the soil pCO_2 of a control set and 6 treatments (each variation with 7 replicas) on LUFA 2.2 soil. Experiments were built Jan 29th-30st, watering started Feb 1st, which was also when grass seeds were added on top and grass started to grow.

The 0.0 variation, top left, is the control and the average and min/max of the 7 control pots is shown as purple line and light purple area in the other 6 amendments graphs as reference. In each amendment graph the black line and gray area show the average and min/max range of the 7 replicas. In most cases the 7 replicas are well aligned.

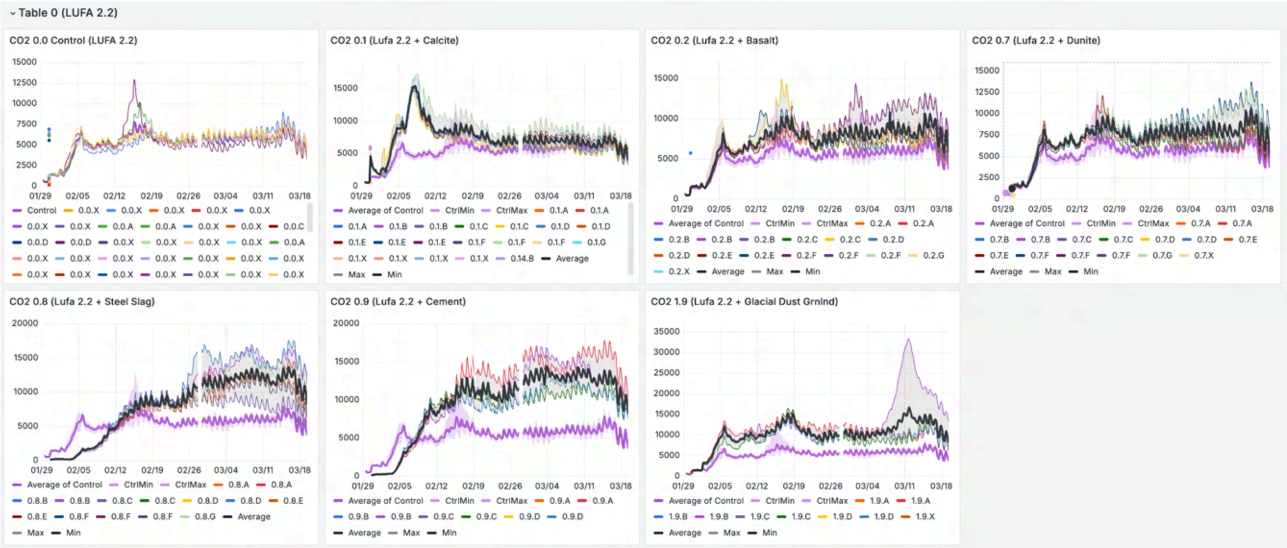


Figure 9-A: First 7 weeks of data for newly set up experiments with LUFA 2.2. 7 replicas per treatment.

Right after setting up the experimental pots, the pCO_2 of the basalt, dunite and glacial dust amendments was very similar to that of the control as one would expect. However, for the other three amendments (steel slag, cement and calcite) mixing in the rock dusts seemed to have had an immediate effect on the resulting soil pCO_2 which was significantly higher for the calcite addition, and significantly lower (even below 100 ppm) for both cement and steel slag amendments.

Over the next few days after the experiment was set up, as we watered the pots and plants started to grow, the pCO_2 increased in all pots, but more so in the rock dust amendments, resulting in higher soil pCO_2 for all rock dust amendments compared to the control. The initially lower pCO_2 in the cement and steel slag replicates thereby surpassed the control's pCO_2 after about 1 and 2 weeks, respectively. Interestingly, the initially much higher pCO_2 in the calcite pots started to decrease again after about 10 days until it ended up being more moderately higher than the control 2 weeks into the experiment. This initial peak of pCO_2 in the calcite amendments could perhaps reflect quick dissolution of the finest $CaCO_3$ at the start of the experiment.

On the LUFA 6S soil the pCO_2 of all variations, including the control, (figure 9-B) went beyond our sensor's limit of 40,000 ppm as soon as we started irrigation. The only exception is the steel slag treatment (1.8) which 2.5 months into the experiment still has lower pCO_2 than the control. So unfortunately we don't have much pCO_2 visibility for the new experiments on LUFA 6S soils, and we remain in the dark for the reason of the high background pCO_2 of this soil as this was not the case with the previous batch of LUFA 6S that we used in the 2023 experiment.

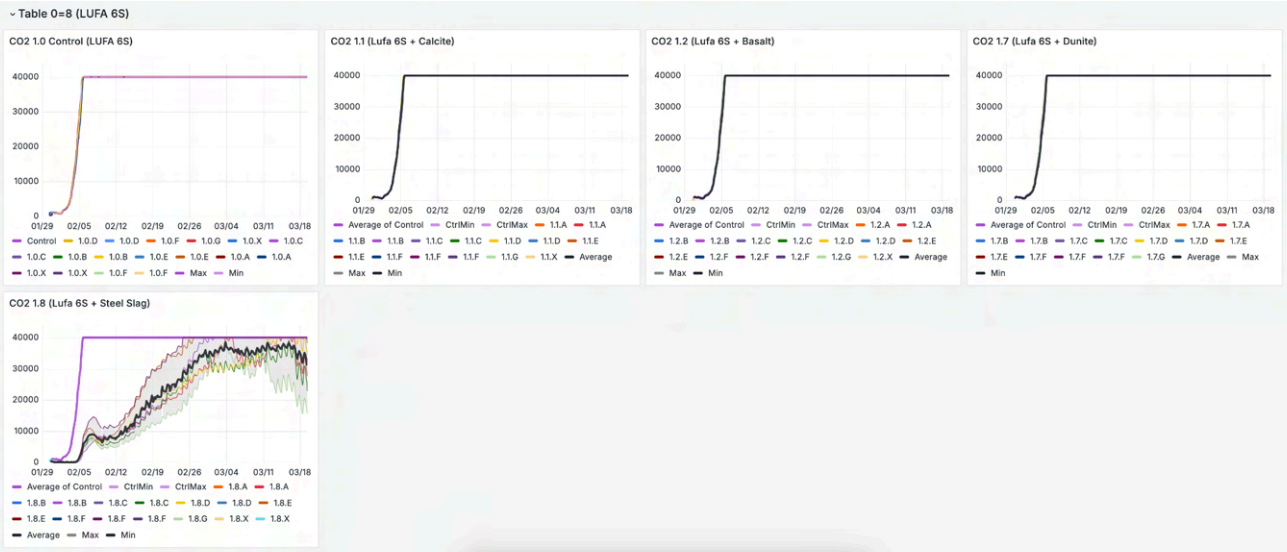


Figure 9-B: First 7 weeks of data for newly set up experiments with LUFA 6S. 7 replicas per treatment.

Looking at the very early fluxmeter data in figure 10 below, we can see that on LUFA 2.2 soil (all 0.x variations plus 1.9) so far only 0.7 (dunite) has a significantly higher CO_2 efflux than the control. Early CO_2 efflux data from the LUFA 6S experiments (= all 1.x variations except 1.9) show that the steel slag treated 1.8 has a significantly lower efflux than all the other pots including control, as already indicated by the pCO_2 data.

Note the inconsistent pattern of fluxes (compared to control) for the pairs 0.1/1.1, 0.2/1.2, 0.7/1.7 and 0.8/1.8. Each pair uses the same amendment, but on two different soils. So from the start of the experiment, the efflux patterns are different for the same rocks when applied to a different soil - let's see how this trend evolves with time as our experiment matures.

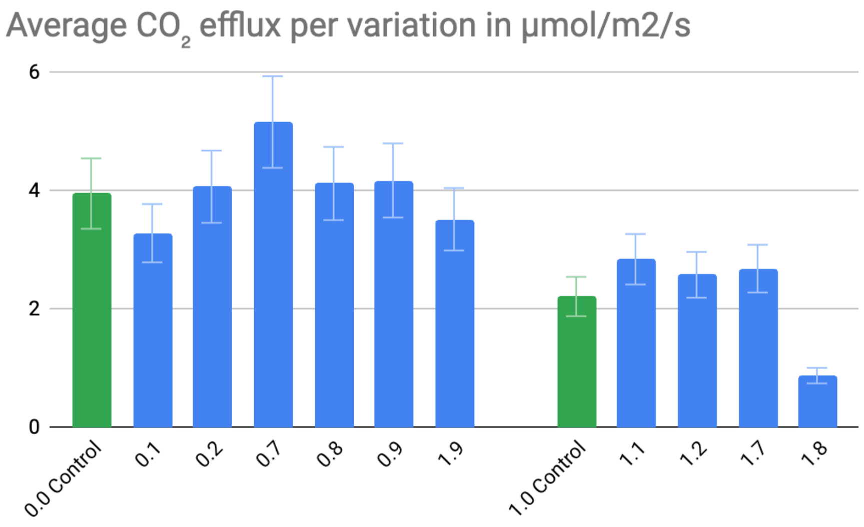


Figure 10: Average CO_2 efflux per variation in µmol/m^2/s between February 20th and March 10th 2024 (x.0 are the respective controls, during darkness only, error bars for 90% CI equal to minus/plus 15% of absolute reading). For all bars: n=7.

So based on our preliminary data we can say that at the start of the experiment the soil CO_2 efflux data show less significant differences between control and amendments than the pCO_2 data do. This suggests that the pots are not (yet?) fully following Fick's 1st law, perhaps because soil gas transport is hindered during initial settling of the pots. The reason could be that the efflux signal builds up more slowly than the pCO_2 signal. It will be interesting to observe over the coming months whether the pCO_2 signal can be used as an early indicator for any later developing CO_2 efflux (and/or even for CDR results?), as we discussed in our paper on why and how we built our fluxmeter army (chapter “Proofing Fick's 1st Law”).

Are pot experiments relevant for EW research?

Of course EW experiments in a greenhouse are not fully replicating the processes in the field. We even intentionally designed our greenhouse setting to be different from Fürth's natural climate to maximize EW reactions (see blog post “Turn it to *11*! The greenhouse tactics that accelerate our EW research”).

But mimicking nature is not the main point of our greenhouse experiment. We think the value of our experiment comes from the facts that (1) we combine as many as 16 soils with 12 rocks, (2) we speed up natural weathering reactions to gain faster CDR signals and understanding and (3) we monitor a range of soil, water and gas metrics across hundreds of rock-soil combinations, in some cases as frequently as every few minutes (we get ca. 5 million data points per day). It would be challenging to replicate such a variety of soil-rock experiments with this range of frequent measurements in the field. We bypass these complications inherent to field trials by bringing the soils to us, instead of going to the geographically dispersed soils every few days.

Our goal is to learn how EW can be measured, preferably finding an “early indicator of future success”. Our previous attempts to achieve this through several outdoor experiments failed because we found that in natural open systems a massive background noise and heterogeneity exist which makes it hard to pick up the slow and diluted signals we expect from weathering.

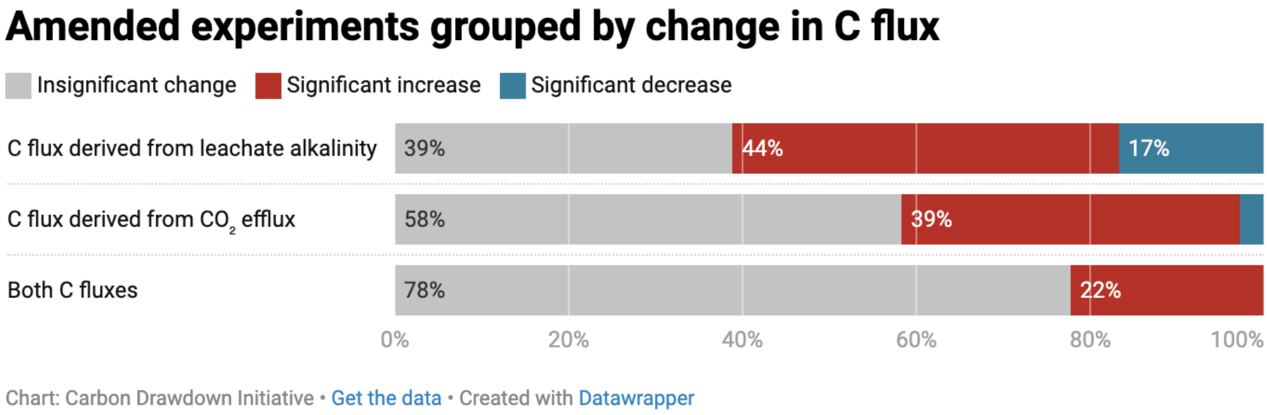
Our reasoning is that we can only try to measure EW outdoors after we have shown that we can measure it in the controlled environment of a greenhouse. Unless we can show here that carbon leaves the system as bicarbonate in the leachate (or is stored in the soil in a climate-crisis-relevant-long-term-ish way) we have not shown a reasonably permanent storage effect of carbon away from the atmosphere, which is what EW is about in the first place.

Once we can successfully track the carbon fluxes and carbon pools in our pots, we can then turn back to the open field. To understand the relationship between greenhouse data and outdoor data we have about 100 pots in the greenhouse with the same rock/soil combinations as in our field experiments. In the end, measurements of outdoor EW experiments will likely look slightly different from results obtained in greenhouse experiments. But looking at the huge variability of results in our greenhouse that we show above, do we really expect this to suddenly all level out in the field where the natural heterogeneity is surely even greater?

Conclusions

Conclusion 1: Increased CO_2 efflux of EW treated soils

The data summary in figure 11 shows that almost half of our 36 rock dust amended experiments (44%) have a significant increase in alkalinity in the soil water leachate compared to their respective control. In addition, more than one third of our experiments (39%) show a significant increase in CO_2 efflux compared to their respective control. Thereby, only 8 experiments (22%) show a significant increase in both alkalinity and CO_2 efflux. No experiment with significantly increased alkalinity shows a decrease of CO_2 efflux.



	No significant change	Significant increase	Significant decrease
C flux derived from leachate alkalinity	14	16	6
C flux derived from CO_2 efflux	21	14	1
Both C fluxes	28	8	0

Figure 11: Number of amended experiments grouped by change in C flux (within the first 11 months after setup) - Data from figure 4-A

These 8 experiments lose carbon both at the top and at the bottom of the pots, with the CO_2 effluxes being at least an order of magnitude larger than the alkalinity fluxes. We do not know yet how this pattern will develop in year 2 and 3, but this observation could be relevant for Life Cycle Assessments (LCA) of CDR projects.

Increases in aboveground biomass do not seem to fully explain this, but rock dust-induced increases in the pH appear to be correlated and might be driving up the soil biotic processes that feed on soil carbon.

While changes in pH, leachate alkalinity and biomass reflect the expected correlations between one another, none of these parameters can explain the increase in CO_2 efflux properly. Soil type alone does not seem to be a reliable predictor as the same soil with different amendments leads to different effects. Likewise, the same amendment on different soils can cause very different results.

So far we have not found a metric that allows us to predict the CO_2 efflux increase that we observe upon amendment for almost half of our soil-rock combinations.

The following key metrics could give us a much better understanding of the situation:

- Measurements of the carbon content in the different soil pools would tell us if and how the carbon content in treated pots has changed compared to their respective controls.
- Dissolution measurements of the amended soils (e.g. using Mg/Ti rates as tracers) could tell us how much of the added rock dust has already been dissolved.
- Sequential leaching of the soil with subsequent analysis of the cations present in the different pools could tell us how many of the cations released during dissolution are still stuck in the soil (and did not do CDR yet).

These measurements require soil sampling from our pots and analyses at specific labs, unfortunately limiting the number of such measurements compared to the vast amounts of data that we obtain from renewable sampling sources such as leachate water and air above the pots. Compared to these non-intrusive sampling methods, taking soil samples might disturb our experiments (we only have 12 liters of soil per pot), so we need to limit the number of soil sampling events as much as possible. We do have some sacrificial pots, duplicate treatments that can be completely ‘harvested’ whilst the main replicates continue the experiment, but only for a few rock-soil combinations so they can only give limited insights compared to the leachate and CO_2 efflux data we are continuously collecting from hundreds of pots.

The first soil sampling of all pots is planned for Q2/2024, one year after the experiment was set up. As the experiment is planned to run for 2-3 years if necessary, we will continue our leachate and CO_2 efflux measurements to further investigate the initial observations above. But we have also started a follow-up experiment that looks more closely at the different soil carbon pools and fluxes, including efflux measurements from day 1 after setup.

It would be very helpful if more EW science projects could measure CO_2 effluxes and/or pCO_2 data so that these questions can be answered soon. If further research shows that we are in certain situations depleting the soil’s carbon pools by adding rock dusts, then the MRV for EW certificates based on certain soil/rock combinations would need to take these additional CO_2 emissions into account, at least on short time scales.

Conclusion 2: The role of soils might be underestimated in EW

In our ongoing greenhouse experiment we see that not only the type of amendment has a strong influence on the carbon related processes in the soil, but that also the soils can react very differently to the same amendments. Our uniquely large array of soil/rock combinations allows us to uncover this strong influence of the soils, even when they come from the same area or even the same farm.

Consequently we recommend all EW projects to incorporate many different soils in weathering experiments and data collection, which might be easier said than done, as the number of soils and fields in commercial experiments is quickly one or two orders of magnitude higher than the number of amendments. How this can be done at a larger scale is not yet clear.

Conclusion 3: CO_2 data might be an early indicator of future success for EW

We found a number of treatment variations with either the same rock or the same soil where the CO_2 efflux (and hence the associated pCO_2 in the soil gas) correlated with the cumulative alkalinity data in the leachate (Figure 5). This needs further investigation, but it is possible that the CO_2 might become a low-cost, scalable, early indicator for EW projects in certain settings as the gas signal could be much faster than leachate or solid phase data. Again, it would be helpful if more EW experiments measure CO_2 based data.

Appendix-Overview

This appendix documents our data and references that might be helpful in understanding our data.

- Appendix 1 has a description of the CO_2 efflux data and the data processing.
- Appendix 2 shows comparisons between alkalinity and CO_2 efflux data for all variants.
- Appendix 3 is a plan of the pot experiments (soil types and amendments).
- Appendix 4 explains our calculations.
- Appendix 5 has the links for data downloads from Github.

Additional references from Carbon Drawdown Initiative relating to this document:

- The recipe describing our greenhouse experiment setup is documented in “Setting up the Carbdown Greenhouse Experiment 2023 (With Recipe And Shopping-list)”.
- The alkalinity data and the mineral/chemical analyses of the amendments are documented in the blog article “CDR Measurement for ERW via Alkalinity in Leachate”.
- The ambient environment of the greenhouse experiment has been documented in blog post “Turn it to *11*! The greenhouse tactics that accelerate our ERW research”.
- Blog article “How We Juggle Over 4 Million Data Points Daily in Real-Time. And Why.” explains our data pipeline.
- The biomass data is documented in “Data from the Greenhouse Experiment, Part 1: Biomass”.

Relevant publications (that we did not already cite in this working paper):

- Paradelo, et al. 2015: Net effect of liming on soil organic carbon stocks: a review.
- Beerling, et al. 2024: Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits.

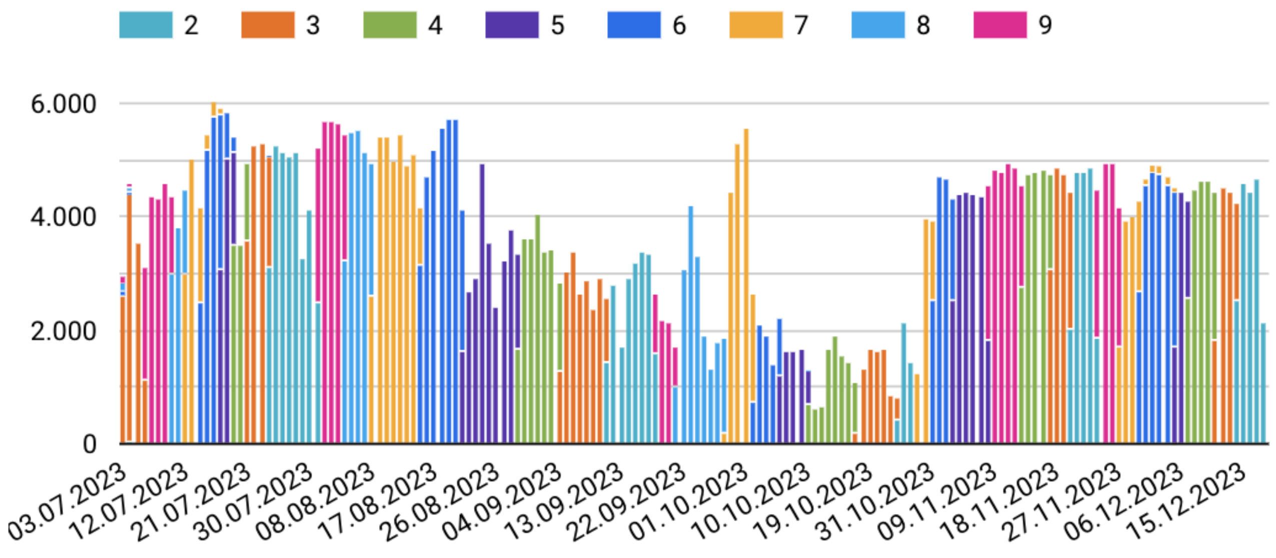
Appendix 1

Description of the CO_2 efflux data and the data processing

Please refer to our article about the development and building process of our fluxmeter army for an in-depth description of how these instruments work.

Since mid July 2023 we are cycling up to 50 autonomous fluxmeters through the almost 400 EW experiments in the greenhouse, one table at a time. The fluxmeters have a transparent chamber and usually stay on the lysimeters for 3-7 days. Once or twice per week we groom the grass on the next table (to minimize the disturbance of photosynthesis by the leaves in the chambers for the next few days) before moving the fluxmeters over to that table. During this process, the position of the fluxmeters is practically randomized every time between the replicas of a variant row. Everytime we restart a complete sweep of the greenhouse at table 9 we also randomize the position of each fluxmeter between variants.

To cover intraday fluctuations we use 24/7 ongoing measurements. On hundreds of experiments this becomes only possible at scale with our fluxmeter army. Sporadic measurements can have "*potential biases ranged from −29 to + 40% in relation to the 24 hr mean*" found Cueva et al. (2017).



Number of daily automated flux measurements, broken down by table (coded in colors)

This gives us 24/7 fluxmeter data for a few days in each month for each table which is then assumed to be this month's average flux data in the further analysis. When we calibrated the fluxmeters against a high-end professional fluxmeter (LI-COR LI-870SC CO_2 Survey Soil Flux Package, i.e. the LI-870 CO_2/H_2O Gas Analyzer with the 8200-01S Smart Chamber) we found that our nightly data (=at darkness) was the best fit. So for the further analysis we filter the data only for data points with a lightmeter-reading of 10 lux or less. Cueva et al. (2017) also found night data to be most suitable for what we want to do: *"We propose a simple method, based on the temporal stability concept, to determine the most appropriate time of the day for manual measurements to capture a representative mean daily Rs value. (..) In general, we found optimum times were at night."*

From the raw data (635.608 automated flux measurements) we removed all data points with more than 10 lux of light (remove daylight data) and fluxes below 0.1 µmol/m²/s (remove stuck fluxmeters and clogged pots, see fluxmeter article), which results in 280,891 data records (36%).

We further processed the data by combining 6 of the 10-min-interval measurements per 4 replicas in one hour (24 values) into their hourly average per variant (19,541 data points). During calibration we found that this average value is inside a plus/minus 15% band of the average of 4 consecutive flux measurements for each of the 4 replicas (average of 16 values per variant) coming from the LI-COR reference fluxmeter. From here on we use the 15% band as our 90% confidence interval for the CO_2 efflux data.

Let's look at the data from table 7 as an example in figure 1-A (taken from appendix 2, figure 2-A):

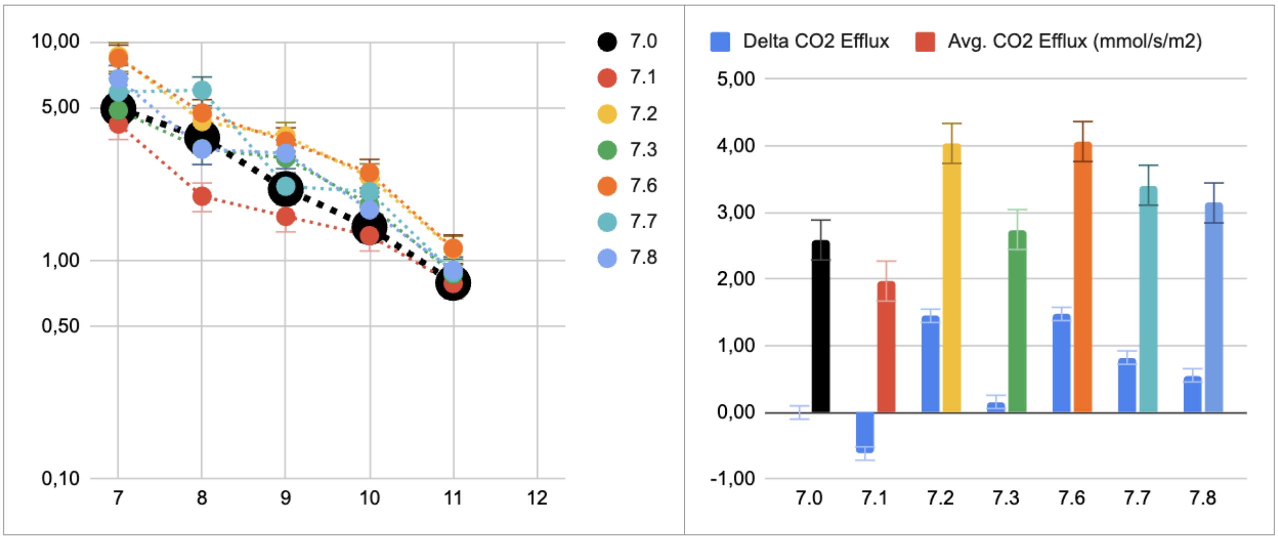


Figure 1-A in µmol/m²/s

On the left we have the monthly data broken down by variant as described above. The uncertainty bars show plus/minus 15% of the absolute value. On the right we see the average of the monthly data points which allow us to compare the area under the curves between control and treatments (which indicates the accumulated flux over time). The differences between control and treatment are shown by the smaller blue bars in the right graph. These graphs for all variations are to be found in Appendix 2.

The relative differences between variants and control do not change much from one month to the next, for most tables these graphs look very stable as you will see below. Given the stable development of these metrics we can assume that sometimes missing monthly data points do not show significantly different signals compared to the already huge variance in some of the data shown here. The longer the experiment runs the more congruent coverage we get.

In figure 2-A in appendix 2 you get an overview of the controls and treatments on tables 2, 5-7 und 9. Whenever there is a significant CO_2 efflux increase in the average graph on the right (compared to control), it is almost always going on all of the time as visible in the left graph.

Throughout all these graphs there are only 3 variants that show a decrease in CO_2 efflux: 7.1, 9.1 and 9.5. The situation in figure 2-B in appendix 2 for table 3 and 4 is less clear: Here we have 10 soils that we had collected from 7 farmers in southern Germany (Orthenau Kreis and Franconia). All of them were treated with 40 t/ha basalt. Here we see 4 with a decrease in efflux, two with an increase and the rest shows no significant change in CO_2 efflux.

Repeatability/reproducibility of the measurements

The next figure 1-C shows how equally treated variants compare to their common control over time. This is a comparison of CO_2 efflux data of experiment rows that are all treated with 40 t/ha Eifelgold basalt (x.2 and x.9). The .9 variant has the same treatment as the .2 variant and is intended to be our sacrificial row of pots where we “kill” one pot every 6-12 months to get access to the full soil column for lab analysis. Relative to their control, most pairs show very similar behavior, except for 9.2/9.9 on the problematic Fürth 1 soil.

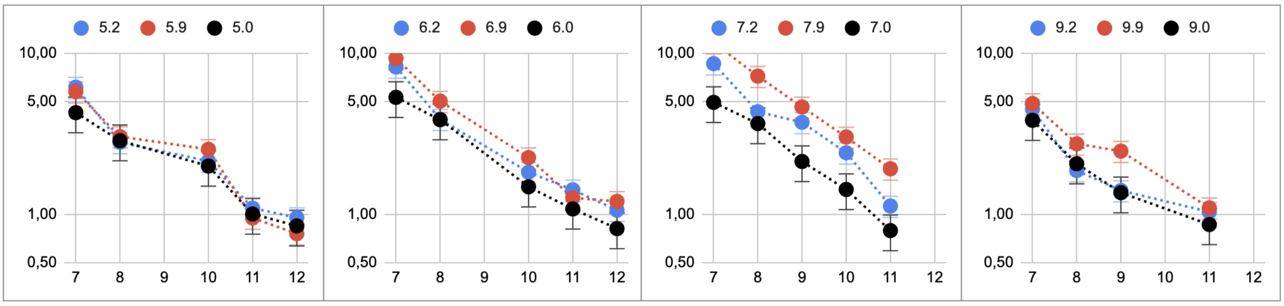


Figure 1-C: comparison of CO_2 efflux data of experiment rows that are all treated with 40 t/ha Eifelgold basalt (x.2 and x.9) in µmol/m²/s. In each graph, the black series (x.0) is the control for that rock-soil combination.

Figure 1-D compares the controls for Fürth soil 1 (9.0) and Fürth soil 2 (2.0) over time (2.0 was started 3 months later). Again, the values are quite similar.

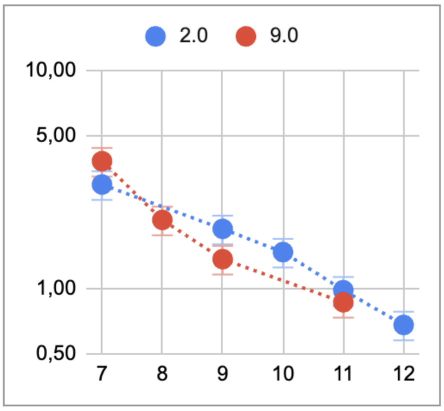


Figure 1-D: Comparison of CO_2 efflux data of Fürth soil 1 (9.0) and Fürth soil 2 (2.0) in µmol/m²/s

Finally, the graph in figure 1-E compares only the data from the control soils on table 2, 5-7 and 9 with one another.

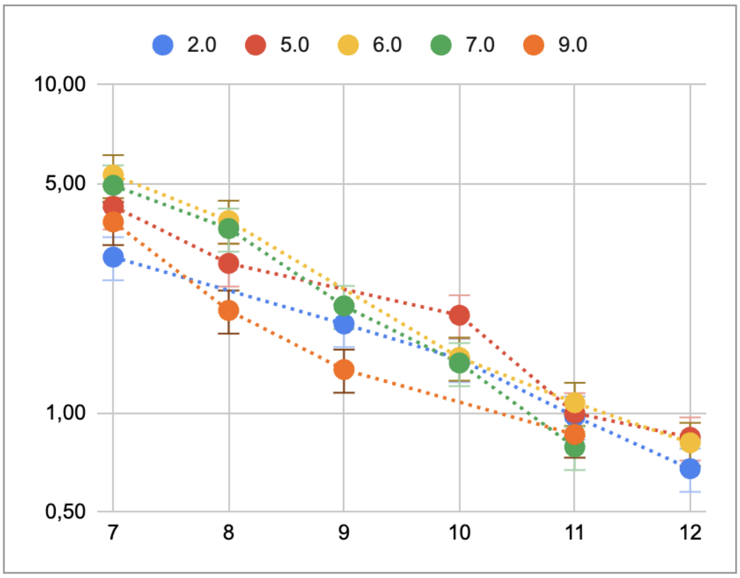


Figure 1-E: Comparison of CO_2 efflux data in µmol/m²/s for control variations of main soils only

The following example graphs in figure 1-F with data from individual flux measurements show how similar the measurements of replicas of one variant often are (4 lines for 4 replicas in each graph). During the day we see negative efflux due to the photosynthesis inside the transparent chamber:

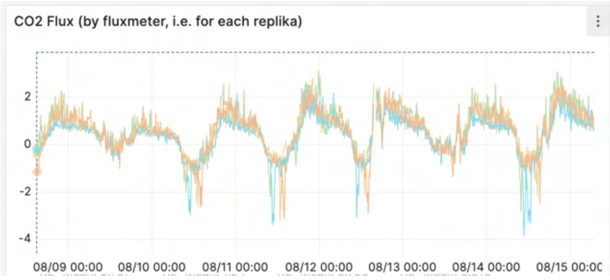
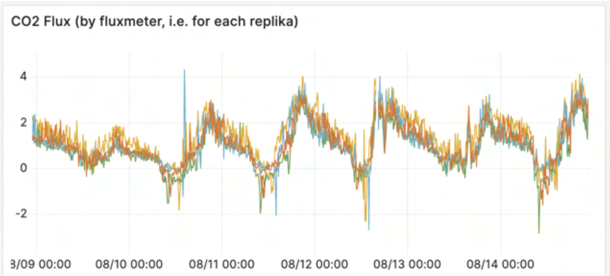
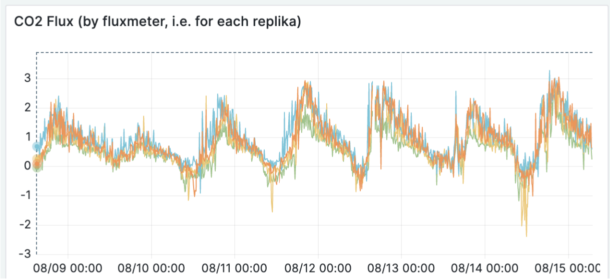
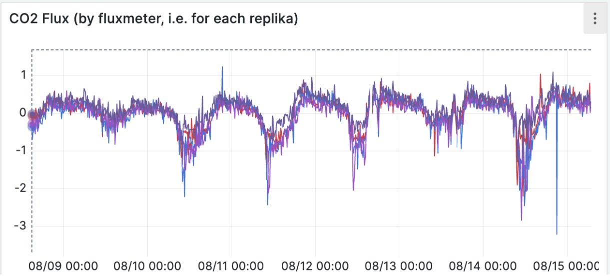
	
7.3	7.6
	
7.8	7.10

Figure 1-F: One week of flux measurements in 10 min interval for all replicas of selected variants

Could effects of carbonates in amendments play a role?

Some of our amendments contain $CaCO_3$ which should weather very fast and cause both alkalinity increase and CO_2 increase (variant 2.1 is crushed concrete which usually contains calcite; x.6 is a diabase which has 8% calcite: x.8 is a steel slag which has 27% calcite). A systematic increase of CO_2 efflux in these calcite-containing treatments compared to their respective controls was however not observed during the months 6-11 after setup. When we first saw this, we thought that the lack of higher CO_2 efflux for the carbonate containing amendments reflected that we had started the efflux measurements too late to pick up this effect. The new experiment series that we set up recently also includes calcite as soil amendment, and the pCO_2 measurements from day 1 do indeed show an initial increase that is unique to that amendment (see Figure 9-A). Two weeks into the experiment, however, the pCO_2 in the calcite amended pots starts to decrease again and eventually resembles the control. This suggests that it was only a small fraction of very fine and reactive calcite that quickly dissolved as soon as we started to irrigate the pots, but that the remaining calcite is dissolving more slowly.

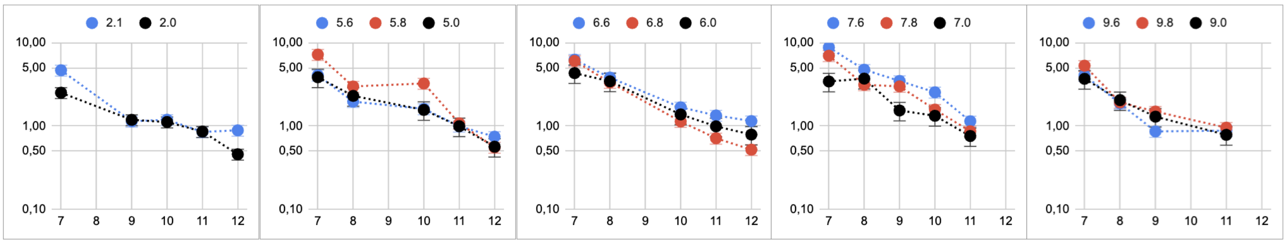
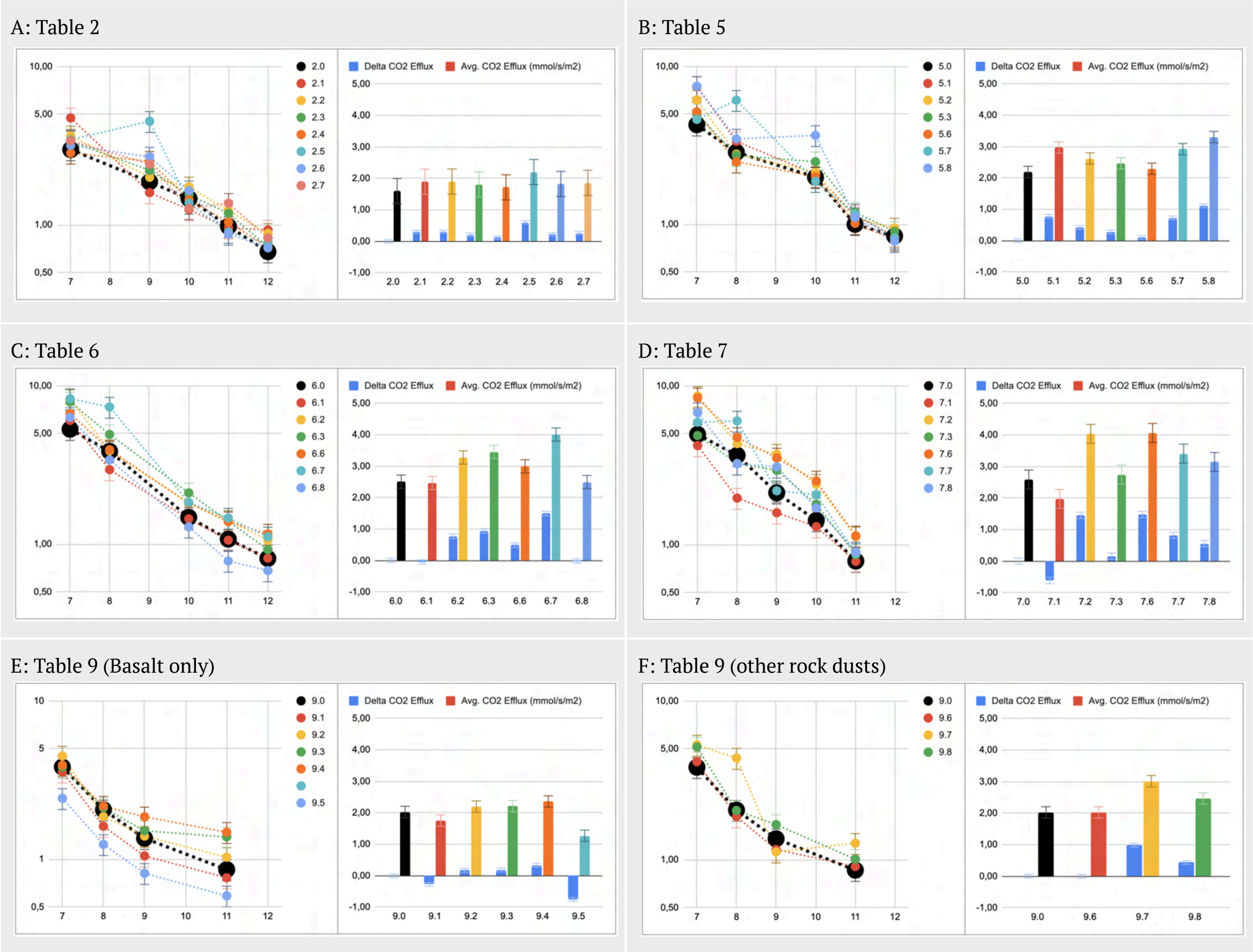


Figure 1-G: Comparison of CO_2 efflux in µmol/m²/s between amendments with carbonate content and their controls

Appendix 2: Flux Data


A: Table 2

B: Table 5

C: Table 6

D: Table 7

E: Table 9 (Basalt only)

F: Table 9 (other rock dusts)

Figure 2-A: Variants' CO_2 efflux data in μmol/m²/s over time (Part 1, for table 2, 5-7 and 9)

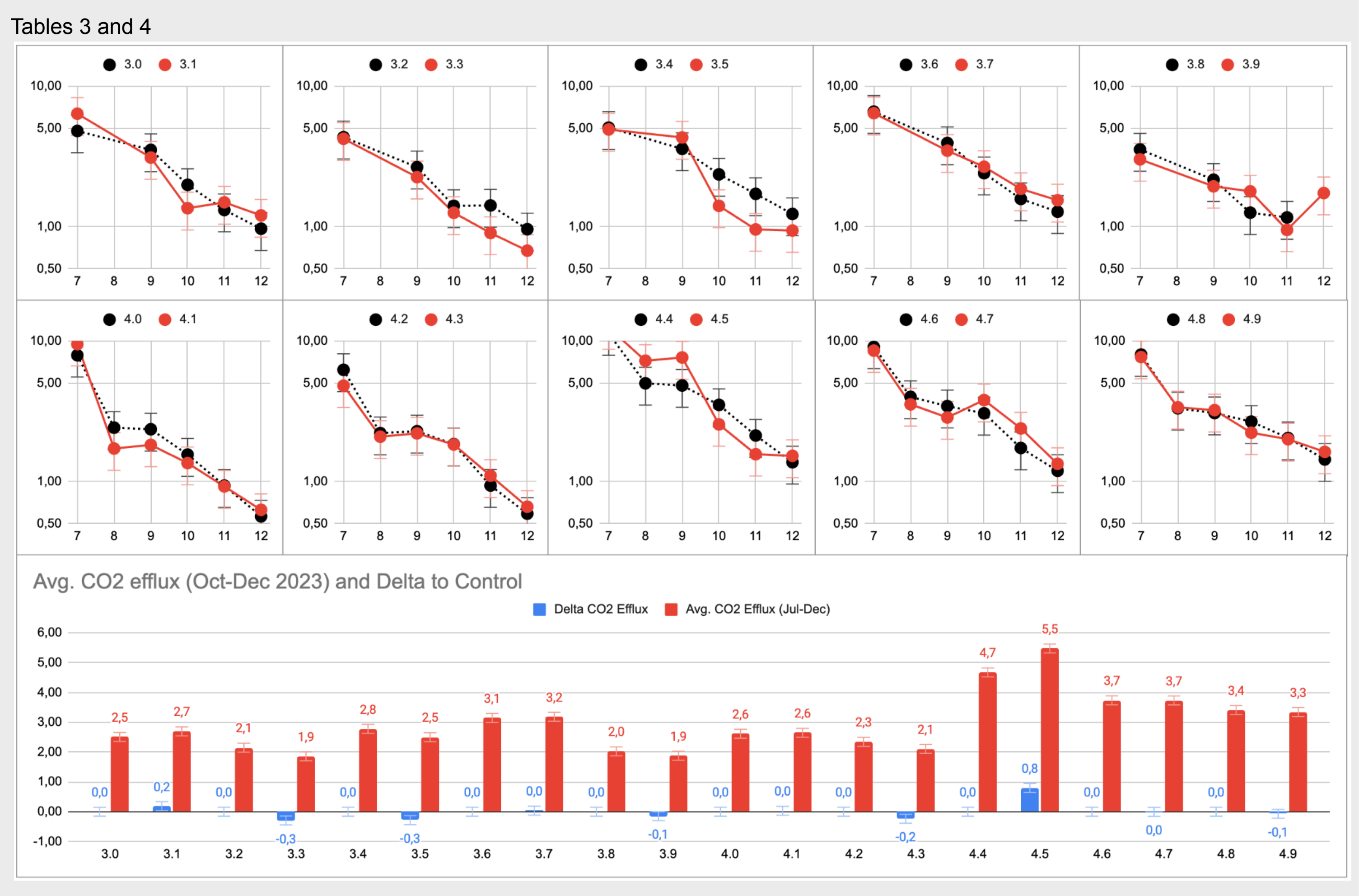
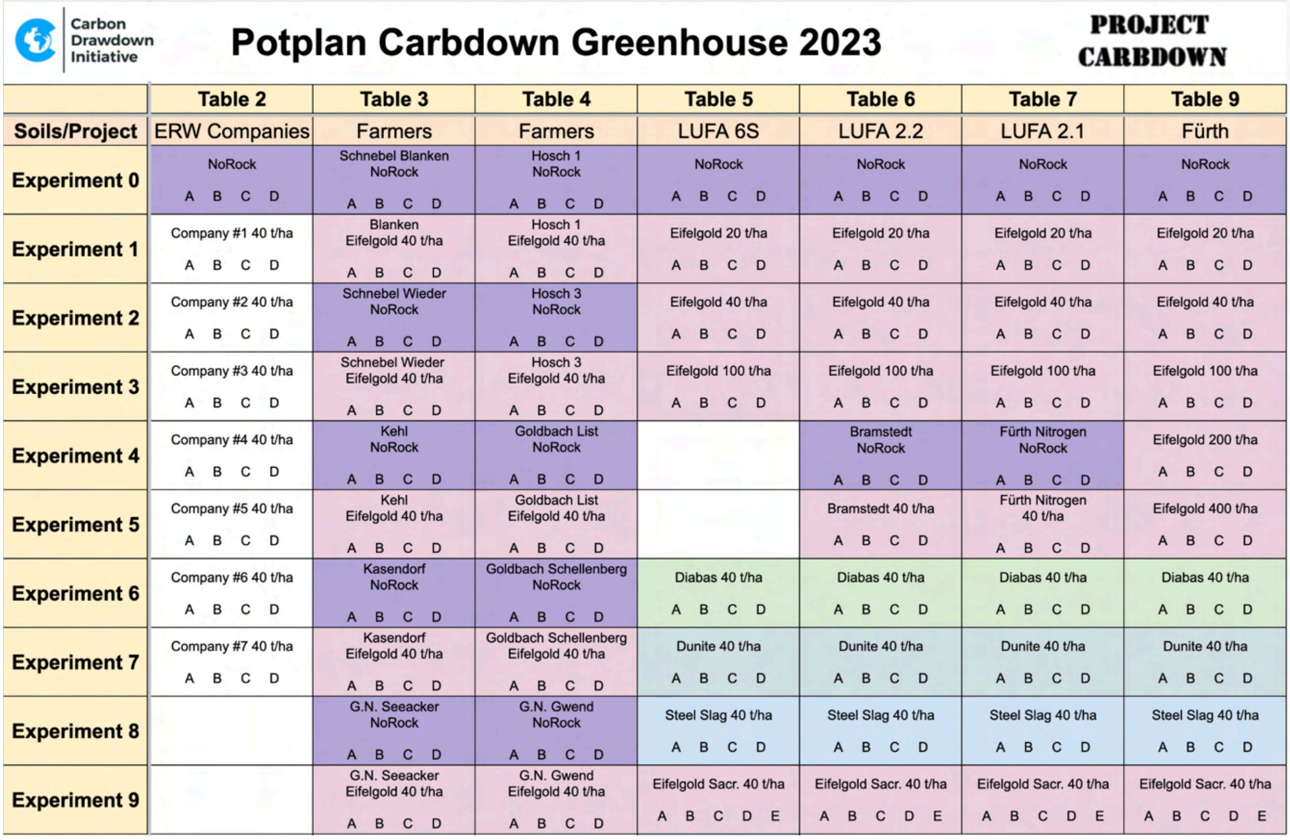


Figure 2-B: Variants' CO_2 efflux data in µmol/m²/s over time (Part 2, table 3 and 4 with 10 soils from 7 farmers)

Appendix 3: Pot plan of the greenhouse (2023 experiments)



Potplan Carbdown Greenhouse 2023

PROJECT CARBDOWN

	Table 2	Table 3	Table 4	Table 5	Table 6	Table 7	Table 9
Soils/Project	ERW Companies	Farmers	Farmers	LUFA 6S	LUFA 2.2	LUFA 2.1	Fürth
Experiment 0	NoRock A B C D	Schnebel Blanken NoRock A B C D	Hosch 1 NoRock A B C D	NoRock A B C D	NoRock A B C D	NoRock A B C D	NoRock A B C D
Experiment 1	Company #1 40 t/ha A B C D	Blanken Eifelgold 40 t/ha A B C D	Hosch 1 Eifelgold 40 t/ha A B C D	Eifelgold 20 t/ha A B C D	Eifelgold 20 t/ha A B C D	Eifelgold 20 t/ha A B C D	Eifelgold 20 t/ha A B C D
Experiment 2	Company #2 40 t/ha A B C D	Schnebel Wieder NoRock A B C D	Hosch 3 NoRock A B C D	Eifelgold 40 t/ha A B C D	Eifelgold 40 t/ha A B C D	Eifelgold 40 t/ha A B C D	Eifelgold 40 t/ha A B C D
Experiment 3	Company #3 40 t/ha A B C D	Schnebel Wieder Eifelgold 40 t/ha A B C D	Hosch 3 Eifelgold 40 t/ha A B C D	Eifelgold 100 t/ha A B C D	Eifelgold 100 t/ha A B C D	Eifelgold 100 t/ha A B C D	Eifelgold 100 t/ha A B C D
Experiment 4	Company #4 40 t/ha A B C D	Kehl NoRock A B C D	Goldbach List NoRock A B C D		Bramstedt NoRock A B C D	Fürth Nitrogen NoRock A B C D	Eifelgold 200 t/ha A B C D
Experiment 5	Company #5 40 t/ha A B C D	Kehl Eifelgold 40 t/ha A B C D	Goldbach List Eifelgold 40 t/ha A B C D		Bramstedt 40 t/ha A B C D	Fürth Nitrogen 40 t/ha A B C D	Eifelgold 400 t/ha A B C D
Experiment 6	Company #6 40 t/ha A B C D	Kasendorf NoRock A B C D	Goldbach Schellenberg NoRock A B C D	Diabas 40 t/ha A B C D	Diabas 40 t/ha A B C D	Diabas 40 t/ha A B C D	Diabas 40 t/ha A B C D
Experiment 7	Company #7 40 t/ha A B C D	Kasendorf Eifelgold 40 t/ha A B C D	Goldbach Schellenberg Eifelgold 40 t/ha A B C D	Dunite 40 t/ha A B C D	Dunite 40 t/ha A B C D	Dunite 40 t/ha A B C D	Dunite 40 t/ha A B C D
Experiment 8		G.N. Seeacker NoRock A B C D	G.N. Gwend NoRock A B C D	Steel Slag 40 t/ha A B C D	Steel Slag 40 t/ha A B C D	Steel Slag 40 t/ha A B C D	Steel Slag 40 t/ha A B C D
Experiment 9		G.N. Seeacker Eifelgold 40 t/ha A B C D	G.N. Gwend Eifelgold 40 t/ha A B C D	Eifelgold Sacr. 40 t/ha A B C D E	Eifelgold Sacr. 40 t/ha A B C D E	Eifelgold Sacr. 40 t/ha A B C D E	Eifelgold Sacr. 40 t/ha A B C D E

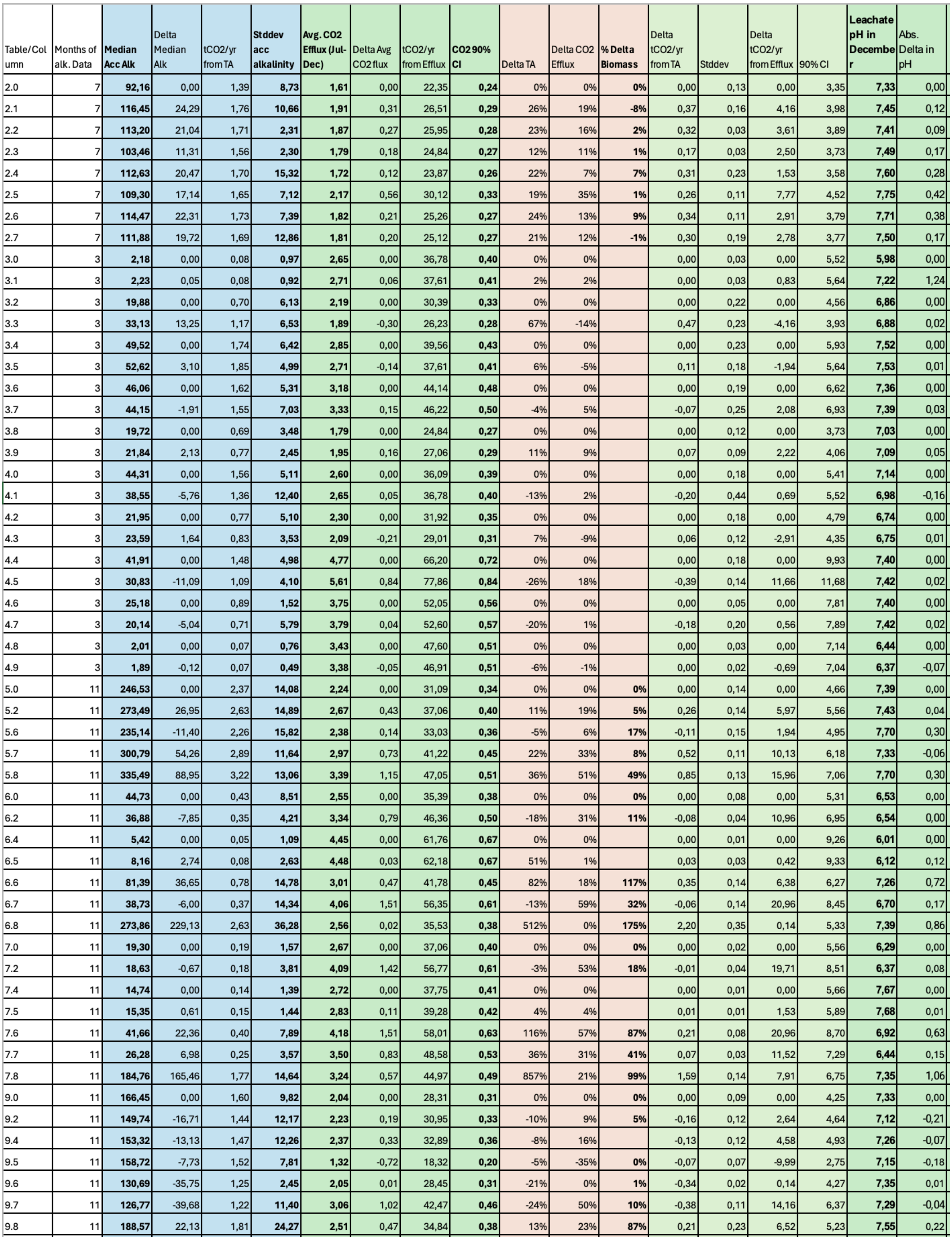
Appendix 4: Calculations

The following formula was used to calculate the carbon fluxes in tCO_2/ha/year from accumulated alkalinity in the leachate water (derived from monthly titrations), background described in our alkalinity article:

$$Carbon\ flux_{from\ TA} = \frac{Accumulated\ Alkalinity\ mmol}{1000\ \frac{mmol}{mol}} \times \frac{44.01\ \frac{g}{mol} \times 10{,}000\ \frac{m^2}{ha}}{1{,}000{,}000\ \frac{g}{t} \times 0.05\ m^2} \times \frac{12}{Number\ of\ monthly\ data\ points} \left[in\ \frac{t\ CO_2}{ha \times year}\right]$$

To convert the average CO_2 efflux in 2023 into tCO_2/ha/year we used the following formula:

$$Carbon\ flux_{from\ Efflux} = \frac{Avg.\ CO2\ Efflux\ \frac{\mu mol}{m^2 \times s}}{1{,}000{,}000\ \frac{\mu mol}{mol}} \times \frac{44.01\ \frac{g}{mol} \times 10{,}000\ \frac{m^2}{ha} \times (3{,}600 \times 24 \times 365)\ \frac{s}{year}}{1{,}000{,}000\ \frac{g}{t}} \qquad \left[in\ \frac{t\ CO_2}{ha \times year}\right]$$



Table/Column	Months of alk. Data	**Median Acc Alk**	Delta Median Alk	tCO2/yr from TA	**Stddev acc alkalinity**	**Avg. CO2 Efflux (Jul-Dec)**	Delta Avg CO2 flux	tCO2/yr from Efflux	**CO2 90% CI**	Delta TA	Delta CO2 Efflux	**% Delta Biomass**	Delta tCO2/yr from TA	Stddev	Delta tCO2/yr from Efflux	90% CI	**Leachate pH in December**	Abs. Delta in pH
2.0	7	**92,16**	0,00	1,39	**8,73**	**1,61**	0,00	22,35	**0,24**	0%	0%	**0%**	0,00	0,13	0,00	3,35	**7,33**	0,00
2.1	7	**116,45**	24,29	1,76	**10,66**	**1,91**	0,31	26,51	**0,29**	26%	19%	**-8%**	0,37	0,16	4,16	3,98	**7,45**	0,12
2.2	7	**113,20**	21,04	1,71	**2,31**	**1,87**	0,27	25,95	**0,28**	23%	16%	**2%**	0,32	0,03	3,61	3,89	**7,41**	0,09
2.3	7	**103,46**	11,31	1,56	**2,30**	**1,79**	0,18	24,84	**0,27**	12%	11%	**1%**	0,17	0,03	2,50	3,73	**7,49**	0,17
2.4	7	**112,63**	20,47	1,70	**15,32**	**1,72**	0,12	23,87	**0,26**	22%	7%	**7%**	0,31	0,23	1,53	3,58	**7,60**	0,28
2.5	7	**109,30**	17,14	1,65	**7,12**	**2,17**	0,56	30,12	**0,33**	19%	35%	**1%**	0,26	0,11	7,77	4,52	**7,75**	0,42
2.6	7	**114,47**	22,31	1,73	**7,39**	**1,82**	0,21	25,26	**0,27**	24%	13%	**9%**	0,34	0,11	2,91	3,79	**7,71**	0,38
2.7	7	**111,88**	19,72	1,69	**12,86**	**1,81**	0,20	25,12	**0,27**	21%	12%	**-1%**	0,30	0,19	2,78	3,77	**7,50**	0,17
3.0	3	**2,18**	0,00	0,08	**0,97**	**2,65**	0,00	36,78	**0,40**	0%	0%		0,00	0,03	0,00	5,52	**5,98**	0,00
3.1	3	**2,23**	0,05	0,08	**0,92**	**2,71**	0,06	37,61	**0,41**	2%	2%		0,00	0,03	0,83	5,64	**7,22**	1,24
3.2	3	**19,88**	0,00	0,70	**6,13**	**2,19**	0,00	30,39	**0,33**	0%	0%		0,00	0,22	0,00	4,56	**6,86**	0,00
3.3	3	**33,13**	13,25	1,17	**6,53**	**1,89**	-0,30	26,23	**0,28**	67%	-14%		0,47	0,23	-4,16	3,93	**6,88**	0,02
3.4	3	**49,52**	0,00	1,74	**6,42**	**2,85**	0,00	39,56	**0,43**	0%	0%		0,00	0,23	0,00	5,93	**7,52**	0,00
3.5	3	**52,62**	3,10	1,85	**4,99**	**2,71**	-0,14	37,61	**0,41**	6%	-5%		0,11	0,18	-1,94	5,64	**7,53**	0,01
3.6	3	**46,06**	0,00	1,62	**5,31**	**3,18**	0,00	44,14	**0,48**	0%	0%		0,00	0,19	0,00	6,62	**7,36**	0,00
3.7	3	**44,15**	-1,91	1,55	**7,03**	**3,33**	0,15	46,22	**0,50**	-4%	5%		-0,07	0,25	2,08	6,93	**7,39**	0,03
3.8	3	**19,72**	0,00	0,69	**3,48**	**1,79**	0,00	24,84	**0,27**	0%	0%		0,00	0,12	0,00	3,73	**7,03**	0,00
3.9	3	**21,84**	2,13	0,77	**2,45**	**1,95**	0,16	27,06	**0,29**	11%	9%		0,07	0,09	2,22	4,06	**7,09**	0,05
4.0	3	**44,31**	0,00	1,56	**5,11**	**2,60**	0,00	36,09	**0,39**	0%	0%		0,00	0,18	0,00	5,41	**7,14**	0,00
4.1	3	**38,55**	-5,76	1,36	**12,40**	**2,65**	0,05	36,78	**0,40**	-13%	2%		-0,20	0,44	0,69	5,52	**6,98**	-0,16
4.2	3	**21,95**	0,00	0,77	**5,10**	**2,30**	0,00	31,92	**0,35**	0%	0%		0,00	0,18	0,00	4,79	**6,74**	0,00
4.3	3	**23,59**	1,64	0,83	**3,53**	**2,09**	-0,21	29,01	**0,31**	7%	-9%		0,06	0,12	-2,91	4,35	**6,75**	0,01
4.4	3	**41,91**	0,00	1,48	**4,98**	**4,77**	0,00	66,20	**0,72**	0%	0%		0,00	0,18	0,00	9,93	**7,40**	0,00
4.5	3	**30,83**	-11,09	1,09	**4,10**	**5,61**	0,84	77,86	**0,84**	-26%	18%		-0,39	0,14	11,66	11,68	**7,42**	0,02
4.6	3	**25,18**	0,00	0,89	**1,52**	**3,75**	0,00	52,05	**0,56**	0%	0%		0,00	0,05	0,00	7,81	**7,40**	0,00
4.7	3	**20,14**	-5,04	0,71	**5,79**	**3,79**	0,04	52,60	**0,57**	-20%	1%		-0,18	0,20	0,56	7,89	**7,42**	0,02
4.8	3	**2,01**	0,00	0,07	**0,76**	**3,43**	0,00	47,60	**0,51**	0%	0%		0,00	0,03	0,00	7,14	**6,44**	0,00
4.9	3	**1,89**	-0,12	0,07	**0,49**	**3,38**	-0,05	46,91	**0,51**	-6%	-1%		0,00	0,02	-0,69	7,04	**6,37**	-0,07
5.0	11	**246,53**	0,00	2,37	**14,08**	**2,24**	0,00	31,09	**0,34**	0%	0%	**0%**	0,00	0,14	0,00	4,66	**7,39**	0,00
5.2	11	**273,49**	26,95	2,63	**14,89**	**2,67**	0,43	37,06	**0,40**	11%	19%	**5%**	0,26	0,14	5,97	5,56	**7,43**	0,04
5.6	11	**235,14**	-11,40	2,26	**15,82**	**2,38**	0,14	33,03	**0,36**	-5%	6%	**17%**	-0,11	0,15	1,94	4,95	**7,70**	0,30
5.7	11	**300,79**	54,26	2,89	**11,64**	**2,97**	0,73	41,22	**0,45**	22%	33%	**8%**	0,52	0,11	10,13	6,18	**7,33**	-0,06
5.8	11	**335,49**	88,95	3,22	**13,06**	**3,39**	1,15	47,05	**0,51**	36%	51%	**49%**	0,85	0,13	15,96	7,06	**7,70**	0,30
6.0	11	**44,73**	0,00	0,43	**8,51**	**2,55**	0,00	35,39	**0,38**	0%	0%	**0%**	0,00	0,08	0,00	5,31	**6,53**	0,00
6.2	11	**36,88**	-7,85	0,35	**4,21**	**3,34**	0,79	46,36	**0,50**	-18%	31%	**11%**	-0,08	0,04	10,96	6,95	**6,54**	0,00
6.4	11	**5,42**	0,00	0,05	**1,09**	**4,45**	0,00	61,76	**0,67**	0%	0%		0,00	0,01	0,00	9,26	**6,01**	0,00
6.5	11	**8,16**	2,74	0,08	**2,63**	**4,48**	0,03	62,18	**0,67**	51%	1%		0,03	0,03	0,42	9,33	**6,12**	0,12
6.6	11	**81,39**	36,65	0,78	**14,78**	**3,01**	0,47	41,78	**0,45**	82%	18%	**117%**	0,35	0,14	6,38	6,27	**7,26**	0,72
6.7	11	**38,73**	-6,00	0,37	**14,34**	**4,06**	1,51	56,35	**0,61**	-13%	59%	**32%**	-0,06	0,14	20,96	8,45	**6,70**	0,17
6.8	11	**273,86**	229,13	2,63	**36,28**	**2,56**	0,02	35,53	**0,38**	512%	0%	**175%**	2,20	0,35	0,14	5,33	**7,39**	0,86
7.0	11	**19,30**	0,00	0,19	**1,57**	**2,67**	0,00	37,06	**0,40**	0%	0%	**0%**	0,00	0,02	0,00	5,56	**6,29**	0,00
7.2	11	**18,63**	-0,67	0,18	**3,81**	**4,09**	1,42	56,77	**0,61**	-3%	53%	**18%**	-0,01	0,04	19,71	8,51	**6,37**	0,08
7.4	11	**14,74**	0,00	0,14	**1,39**	**2,72**	0,00	37,75	**0,41**	0%	0%		0,00	0,01	0,00	5,66	**7,67**	0,00
7.5	11	**15,35**	0,61	0,15	**1,44**	**2,83**	0,11	39,28	**0,42**	4%	4%		0,01	0,01	1,53	5,89	**7,68**	0,01
7.6	11	**41,66**	22,36	0,40	**7,89**	**4,18**	1,51	58,01	**0,63**	116%	57%	**87%**	0,21	0,08	20,96	8,70	**6,92**	0,63
7.7	11	**26,28**	6,98	0,25	**3,57**	**3,50**	0,83	48,58	**0,53**	36%	31%	**41%**	0,07	0,03	11,52	7,29	**6,44**	0,15
7.8	11	**184,76**	165,46	1,77	**14,64**	**3,24**	0,57	44,97	**0,49**	857%	21%	**99%**	1,59	0,14	7,91	6,75	**7,35**	1,06
9.0	11	**166,45**	0,00	1,60	**9,82**	**2,04**	0,00	28,31	**0,31**	0%	0%	**0%**	0,00	0,09	0,00	4,25	**7,33**	0,00
9.2	11	**149,74**	-16,71	1,44	**12,17**	**2,23**	0,19	30,95	**0,33**	-10%	9%	**5%**	-0,16	0,12	2,64	4,64	**7,12**	-0,21
9.4	11	**153,32**	-13,13	1,47	**12,26**	**2,37**	0,33	32,89	**0,36**	-8%	16%		-0,13	0,12	4,58	4,93	**7,26**	-0,07
9.5	11	**158,72**	-7,73	1,52	**7,81**	**1,32**	-0,72	18,32	**0,20**	-5%	-35%	**0%**	-0,07	0,07	-9,99	2,75	**7,15**	-0,18
9.6	11	**130,69**	-35,75	1,25	**2,45**	**2,05**	0,01	28,45	**0,31**	-21%	0%	**1%**	-0,34	0,02	0,14	4,27	**7,35**	0,01
9.7	11	**126,77**	-39,68	1,22	**11,40**	**3,06**	1,02	42,47	**0,46**	-24%	50%	**10%**	-0,38	0,11	14,16	6,37	**7,29**	-0,04
9.8	11	**188,57**	22,13	1,81	**24,27**	**2,51**	0,47	34,84	**0,38**	13%	23%	**87%**	0,21	0,23	6,52	5,23	**7,55**	0,22

All data (measurement data in bold, others are derived data)

file "Carbdown Greenhouse - C Flux Data 2023.xlsx" on Github

Appendix 5: Data on Github

We have uploaded our data to a Github repository at https://github.com/dirkpaessler/carbdown. For the time being this is a private repository so we know who is accessing the data, it will be publicly available later. To access our data please create a Github account at https://github.com/signup and send us your account name to info@carbon-drawdown.de so we can give you access to the repository.

License

Please note that the data is licensed under the creative commons license CC-BY-SA-4.0 Attribution-NonCommercial-ShareAlike 4.0 International. Simply said, you can download and work with this data for non-commercial and scientific projects as long as you attribute us as the creator of the data and share derived data with the same license.

You are free to:

Share — copy and redistribute the material in any medium or format

Adapt — remix, transform, and build upon the material

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit , provide a link to the license, and indicate if changes were made . You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

NonCommercial — You may not use the material for commercial purposes .

ShareAlike — If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original.

No additional restrictions — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

Notices:

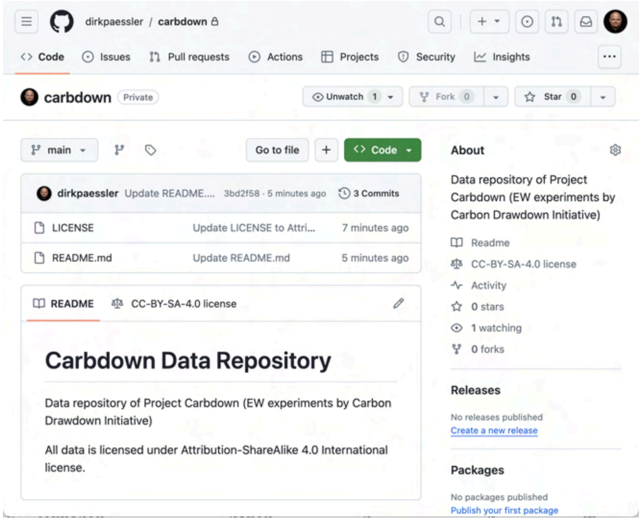
You do not have to comply with the license for elements of the material in the public domain or where your use is permitted by an applicable exception or limitation .

No warranties are given. The license may not give you all of the permissions necessary for your intended use. For example, other rights such as publicity, privacy, or moral rights may limit how you use the material.

We are happy to support commercial licensing (e.g. commercially used non-public models derived in part from our data) please contact info@carbon-drawdown.de.

Available data files

- Carbdown Greenhouse - C Flux Data 2023.xlsx (base data for the graphs in this paper)
- Carbdown Greenhouse - Monthly Alkalinity Data per Replica 2023.xlsx
- Carbdown Greenhouse - Monthly Alkalinity Data per Variant 2023.xlsx
- Carbdown Greenhouse CO2 efflux data 2023 (hourly averages per variant, filtered for light _10 lux and clogged pots).xlsx
- Carbdown Greenhouse pCO2 sensors 2023 (daily avg. data per replica).xlsx
- Carbdown Greenhouse - Biomass Data 1st half of 2023 (Jan-Jul).xlsx
-



dirkpaessler Update README.... 3bd2f58 · 5 minutes ago 3 Commits

LICENSE	Update LICENSE to Attri...	7 minutes ago
README.md	Update README.md	5 minutes ago

README CC-BY-SA-4.0 license

Carbdown Data Repository

Data repository of Project Carbdown (EW experiments by Carbon Drawdown Initiative)

All data is licensed under Attribution-ShareAlike 4.0 International license.

Data repository of Project Carbdown (EW experiments by Carbon Drawdown Initiative)

Readme
CC-BY-SA-4.0 license
Activity
0 stars
1 watching
0 forks

Releases

No releases published
Create a new release

Packages

No packages published
Publish your first package

Wilhelmshavener Str. 64, 90766 Fuerth, Germany
www.carbon-drawdown.de