https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

Technical note: Lys-clim, a combination of lysimeters and an atmospheric conditions simulator to study biogeochemical processes in the shallow critical zone.

Baptiste Hulin[1,2], Scott Saleska[3,4,5], Didier Jehanno[2], Simon Chollet[2], Katerina Dontsova[3,4], Hannes Bauser[6], Valerie Milici[3,5], and Samuel Abiven[1,2]

[1]Laboratoire de Géologie, CNRS—École Normale supérieure, PSL University, Paris, France
[2]Centre de Recherche en Ecologie Expérimentale et Prédictive (CEREEP-Ecotron Ile de France), Ecole Normale Supérieure, CNRS, PSL Research University, Paris, France
[3] Biosphere 2, University of Arizona, Oracle, Arizona, USA
[4]Department of Environmental Science, University of Arizona, Tucson, Arizona, USA
[5]Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, Arizona, USA
[6]Department of Geoscience, University of Nevada, Las Vegas, USA

Correspondence: Baptiste Hulin (baptiste.hulin@yahoo.com)

Abstract. Studying the Critical Zone (CZ), i.e. the outermost envelope of Earth, and its bio-geochemical processes requires an interdisciplinary approach. The deployment of critical zone observatories has led to significant scientific advances but does not offer the possibility of comparing treatments or apprehending different climatic scenarios. Conversely, mesocosm studies are often discipline-specific and can be limited in scope. Here, we propose a complementary approach that relies on the combination of 15 lysimeters and an atmospheric conditions simulator . The lysimeters have been equipped to allow for a detailed monitoring of the water flow, which connects most biogeochemical processes in the critical zone. This monitoring relies on scales, tipping buckets, soil moisture sensors and a facilitated high frequency sampling of discharge water. Besides, in-situ continuous gas analysis is enabled by a 45-channel manifold. The simulator is a 81 m^3 isolated chamber that enables regulation of temperature; atmospheric CO_2; relative humidity; quantity and quality of irrigation water and quantity and quality of light. We evaluate the design in terms of its ability to assess the interactions between CZ processes. The main advantages of this set-up are as follows: it allows for the simulation of future climates or extreme events; it enables replication and the application of different treatments, facilitating the isolation of processes and the assessment of anthropogenic impacts; and it provides automated data acquisition.

1 Introduction

Natural habitats are shaped by the coupling of geology, climate and living organisms over time in the outer envelope of earth. This premise led to the notion of Critical Zone (CZ), that refers to the superficial layer of the terrestrial crust supporting these interactions, and therefore ecosystems (NRC, 2001). Although its spatial limits vary across the literature, it generally relates to the zone between the 'top of the canopy layer down to the bottom of the aquifer' (Giardino and Houser, 2015). Besides, the term CZ aims at drawing attention to all natural and anthropogenic processes relevant for life sustainability, including human

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

life, taking place in this zone. For instance, considering drivers such as environmental policies or farming practices could enrich our understanding of the CZ (Latour, 2014). Therefore, its study in the most holistic way is crucial to comprehend challenges imposed by climate change, resources limitations or anthropogenic pressure on land, and requires interdisciplinarity (Richter and Mobley, 2009).

To examine this complexity, Critical Zone Observatories (CZOs) have been deployed across the globe in the last two decades leading to significant conceptual advances (Brantley et al., 2017; Guo and Lin, 2016). CZOs are commonly instrumented watersheds that comprise a set of various sensors (meteorological stations, flux towers, temperature and moistures sensors for soils,. . .) and sampling facilities. When assembled in a network, they provide valuable measurements along climatic, lithologic or human pressure transects (Banwart et al., 2013; Gaillardet et al., 2018; White et al., 2015). CZOs provide understanding of CZ processes under actual climates but their extrapolation under future climates is uncertain due to, among others, threshold effects (Guo and Lin, 2016) or nonlinear responses to changes (Chen et al., 2019).

To apprehend these changes, experimental approaches are favoured. Field trials that target specific climate parameters have emerged already decades ago, such as free-air CO_2 enrichment (FACE) (Kimball et al., 2002; Okada et al., 2001) or free air temperature increase (FATI) (Nijs et al., 1996). Even though these trials are not necessarily designed for holistic approaches and suitable to CZ studies, some provide a valuable facility for interdisciplinary research. The EucFACE experiment, in Australia, is one of the representative examples (Norby et al., 2016) with more than 80 publications covering various topics. Complementary to the field, other tools exist to study CZ, under the light of climate change or not. Experimentation in mesocosms, although they are less realistic than field trials, allow more replication and tend to improve our mechanistic understanding of processes (Stewart et al., 2013), which is important to predict the future functioning of ecosystems (Helmuth et al., 2005). Lastly, ecotrons, which enable the reproduction of environmental conditions, are valuable to disentangle ecosystem mechanisms and to assess the impact of climate projections and extreme events (Roy et al., 2021). In particular, they enable multifactor studies, which is necessary to assess the response of ecosystems to the complex interactions of global change factors (Rillig et al., 2019).

We believe that there is a need for facilities to study the CZ that would allow 1) a multidisciplinary approach; 2) a simultaneous forcing of atmospheric conditions and 3) replicates to compare treatments and assess the variability. For this purpose, we present here an experimental design that combines mesocosms and an ecotron (here an atmospheric conditions simulator) to propose a way of studying CZ. This set-up is intended to be complementary to CZOs. It allows replication, controlling the atmospheric conditions, and choosing the substrate supporting the ecosystem. It focuses on processes of the shallow CZ. In our proposed design, while emphasis was placed on hydrology as water is the common thread linking CZ compartments (Giardino and Houser, 2015), efforts were made to instrument the system so that interdisciplinary approaches are facilitated. Here, we describe and evaluate the design in the light of its capability to link multiple CZ processes.

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

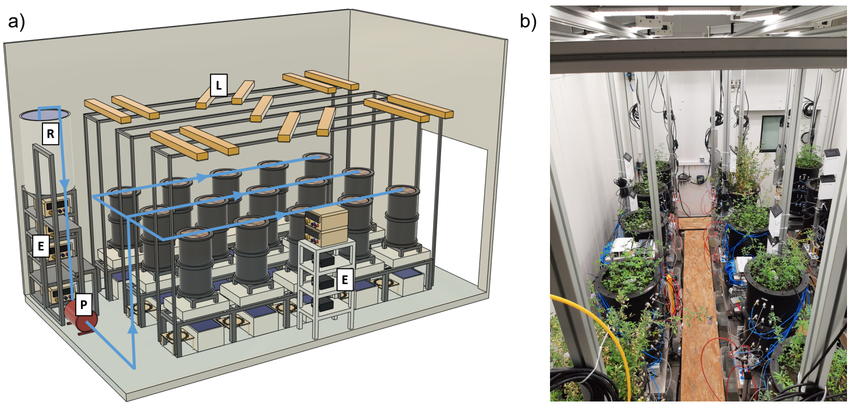

Figure 1. a) Schematic view of the experimental design. L = LED bars; R = Water Reservoir; E = Electronic bay; P = Irrigation pump. b) A photograph of the launch experiment. *Medicago sativa* has been sown for two months in the basalt substrate.

2 DESIGN AND METHODS

2.1 GENERAL DESIGN

The set-up comprises 15 identical instrumented mesocosms of 75-L volume placed in an atmospheric conditions simulator (ecotron) at the CEREEP-Ecotron Ile De France experimental platform (48°17′11′′ N, 2°41′46′′ E) (Fig. 1a). The aim of combining such a simulator and mesocosms is to support the experimental reproduction of various terrestrial ecosystems, as well as future climate scenarios and extreme events. Although the layout of the mesocosms is fixed, the placement of most sensors, their number and location, can be changed as needed. Data acquisition and control of mesocosm instrumentation is centralised by a python program running on a main computer which is linked to instruments by an electronic bay (Fig. 1a). Atmospheric conditions regulation (temperature, relative humidity and gas composition) is ensured by a separate control center, inherent to the ecotron.

2.2 ATMOSPHERIC CONDITIONS SIMULATOR

The experimental set-up is placed in a 81 m^3 controlled ecotron chamber. Besides the chamber, the facility comprises a laboratory module, a heat and cold production module and a control center. The ceiling height of 4.63 meters enables comfortable manipulation as well as establishment of tall plants such as young trees. Thermal insulation consists of 17 cm thick polyurethane foam walls. The atmospheric conditions can be designed manually, or can be implemented from a weather station file with a resolution time of 5 minutes. The following parameters can be monitored by the control center: air temperature, Relative Humidity (RH) and atmospheric gas composition. Each of these parameters is continuously measured by a sensor every minute. If a difference with the target value is detected, an adjusting process is launched. Lightning is controlled separately by the python

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

program of the main computer and irrigation is semi-manual. The following sections provide more details about atmospheric conditions regulation.

2.2.1 TEMPERATURE

Temperature is controlled by a glycol water circuit, four heat exchangers, and heating resistors. Glycol water is cooled by a heat pump and directed to the heat exchangers, that also comprise resistors. It allows the cooling or heating of the air in the chamber which is drawn by ceiling fans to the exchanger. Once mixed, this air is brought back to the chamber through a honeycomb grid. The heat pump temperature is adjusted by the control center according to the chamber's temperature records (ROTRONIC - HC2-SH).

2.2.2 RELATIVE HUMIDITY

RH of air is the partial pressure of water vapour divided by the maximum partial pressure of water vapour in given temperature and pressure conditions. It is continuously measured by a sensor (ROTRONIC - HC2-SH). If the measured value is below the set point, cold water vapour is injected, after being produced by an adiabatic ultrasonic humidifier (TEDDINGTON VAPATRONICS- HU85). If the measure is above the setpoint, air is drawn to an air dryer (DESSICA - DT400) filled with a silica gel desiccant that is self-regenerated.

2.2.3 ATMOSPHERIC COMPOSITION

The air of the chamber can be either renewed or recycled in a closed circuit. Even when monitoring it, a periodical renewal for the sake of ecosystem health is relevant. To achieve this, the cell air is extracted by a ventilation box (FRANCE AIR - Rectilys 2 ECM) and replenishment with external air is ensured by a filter trap. When monitoring air composition, the most flexible parameter is CO_2 concentration. It is continuously measured (analyzer : LICOR - LI-830). It can be raised through the means of CO_2 injections from a gas bottle (99 % CO_2) regulated by a flow meter (ALICAT). The chamber's CO_2 concentration can be lowered to the one outside the facility, but not lower. Other gases could be monitored using the same approach. It would however require the adapted analyzer to measure the air composition.

2.2.4 IRRIGATION

Irrigation is provided by drippers that can be chosen for the desired flow rate. To date, 6 drippers (GARDENA - 13312-20) with a constant flow rate of 2 L.min^{-1} are installed in each mesocosm. The water is pumped from a 300 L stainless steel tank (Fig. 1). The latter can be filled with the desired water type and can be labelled with tracers if needed. Air is bubbled into the tank to maximise gas equilibration with the atmosphere. The pump is launched by the program. Water is delivered in short pulses to adjust the effective irrigation rate.

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

2.2.5 LIGHTNING

The artificial lighting is composed of 15 Light-Emitting Diode (LED) bars (AGC LIGHTNING CO. - HL06-600), situated 160 cm above the top of the columns (Fig. 1). Each bar is composed of two light sources: one emitting in the visible wavelengths (550 Watts) and the other in the near-infrared wavelengths (75 Watts). Each source is controllable in 10 stages, from 0 % (off) to 100 % of the maximum intensity. The finest frequency to change light is 30 seconds.

2.3 MESOCOSM SET-UP

2.3.1 MESOCOSM DESCRIPTION

The mesocosms are 72-cm-high columns made of black HDPE with a diameter of 36.5 cm. 24 7-mm-wide apertures on the side at 4 depths enable the in-situ mounting of various sensors, described in the following sections (Fig. 2). Water tightness is guaranteed by cable glands. An 7-mm-wide aperture at the bottom allows water to drain out. The substrate is filled in manually. It is raised by 3 cm over the column's bottom using a propylene grid to facilitate water drainage.

2.3.2 WATER BALANCE

The sensors described in this section aim to establish a water balance for each mesocosm, as described in equation 1 adapted from Pütz et al. (2018):

$$\Delta W = I + D - (S + B + ET) \quad (1)$$

where ΔW is the weight change of the filled mesocosm, I is irrigation, D is dew, S is seepage, B is biomass change and ET is evapotranspiration. Each mesocosm is set on a scale (GRAM - K3-F3-300) with a 50-grams resolution, which translates to 0.5 mm of precipitation on the column's surface. The monitoring of ΔW allows a deduction of the missing terms of the equation 1. Seepage is directed from the bottom of the column to a rain gauge (DAVIS) that records it, before reaching the collection reservoir. The rain gauge, which is a tipping bucket, has a sensitivity of 4.12 mL $\pm$ 0.11 mL (standard deviation, personal calculation, n = 67). One tilt is therefore equivalent to 0.04 mm. The formation of dew (D) could be partially modelled from the RH and temperature data of the climatic cell. Four moisture and temperature sensors (METER - Teros 12) are deployed at the surface of the substrate and at 10, 24 and 52 cm depth to monitor variability along the profile.

2.3.3 GAS MEASUREMENTS

In order to analyse the gas phase composition of the substrate, an automated gas circuit is deployed in all 15 mesocosms (Fig. 2). Pore gas enters a pipe circuit through a membrane (3M - Membrana) located in the mesocosm that is permeable only to gases. The circuit is a loop to which gas analyzers are connected, so that air can flow back to the mesocosm. Air flow is provided by a pump. To monitor a large number of channels (different depths or mesocosms) with a limited number of analyzers, a manifold encloses the analyzers. It consists of 16 solenoid valves upstream of the analyzers, and 16 downstream. They are controlled by

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

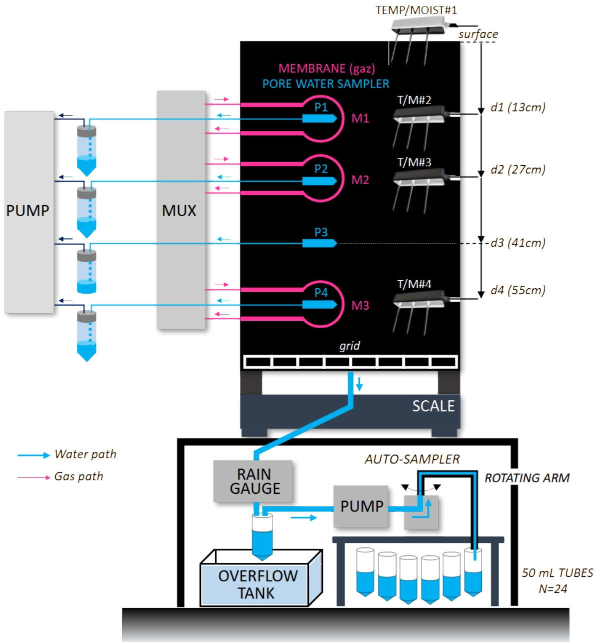

Figure 2. Schematic representation of the instrumented mesocosm. Water flows out at the bottom of the column. Discharge is then recorded by the rain gauge (tipping bucket) and dynamically sampled by the autosampler. The excess water flows into the overflow tank, where it can also be sampled. Four temperature and moisture sensors, as well as four pore water samplers are installed in the column. Pore water is directed to 50 mL tubes with a vacuum pump (PUMP). Gas is pumped out through the membranes according to the channel selected by the manifold (MUX) and then directed to the analysers.

the main computer: valves are open in turn for a set time to create a loop flow. One channel is dedicated to the flush: in between each channel selection, the circuit is flushed with air flowing through soda lime. Three sets of analysers (LICOR - LI 830 for CO_2 and PYROSCIENCE - Firesting logger and flowthrough cell sensors, for O_2) and manifolds are installed, allowing the monitoring of 45 channels in the chambers (3 depths times 15 mesocosms). Measurement time was set to 4 minutes for each channel. Only the last data point from this interval is preserved to avoid alteration induced by the channel change. A detailed description of the manifold has been made open access (Hulin et al., 2025).

2.3.4 CONTINUOUS DATA ACQUISITION

Most of the continuously recorded data are centralised on the main computer. Data are transferred through serial links to the interfaces of the electronic bay, and then through Ethernet to the main computer. For tipping buckets, an additional interface formed by an Arduino microcontroller stores data temporarily until recovery by the computer. A Python program acquires instruments data at various frequencies and creates a new file every day to store the data. These files are transferred to a cloud

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

Table 1. Acquisition frequencies of the different instruments.

Measure	Acquisition frequency	Data recovery
Mesocosm weight	75 seconds	Automated
In situ temperature and moisture	5 minutes	Manual
In situ gas composition (O_2 and CO_2)	120 minutes	Automated
Discharge (tipping buckets)	5 seconds (count recovery)	Automated
Cell atmospheric parameters (Temperature, RH, ambient CO_2)	60 seconds	Manual

every hour. For moisture and temperature sensors, as well as for atmospheric measurements, data have to be collected manually from a datalogger (METER - ZL6) and the central supervision respectively. Table 1 summarizes acquisition frequencies for the different sensors. The codes to control and acquire data for the tipping buckets and the dynamic autosamplers have been made open access (Chollet, 2025).

2.3.5 SAMPLE COLLECTION

Both pore water and drainage water can be collected (Fig. 2). To sample pore water, quartz suction cells (PRENART - Super Quartz) are placed in the mesocosm for the whole experiment duration. Water is flowing out from the side of the column under vacuum. Drainage water can be collected in 2 different ways: 1) From the collection reservoir situated below the mesocosm. This allows to integrate seepage events since the reservoir was last emptied. 2) Dynamically, by sampling in a 50-mL tube situated directly at the outlet of the drainage pipe with an autosampler (Fig. 2). The autosampler is made of a peristaltic pump and a rotating arm that directs water to 50 mL tubes. Sampling frequency can be chosen. It is controlled by an Arduino board (Arduino - UNO R3). Samples have to be removed manually at least every 24 samples.

2.4 DESIGN EVALUATION

We evaluated our design in two stages: an assessment of the quality of atmospheric conditions reproduction, and an evaluation of the mesocosm instrumentation.

Firstly, we ran a six day atmospheric conditions simulation to assess the regulation of temperature, RH and atmospheric CO_2 concentration. A setpoint file for these 3 parameters was implemented in the ecotron control center. We chose to simulate rapid variations to evaluate the reactivity of the simulator, rather than real atmospheric conditions. Temperature was set to vary from 6 to 36 °C, RH from 50 to 84 % and CO_2 from 550 to 734 ppm. We measured these 3 parameters every minute, and calculated the deviation from the setpoint. The lights were on (100 % for the two sources) during the whole simulation. At the end of the simulation, we assessed the light quantity and its heterogeneity by measuring the Photosynthetic Photon Flux Density (PPFD), which is the incoming flux of photons in the Photosynthetically Active Radiation (PAR) spectral range, at the surface of each

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

mesocosm. After that, we assessed the light quality by varying the intensity of the near-infrared light source from 0 to 100 % while keeping the visible source at 100% and by analysing the spectrum in the PAR range for each combination. We calculated the Red:Far-Red (R:FR) ratios by using the amount of photons integrated in the range 650 to 670 nm for red and 720 to 740 nm for far-red, and compared to natural light sources.

Then, we used the preliminary results of a first experiment with this set-up (Fig. 1b) to evaluate the functioning of the instrumentation of the mesocosms and its relevance. The aim of this experiment is to describe the evolution of a basaltic substrate after the introduction of higher plants. To do so, we grew alfalfa (*Medicago sativa*) on ground basalt for 6 months. We used 3 treatments: bare control without alfalfa, alfalfa without fertilisation and alfalfa with fertilisation. We assessed the instrumentation in 3 steps: we evaluated 1) the relevance of the autosamplers; 2) the gas manifold and 3) the capacity of the hydrological instrumentation to establish a water balance. Firstly, to evaluate the autosamplers, we performed a two-hour frequency sampling by running an autosampler during a large drainage event to sample discharge water every two hours at the bottom of a non-planted mesocosm. We then measured the electrical conductivity of the sampled water to assess its temporal evolution and its evolution with the volume, by coupling results with tipping buckets data. Secondly, we measured in situ CO_2 concentration during the growth of the plants at 3 different depths in a planted mesocosm without fertilisation. We examined whether the measuring frequency was sufficient to capture variations linked to plant activity. Thirdly, we calculated evapotranspiration for planted mesocosm (with or without fertilisation) and for control mesocosms (3 replicates for each) with equation (1) with a five minute step-by-step resolution. To do so, seepage was recorded with tipping buckets, ΔW with scales and irrigation rate was deduced from irrigation time and drippers flow rate. The data were summed up every 5 minutes to be used in the equation. We did not take dew into consideration as none was observed and we considered biomass change negligible.

3 RESULTS

3.1 ATMOSPHERIC CONDITIONS SIMULATIONS

Results of the atmospheric conditions simulation performance test are shown in Fig. 3. Temperature, RH and atmospheric CO_2 concentrations show very little deviation from the setpoint. The latter follows a normal distribution with standard deviations of the relative error for temperature, RH and CO_2 concentrations being 1.96 %, 2.09 % and 1.50 % respectively. A 40-minute intervention in the chamber on day 3 (Fig. 3) when doors were opened led to a rapid equilibrium with ambient CO_2. However, the deviation to the setpoint was brought back below 5 % less than 10 minutes after the end of the intervention. The average PPFD measured at the top of the mesocosms is 450 μmol m^{-2} s^{-1} with a standard deviation of 15.7 μmol m^{-2} s^{-2} (n = 15). The minimum value is 433 μmol m^{-2} s^{-1} and the maximum is 480 μmol m^{-2} s^{-1}. The control of the two light sources enables us to simulate R:FR ratios from 0.71 to 3.58 (Fig. 4) thereby reproducing varied environments such as undergrowth or daily variations.

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

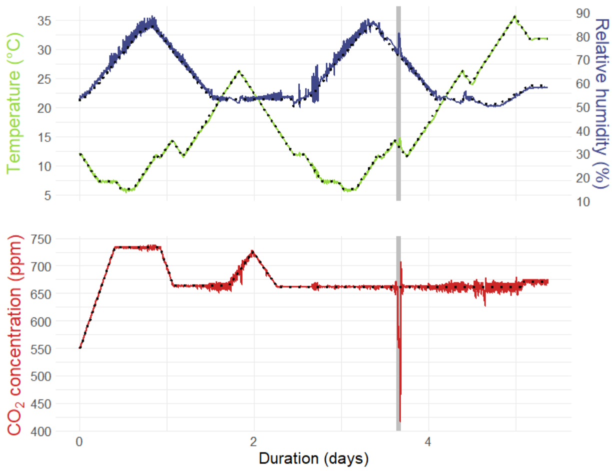

Figure 3. Results of the atmospheric conditions simulation performance test. Coloured solid and dotted lines are measurements and setpoints respectively. The shaded area corresponds to a time of human intervention in the cell (opening of the doors).

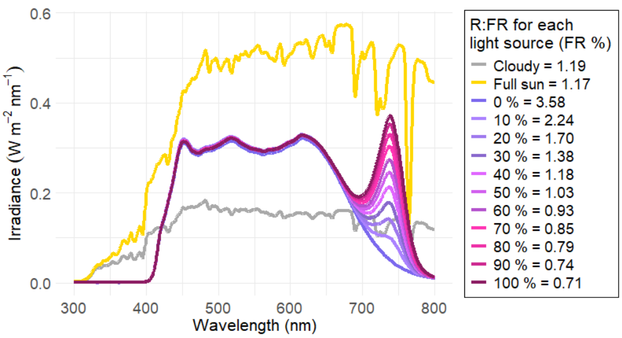

Figure 4. Light spectrum of artificial lights and sunlight. Sunlight was measured during both clear and cloudy sky conditions, on 10 January 2025. For the artificial lights, we set the sun-like source to 100 % and we varied the near-infrared source from 0 to 100 %. We report the R:FR ratios in the legend. The ratio was calculated by using the amount of photons integrated in the range 650 to 670 nm for red and 720 to 740 nm for far-red.

3.2 DYNAMIC SAMPLING

The discharge event on which we evaluated the autosampler lasted for 42 hours and yielded 277 mm of seepage (Fig. 5). During this time, we could collect 14 water samples with enough water to measure electrical conductivity. Indeed, the discharge was irregular, there were two-hours time slots with only very little water leaving the mesocosm. Thanks to the autosampler, we were able to observe a temporal evolution that showed a decrease of the conductivity with time (Fig. 5). Combining these measurements with tipping buckets records also allowed to obtain a concentration-discharge relationship and then to fit a decreasing exponential model explaining conductivity evolution with discharge (mean absolute percentage error = 4.4 %).

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

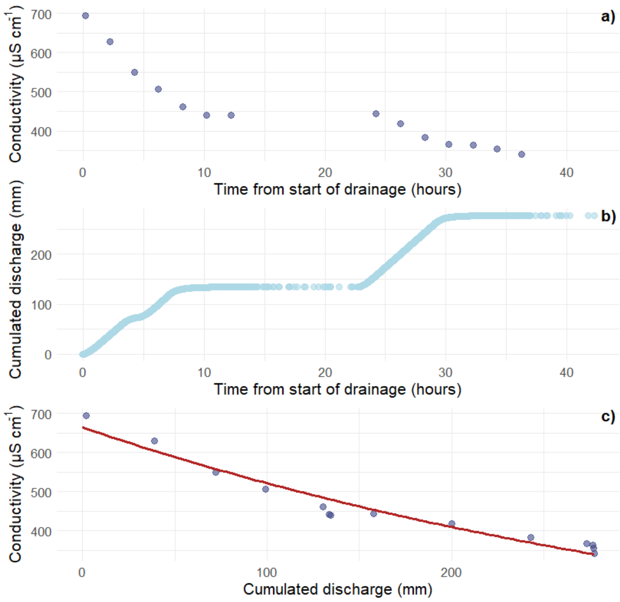

Figure 5. Conductivity measurements of discharge water during a drainage event, acquired with an autosampler. a) Conductivity vs. time. b) Cumulative discharge vs. time. Each blue point represents an acquisition of the tipping buckets data. c) Conductivity vs. cumulative discharge. The red line is a fitted decreasing exponential model.

3.3 GAS MEASUREMENTS

A measuring time of 4 minutes per channel for CO_2 provided around 9 data points in this interval, from which we retained only the last one after data cleaning. Indeed, during this time interval, CO_2 values increase as there is air remaining in the system that comes from the previous flushing with soda lime and that has a concentration close to zero. Then, CO_2 tends to reach a plateau, indicating that it is relevant to use the values on the plateau, such as the last one. 4 minutes is the critical minimum time, as the plateau is not attained for 100 % of the sampling intervals. More details on the data post-processing are available at Hulin et al. (2025). With a 4-minutes analysis, the time before returning to the same channel is 120 minutes. We observed that this frequency is sufficient to catch daily variations induced by respiration for instance. Indeed, we see in Fig. 6 respiration patterns for *Medicago sativa*, with CO_2 values increasing during the day and decreasing in the dark. The deployment of gas-permeable membranes at different depths allowed to identify clear differences along the vertical profile.

3.4 WATER BALANCE

Calculating evapotranspiration with a 5-minute resolution time showed as expected that *ET* rates for fertilised plants are clearly higher than for non-fertilised plants (Fig. 7). The latter, at this stage, show no differences with the control mesocosms. The calculation captured the daily variation, with a higher *ET* rate during daytime. The charts display peaks in the cumulative curves, as well as jumps downwards, indicating instantaneous inconsistent negative *ET* rates. However, negative rates are

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

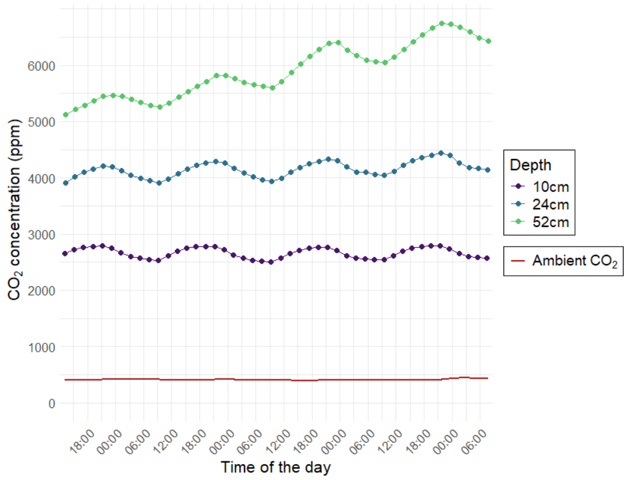

Figure 6. Example of in situ pore CO_2 concentration curves. The values are from a mesocosm without fertilisation. The red curve shows the atmospheric concentration in the ecotron cell. Each point displays the last measurement of a 4-minute acquisition time.

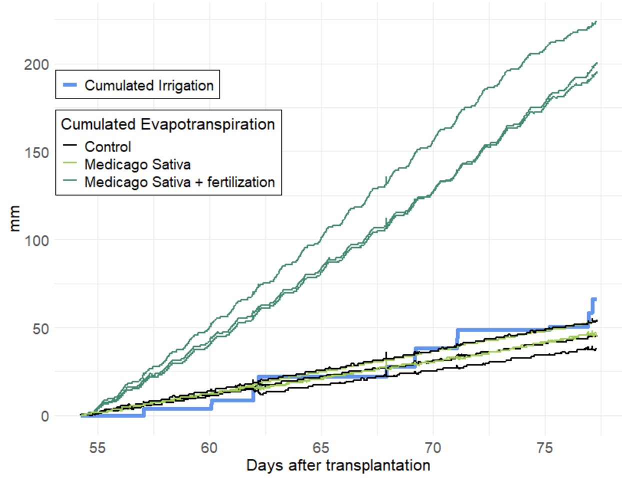

Figure 7. Cumulative evapotranspiration of different treatments. Each line represents a replicate, i.e. one mesocosm (n=3). Transplantation refers to the day at which the alfalfa seedlings were transplanted into the mesocosms.

rapidly compensated and therefore do not prevent the reading of a longer trend. Besides, these peaks reflect noise in the mass and irrigation data that are common in lysimetry data and that can be corrected with smoothing methods for instance (Vaughan et al., 2007).

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

4 DISCUSSION

4.1 COMBINATION OF MESOCOSMS AND ECOTRON

In this section, we discuss the relevance of using this combination of ecotron and mesocosms to provide: 1) a suitable environment for simulating ecosystem development, in particular plant growth; and 2) a tool to address research questions under a broad variety of climates.

Growth chambers, despite offering better reproducibility than greenhouses for plant experimentation (Milcu et al., 2018), tend to simplify the environmental parameters and therefore limit extrapolation of results while ecotrons, by getting closer to outside parameters, are expected to allow more realistic experimentation (Roy et al., 2021). For instance, introducing fluctuations in the light regime leads to biomass production that is more similar to outdoor comparisons (Chiang et al., 2020; Vialet-Chabrand et al., 2017) even if differences in other plant traits remain pronounced, mainly due to light quality (Annunziata et al., 2017). We therefore think that allowing irradiance fluctuations every 30 seconds if necessary is relevant. On the other hand, the maximum light intensity (450 μmol m^{-2} s^{-2} for the PAR) is likely to be insufficient for a broad range of plants. We will therefore have to increase it by lowering the height of the lights or improving reflectance.

Poorter et al. (2012) recommend for the mesocosms to not exceed 2 g of total biomass for a rooting volume of 1 L to limit pot size effects, and to remain below 1 g L^{-1} to be optimal. For the 75-L columns with a surface of 1046 cm^2, this translates into 14.4 and 7.2 tons of dry biomass per hectare, respectively. It allows to grow a broad range of crops but can be limiting for the higher end, such as miscanthus. However, rooting is likely to be limited by the column height as plant roots often exceed 72 cm (Canadell et al., 1996).

Beside mimicking reality, we highlight 3 main advantages for CZ studies in ecotrons: simulating future climates, isolating driving parameters and studying sites from around the world. Many uncertainties remain concerning the evolution of CZ processes under climate change that influence, to name but a few, groundwater recharge (Smerdon, 2017) or food production (Mbow et al., 2020). In order to tackle these challenges, multi-parameter approaches when simulating future atmospheric conditions are essential for capturing the complexity of climate change impacts (Rineau et al., 2019). This applies to long-term trends as well as to extreme events. The ecotron chamber, by controlling at least 5 parameters (hygrometry, irradiance, temperature, precipitation, and atmospheric composition) that could be emulated with regional climate models (Vanderkelen et al., 2020), can achieve necessary complexity. On the other hand, the set-up also allows isolation of driving parameters, be it climatic or treatments in the mesocosm. This is valuable for improving our mechanistic understanding of CZ processes and their modelling (Rineau et al., 2019). Finally, we suggest that such designs can help studying areas of the world that are under-represented in the literature due to complicated access or a lack of scientific and financial resources. Indeed, the list of CZOs assembled by Banwart et al. (2013) reveals geographical inequalities with a high density in the United States and European Union countries, relative to the rest of the world. Nevertheless, the chamber's temperature range limits simulation to warm climates, where many countries have high vulnerability to climate change (Birkmann et al., 2022).

We emphasise that the combination of mesocosms (Fraser and Keddy, 1997; Stewart et al., 2013) and an ecotron (Roy et al., 2021) is an essential tool for studying the effect of climate change on ecosystems. Comparing the results with laboratory, field

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

and natural experiments, which all have advantages (Diamond, 1983) still remains beneficial as ecosystem reproduction is always challenging, even though ecotrons limit the gap with outside parameters.

4.2 CROSSING DATA TO CROSS DISCIPLINES

Interdisciplinarity in science has been promoted as an essential approach to tackle grand challenges (NRC, 2001) and environmental sciences fall within this framework (Hicks et al., 2010). To encourage collaboration between scientific disciplines, which is a first step towards interdisciplinarity, the experimental design aims at enabling the acquisition of diverse data. In this section, we first review the range, the relevance, and the quality of the data provided by the instrumentation of the mesocosms, and then their complementarity.

Hydrological instrumentation of mesocosms enabled a quantitative assessment of the water balance, similar to field lysimeters (Goss and Ehlers, 2009). For instance, the use of rain gauges provides a temporal characterisation of drainage. In the field, this is often achieved by using water balance models that need soil, plant, and atmospheric parameters and that are calibrated against lysimetry and tracer test data (Gee and Hillel, 1988; Lidón et al., 1999) or geophysical measurements (Arora et al., 2019). In addition, labelling of irrigation water with stable isotopes is made possible by the tank upstream of the drippers (Fig. 1), which enables water tracing (Koeniger et al., 2010). This instrumentation helps reduce the historical distinction between surface-water hydrology and groundwater hydrology (Gee and Hillel, 1988), and is therefore valuable for studies on pollution or groundwater recharge, for which data are scarce (Moeck et al., 2020). However, we have to admit that the limited size of mesocosms will likely lead to omission of major water transfer processes in the vadose zone, such as preferential flow (Hendrickx and Flury, 2001). We also point out that the water balance established, and summarized by equation 1, is simplified. Indeed, the original equation from Pütz et al. (2018) comprises other terms such as runoff and capillary rise. These two processes are not modeled under the current experimental design, whereas their consideration is crucial when considering pollutant transfer or soil porosity replenishment for instance. Besides, we have to point out that wind, a crucial factor influencing ET, is not simulated and that heat exchange between the soil and the atmosphere is biased by the exposition of the lysimeter walls.

In the field, CZ water sampling is achieved with suction cups or boreholes (Arora et al., 2019), which gets more challenging with depth. Therefore, having a direct access to seepage water through the overflow tank or the autosampler (Fig. 2) facilitates collection of samples for geochemical or biological analysis. Moreover, the use of autosamplers allows to capture and model variations of seepage water composition with time or discharge when combined with tipping buckets (Fig. 7). Pore water sampling with suction cells is complementary as it targets specific substrate layers or the rhizosphere, which is a hotspot for biogeochemical transformations (Hinsinger et al., 2006).

The automated gas system enabled gas sampling and analysis in 3 layers for each of the 15 mesocosms with a 90 minutes frequency, which makes it a powerful tool to study gas dynamics along a depth gradient. It is originally equipped to measure O_2 and CO_2, which are involved in biotic and abiotic CZ processes. Cross-indexing the data from the two allows us to obtain ratios that can help to distinguish sources from emissions (Sánchez-Cañete et al., 2018). The manifold could also support other analyzers to capture gases such as NO_2 and CH_4, that account for a significant part of the soil greenhouse gas budget (Carlson et al., 2017).

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

A limit to this interdisciplinarity is the size of the object to study. Indeed, in the frame of CZ, part of the observations are addressing much larger compartments than our structure, like complex ecosystems, or ground water. Here we are bound to a few plants and the discharge zone. To summarize, the design allows a continuous acquisition of gas and hydrological data, and offers the possibility to collect diverse water samples. We believe that the instruments are complementary for CZ studies as the gases and water in the pore space determine the biogeochemical reactions, by being both reactants and transporters (Giardino and Houser, 2015; Perdrial et al., 2015). Coupling the different data is therefore essential to achieve the most thorough understanding of the system, even though their exhaustive analysis requires overcoming scientific domain specificity, which can be challenging (MacLeod, 2018).

4.3 EXPERIMENTAL PERSPECTIVES

The purpose of this last section is to give examples of studies that would benefit from such a design. This is not exhaustive, we simply highlight model experiments that require several disciplines to address societal challenges.

Nature Based Solutions (NBS) offer some of the best examples. They are defined as 'solutions to societal challenges that involve working with nature' (Seddon et al., 2021). They can target a specific ecosystem service, for instance atmospheric CO_2 removal, but often also have co benefits and adverse side effects. For citizens or stakeholders to discuss whether or not to adopt it, a thorough assessment of the consequences must first be carried out, if possible in the light of climate change (Calliari et al., 2019). Let us consider Enhanced Rock Weathering (ERW) as an example. It could be considered a NBS as it mimics a natural process that consumes CO_2: rock weathering. Its potential for CO_2 sequestration is large (Beerling et al., 2020), it has potential co-benefits such as improved productivity by supplying nutrients and increasing pH (Edwards et al., 2017) and pitfalls such as trace element pollution (Dupla et al., 2023). CO_2 sequestration could be quantified with gas measurements (Sánchez-Cañete et al., 2018) and discharge water analysis (Beaulieu et al., 2012), while co-benefits can be evaluated by measuring biomass and changes in soil chemistry through the suction cells, and trace element pollution by water analysis in the porosity and in the discharge. The 15 columns offer the possibility to replicate several treatments, such as different crops or application rates.

Another example is groundwater pollution. Keesstra et al. (2012) pointed out the need to combine agronomic and hydrological approaches to investigate pollutant transport through soils. The experimental set-up facilitates sampling of the water leaving the soil and thus its characterisation. For the dissolved pollutants, their fate along the soil profile can be traced with pore water samplers. As a complement, water flow could be quantified with hydrology instrumentation. The 15 columns allow to compare different land uses, which are drivers of groundwater quality and recharge (Lerner and Harris, 2009).

5 Conclusions

This paper describes a new experimental set-up to study the shallow critical zone based on a combination of 15 lysimeters and an atmospheric conditions simulator. The instrumentation of the lysimeters was evaluated and has enabled the detection of daily variations in the water balance or in the CO_2 concentration at different depths of the substrate. The different options for sampling facilitate the characterisation of water chemistry, notably in a dynamic way. The ecotron chamber was able to accurately simulate atmospheric parameters with a resolution time of 5 minutes, allowing a reliable atmospheric conditions reproduction, which is beneficial for studies involving plant growth.

The set-up is subject to limitations that are inherent to study in mesocosms such as size limitations or wall effects. However, it allows replication and therefore the introduction of the human factor as a treatment, which is hardly achievable in CZOs. The data variety that it can provide makes it a relevant support to foster interdisciplinarity and to apprehend complex ecosystems, especially in the light of climate change.

Code availability. A folder containing the tree structure, the Python and Arduino codes, the configuration files, as well as the description files that enable the autosampler and the tipping buckets to run is available at https://doi.org/10.5281/zenodo.16792602.

Data availability. CO_2 data to evaluate the gas manifold are available at https://doi.org/10.5281/zenodo.16928632, along with a detailed description of the device. Other data are available on demand.

Author contributions. All the authors designed the set-up. SC designed the control and command system. DJ and BH assembled the structure. BH conducted the data analysis and wrote the original draft. All the authors contributed to writing the final manuscript. SA and SS leaded the project and the fundraising.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors would like to thank the technical team at CEREEP-Ecotron IDF who helped on setting up the structure. They also would like to thank the members of the Biosphere 2 group, in particular Peter Troch; Jon Chorover; Régis Ferrière; Faviana Cubello; Aaron Bugaj and Wei Ren, who gave their time to refine the design. ChatGPT was used as a support to produce some of the figures.

Financial support. This research has been supported by the CNRS, notably via the MITI mission, and by the University of Arizona. It also received government funding managed by the French National Research Agency under the 'France 2030' programme (reference ANR-24-INBS-0001 AnaEE-France) and by the U.S. National Science Foundation (Award 2121155).

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

References

Annunziata, M. G., Apelt, F., Carillo, P., Krause, U., Feil, R., Mengin, V., Lauxmann, M. A., Köhl, K., Nikoloski, Z., Stitt, M., and Lunn, J. E.: Getting Back to Nature: A Reality Check for Experiments in Controlled Environments, Journal of Experimental Botany, 68, 4463–4477, https://doi.org/10.1093/jxb/erx220, 2017.

Arora, B., Dwivedi, D., Faybishenko, B., Jana, R. B., and Wainwright, H. M.: Understanding and Predicting Vadose Zone Processes, Reviews in Mineralogy and Geochemistry, 85, 303–328, https://doi.org/10.2138/rmg.2019.85.10, 2019.

Banwart, S. A., Chorover, J., Gaillardet, J., Sparks, D. W., T Anderson, S., Aufdenkampe, A., Bernasconi, S., Brantley, S., Chadwick, O., and Dietrich, W. L. E.: Sustaining Earths Critical Zone Basic Science and Interdisciplinary Solutions for Global Challenges, Tech. rep., The University of Sheffield, United Kingdom, 2013.

Beaulieu, E., Goddéris, Y., Donnadieu, Y., Labat, D., and Roelandt, C.: High Sensitivity of the Continental-Weathering Carbon Dioxide Sink to Future Climate Change, Nature Climate Change, 2, 346–349, https://doi.org/10.1038/nclimate1419, 2012.

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J.-F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., Hansen, J., and Banwart, S. A.: Potential for Large-Scale CO2 Removal via Enhanced Rock Weathering with Croplands, Nature, 583, 242–248, https://doi.org/10.1038/s41586-020-2448-9, 2020.

Birkmann, J., Liwenga, E., Pandey, R., Boyd, E., Djalante, R., Gemenne, F., Leal Filho, W., Pinho, P., Stringer, L., and Wrathall, D.: Poverty, Livelihoods and Sustainable Development. In: Climate Change 2022: Impacts,Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Tech. rep., Cambridge University Press, Cambridge, United Kingdom, 2022.

Brantley, S. L., McDowell, W. H., Dietrich, W. E., White, T. S., Kumar, P., Anderson, S. P., Chorover, J., Lohse, K. A., Bales, R. C., Richter, D. D., Grant, G., and Gaillardet, J.: Designing a Network of Critical Zone Observatories to Explore the Living Skin of the Terrestrial Earth, Earth Surface Dynamics, 5, 841–860, https://doi.org/10.5194/esurf-5-841-2017, 2017.

Calliari, E., Staccione, A., and Mysiak, J.: An Assessment Framework for Climate-Proof Nature-Based Solutions, Science of The Total Environment, 656, 691–700, https://doi.org/10.1016/j.scitotenv.2018.11.341, 2019.

Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A., Sala, O. E., and Schulze, E.-D.: Maximum Rooting Depth of Vegetation Types at the Global Scale, Oecologia, 108, 583–595, https://doi.org/10.1007/BF00329030, 1996.

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connell, C. S., Johnson, J. A., Saatchi, S., and West, P. C.: Greenhouse Gas Emissions Intensity of Global Croplands, Nature Climate Change, 7, 63–68, https://doi.org/10.1038/nclimate3158, 2017.

Chen, N., Zhu, J., Zhang, Y., Liu, Y., Li, J., Zu, J., and Huang, K.: Nonlinear Response of Ecosystem Respiration to Multiple Levels of Temperature Increases, Ecology and Evolution, 9, 925–937, https://doi.org/10.1002/ece3.4658, 2019.

Chiang, C., Bånkestad, D., and Hoch, G.: Reaching Natural Growth: The Significance of Light and Temperature Fluctuations in Plant Performance in Indoor Growth Facilities, Plants, 9, 1312, https://doi.org/10.3390/plants9101312, 2020.

Chollet, S.: Control Codes and Descriptions of Two Low-Cost Hydrological Instruments: A Homemade Autosampler and a Tipping Bucket Rain Gauge (DAVIS)., Zenodo, https://doi.org/10.5281/zenodo.16792603, 2025.

Diamond, J. M.: Ecology: Laboratory, Field and Natural Experiments, Nature, 304, 586–587, https://doi.org/10.1038/304586a0, 1983.

Dupla, X., Möller, B., Baveye, P. C., and Grand, S.: Potential Accumulation of Toxic Trace Elements in Soils during Enhanced Rock Weathering, European Journal of Soil Science, 74, e13 343, https://doi.org/10.1111/ejss.13343, 2023.

Edwards, D. P., Lim, F., James, R. H., Pearce, C. R., Scholes, J., Freckleton, R. P., and Beerling, D. J.: Climate Change Mitigation: Potential Benefits and Pitfalls of Enhanced Rock Weathering in Tropical Agriculture, Biology Letters, 13, 20160 715, https://doi.org/10.1098/rsbl.2016.0715, 2017.

Fraser, L. H. and Keddy, P.: The Role of Experimental Microcosms in Ecological Research, Trends in Ecology & Evolution, 12, 478–481, https://doi.org/10.1016/S0169-5347(97)01220-2, 1997.

Gaillardet, J., Braud, I., Hankard, F., Anquetin, S., Bour, O., Dorfliger, N., De Dreuzy, J., Galle, S., Galy, C., Gogo, S., Gourcy, L., Habets, F., Laggoun, F., Longuevergne, L., Le Borgne, T., Naaim-Bouvet, F., Nord, G., Simonneaux, V., Six, D., Tallec, T., Valentin, C., Abril, G., Allemand, P., Arènes, A., Arfib, B., Arnaud, L., Arnaud, N., Arnaud, P., Audry, S., Comte, V. B., Batiot, C., Battais, A., Bellot, H., Bernard, E., Bertrand, C., Bessière, H., Binet, S., Bodin, J., Bodin, X., Boithias, L., Bouchez, J., Boudevillain, B., Moussa, I. B., Branger, F., Braun, J. J., Brunet, P., Caceres, B., Calmels, D., Cappelaere, B., Celle-Jeanton, H., Chabaux, F., Chalikakis, K., Champollion, C., Copard, Y., Cotel, C., Davy, P., Deline, P., Delrieu, G., Demarty, J., Dessert, C., Dumont, M., Emblanch, C., Ezzahar, J., Estèves, M., Favier, V., Faucheux, M., Filizola, N., Flammarion, P., Floury, P., Fovet, O., Fournier, M., Francez, A. J., Gandois, L., Gascuel, C., Gayer, E., Genthon, C., Gérard, M. F., Gilbert, D., Gouttevin, I., Grippa, M., Gruau, G., Jardani, A., Jeanneau, L., Join, J. L., Jourde, H., Karbou, F., Labat, D., Lagadeuc, Y., Lajeunesse, E., Lastennet, R., Lavado, W., Lawin, E., Lebel, T., Le Bouteiller, C., Legout, C., Lejeune, Y., Le Meur, E., Le Moigne, N., Lions, J., Lucas, A., Malet, J. P., Marais-Sicre, C., Maréchal, J. C., Marlin, C., Martin, P., Martins, J., Martinez, J. M., Massei, N., Mauclerc, A., Mazzilli, N., Molénat, J., Moreira-Turcq, P., Mougin, E., Morin, S., Ngoupayou, J. N., Panthou, G., Peugeot, C., Picard, G., Pierret, M. C., Porel, G., Probst, A., Probst, J. L., Rabatel, A., Raclot, D., Ravanel, L., Rejiba, F., René, P., Ribolzi, O., Riotte, J., Rivière, A., Robain, H., Ruiz, L., Sanchez-Perez, J. M., Santini, W., Sauvage, S., Schoeneich, P., Seidel, J. L., Sekhar, M., Sengtaheuanghoung, O., Silvera, N., Steinmann, M., Soruco, A., Tallec, G., Thibert, E., Lao, D. V., Vincent, C., Viville, D., Wagnon, P., and Zitouna, R.: OZCAR: The French Network of Critical Zone Observatories, Vadose Zone Journal, 17, 1–24, https://doi.org/10.2136/vzj2018.04.0067, 2018.

Gee, G. W. and Hillel, D.: Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods, Hydrological Processes, 2, 255–266, https://doi.org/10.1002/hyp.3360020306, 1988.

Giardino, J. R. and Houser, C.: Introduction to the Critical Zone, in: Developments in Earth Surface Processes, vol. 19, pp. 1–13, Elsevier, ISBN 978-0-444-63369-9, https://doi.org/10.1016/B978-0-444-63369-9.00001-X, 2015.

Goss, M. J. and Ehlers, W.: The Role of Lysimeters in the Development of Our Understanding of Soil Water and Nutrient Dynamics in Ecosystems, Soil Use and Management, 25, 213–223, https://doi.org/10.1111/j.1475-2743.2009.00230.x, 2009.

Guo, L. and Lin, H.: Critical Zone Research and Observatories: Current Status and Future Perspectives, Vadose Zone Journal, 15, 1–14, https://doi.org/10.2136/vzj2016.06.0050, 2016.

Helmuth, B., Kingsolver, J. G., and Carrington, E.: Biophysics, Physiological Ecology, and Climate Change: Does Mechanism Matter?, Annual Review of Physiology, 67, 177–201, https://doi.org/10.1146/annurev.physiol.67.040403.105027, 2005.

Hendrickx, J. M. and Flury, M.: Uniform and Preferential Flow Mechanisms in the Vadose Zone, Conceptual models of flow and transport in the fractured vadose zone, pp. 149–187, 2001.

Hicks, C. C., Fitzsimmons, C., and Polunin, N. V.: Interdisciplinarity in the Environmental Sciences: Barriers and Frontiers, Environmental Conservation, 37, 464–477, https://doi.org/10.1017/S0376892910000822, 2010.

https://doi.org/10.5194/egusphere-2025-4243
Preprint. Discussion started: 13 October 2025

Hinsinger, P., Plassard, C., and Jaillard, B.: Rhizosphere: A New Frontier for Soil Biogeochemistry, Journal of Geochemical Exploration, 88, 210–213, https://doi.org/10.1016/j.gexplo.2005.08.041, 2006.

Hulin, B., Jehanno, D., Chollet, S., and Abiven, S.: Description of a 16-Channel Gas Manifold., Zenodo, https://doi.org/10.5281/zenodo.16928632, 2025.

Keesstra, S., Geissen, V., Mosse, K., Piiranen, S., Scudiero, E., Leistra, M., and Van Schaik, L.: Soil as a Filter for Groundwater Quality, Current Opinion in Environmental Sustainability, 4, 507–516, https://doi.org/10.1016/j.cosust.2012.10.007, 2012.

Kimball, B., Kobayashi, K., and Bindi, M.: Responses of Agricultural Crops to Free-Air CO2 Enrichment, in: Advances in Agronomy, vol. 77, pp. 293–368, Elsevier, ISBN 978-0-12-000795-0, https://doi.org/10.1016/S0065-2113(02)77017-X, 2002.

Koeniger, P., Leibundgut, C., Link, T., and Marshall, J. D.: Stable Isotopes Applied as Water Tracers in Column and Field Studies, Organic Geochemistry, 41, 31–40, https://doi.org/10.1016/j.orggeochem.2009.07.006, 2010.

Latour, B.: Some Advantages of the Notion of "Critical Zone" for Geopolitics, Procedia Earth and Planetary Science, 10, 3–6, https://doi.org/10.1016/j.proeps.2014.08.002, 2014.

Lerner, D. N. and Harris, B.: The Relationship between Land Use and Groundwater Resources and Quality, Land Use Policy, 26, S265–S273, https://doi.org/10.1016/j.landusepol.2009.09.005, 2009.

Lidón, A., Ramos, C., and Rodrigo, A.: Comparison of Drainage Estimation Methods in Irrigated Citrus Orchards, Irrigation Science, 19, 25–36, https://doi.org/10.1007/s002710050068, 1999.

MacLeod, M.: What Makes Interdisciplinarity Difficult? Some Consequences of Domain Specificity in Interdisciplinary Practice, Synthese, 195, 697–720, https://doi.org/10.1007/s11229-016-1236-4, 2018.

Mbow, C., Rosenzweig, C. E., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Ruane, A. C., Liwenga, E., Pradhan, P., and Rivera-Ferre, M. G.: Food Security. In : Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, Tech. rep., IPCC, 2020.

Milcu, A., Puga-Freitas, R., Ellison, A. M., Blouin, M., Scheu, S., Freschet, G. T., Rose, L., Barot, S., Cesarz, S., Eisenhauer, N., Girin, T., Assandri, D., Bonkowski, M., Buchmann, N., Butenschoen, O., Devidal, S., Gleixner, G., Gessler, A., Gigon, A., Greiner, A., Grignani, C., Hansart, A., Kayler, Z., Lange, M., Lata, J.-C., Le Galliard, J.-F., Lukac, M., Mannerheim, N., Müller, M. E. H., Pando, A., Rotter, P., Scherer-Lorenzen, M., Seyhun, R., Urban-Mead, K., Weigelt, A., Zavattaro, L., and Roy, J.: Genotypic Variability Enhances the Reproducibility of an Ecological Study, Nature Ecology & Evolution, 2, 279–287, https://doi.org/10.1038/s41559-017-0434-x, 2018.

Moeck, C., Grech-Cumbo, N., Podgorski, J., Bretzler, A., Gurdak, J. J., Berg, M., and Schirmer, M.: A Global-Scale Dataset of Direct Natural Groundwater Recharge Rates: A Review of Variables, Processes and Relationships, Science of The Total Environment, 717, 137 042, https://doi.org/10.1016/j.scitotenv.2020.137042, 2020.

Nijs, I., Kockelbergh, F., Teughels, H., Blum, H., Hendrey, G., and Impens, I.: Free Air Temperature Increase (FATI): A New Tool to Study Global Warming Effects on Plants in the Field, Plant, Cell & Environment, 19, 495–502, https://doi.org/10.1111/j.1365-3040.1996.tb00343.x, 1996.

Norby, R. J., De Kauwe, M. G., Domingues, T. F., Duursma, R. A., Ellsworth, D. S., Goll, D. S., Lapola, D. M., Luus, K. A., MacKenzie, A. R., Medlyn, B. E., Pavlick, R., Rammig, A., Smith, B., Thomas, R., Thonicke, K., Walker, A. P., Yang, X., and Zaehle, S.: Model–Data Synthesis for the next Generation of Forest Free-Air CO2 Enrichment (FACE) Experiments, New Phytologist, 209, 17–28, https://doi.org/10.1111/nph.13593, 2016.

NRC, x.: Basic Research Opportunities in Earth Science, National Academies Press, Washington, D.C., ISBN 978-0-309-07133-8, https://doi.org/10.17226/9981, 2001.

Okada, M., Lieffering, M., Nakamura, H., Yoshimoto, M., Kim, H. Y., and Kobayashi, K.: Free-air CO_2 Enrichment (FACE) Using Pure CO_2 Injection: System Description, New Phytologist, 150, 251–260, https://doi.org/10.1046/j.1469-8137.2001.00097.x, 2001.

Perdrial, J., Thompson, A., and Chorover, J.: Soil Geochemistry in the Critical Zone: Influence on Atmosphere, Surface- and Groundwater Composition, in: Developments in Earth Surface Processes, vol. 19, pp. 173–201, Elsevier, ISBN 978-0-444-63369-9, https://doi.org/10.1016/B978-0-444-63369-9.00006-9, 2015.

Poorter, H., Bühler, J., Van Dusschoten, D., Climent, J., and Postma, J. A.: Pot Size Matters: A Meta-Analysis of the Effects of Rooting Volume on Plant Growth, Functional Plant Biology, 39, 839, https://doi.org/10.1071/FP12049, 2012.

Pütz, T., Fank, J., and Flury, M.: Lysimeters in Vadose Zone Research, Vadose Zone Journal, 17, 1–4, https://doi.org/10.2136/vzj2018.02.0035, 2018.

Richter, D. d. B. and Mobley, M. L.: Monitoring Earth's Critical Zone, Science, 326, 1067–1068, https://doi.org/10.1126/science.1179117, 2009.

Rillig, M. C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C. A., Buchert, S., Wulf, A., Iwasaki, A., Roy, J., and Yang, G.: The Role of Multiple Global Change Factors in Driving Soil Functions and Microbial Biodiversity, Science, 366, 886–890, https://doi.org/10.1126/science.aay2832, 2019.

Rineau, F., Malina, R., Beenaerts, N., Arnauts, N., Bardgett, R. D., Berg, M. P., Boerema, A., Bruckers, L., Clerinx, J., Davin, E. L., De Boeck, H. J., De Dobbelaer, T., Dondini, M., De Laender, F., Ellers, J., Franken, O., Gilbert, L., Gudmundsson, L., Janssens, I. A., Johnson, D., Lizin, S., Longdoz, B., Meire, P., Meremans, D., Milbau, A., Moretti, M., Nijs, I., Nobel, A., Pop, I. S., Puetz, T., Reyns, W., Roy, J., Schuetz, J., Seneviratne, S. I., Smith, P., Solmi, F., Staes, J., Thiery, W., Thijs, S., Vanderkelen, I., Van Landuyt, W., Verbruggen, E., Witters, N., Zscheischler, J., and Vangronsveld, J.: Towards More Predictive and Interdisciplinary Climate Change Ecosystem Experiments, Nature Climate Change, 9, 809–816, https://doi.org/10.1038/s41558-019-0609-3, 2019.

Roy, J., Rineau, F., De Boeck, H. J., Nijs, I., Pütz, T., Abiven, S., Arnone, J. A., Barton, C. V. M., Beenaerts, N., Brüggemann, N., Dainese, M., Domisch, T., Eisenhauer, N., Garré, S., Gebler, A., Ghirardo, A., Jasoni, R. L., Kowalchuk, G., Landais, D., Larsen, S. H., Leemans, V., Le Galliard, J.-F., Longdoz, B., Massol, F., Mikkelsen, T. N., Niedrist, G., Piel, C., Ravel, O., Sauze, J., Schmidt, A., Schnitzler, J.-P., Teixeira, L. H., Tjoelker, M. G., Weisser, W. W., Winkler, B., and Milcu, A.: Ecotrons: Powerful and Versatile Ecosystem Analysers for Ecology, Agronomy and Environmental Science, Global Change Biology, 27, 1387–1407, https://doi.org/10.1111/gcb.15471, 2021.

Sánchez-Cañete, E. P., Barron-Gafford, G. A., and Chorover, J.: A Considerable Fraction of Soil-Respired CO2 Is Not Emitted Directly to the Atmosphere, Scientific Reports, 8, 13 518, https://doi.org/10.1038/s41598-018-29803-x, 2018.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., and Turner, B.: Getting the Message Right on Nature-based Solutions to Climate Change, Global Change Biology, 27, 1518–1546, https://doi.org/10.1111/gcb.15513, 2021.

Smerdon, B. D.: A Synopsis of Climate Change Effects on Groundwater Recharge, Journal of Hydrology, 555, 125–128, https://doi.org/10.1016/j.jhydrol.2017.09.047, 2017.

Stewart, R. I., Dossena, M., Bohan, D. A., Jeppesen, E., Kordas, R. L., Ledger, M. E., Meerhoff, M., Moss, B., Mulder, C., Shurin, J. B., Suttle, B., Thompson, R., Trimmer, M., and Woodward, G.: Mesocosm Experiments as a Tool for Ecological Climate-Change Research, in: Advances in Ecological Research, vol. 48, pp. 71–181, Elsevier, ISBN 978-0-12-417199-2, https://doi.org/10.1016/B978-0-12-417199-2.00002-1, 2013.

Vanderkelen, I., Zscheischler, J., Gudmundsson, L., Keuler, K., Rineau, F., Beenaerts, N., Vangronsveld, J., Vicca, S., and Thiery, W.: A Novel Method for Assessing Climate Change Impacts in Ecotron Experiments, International Journal of Biometeorology, 64, 1709–1727, https://doi.org/10.1007/s00484-020-01951-8, 2020.

Vaughan, P. J., Trout, T. J., and Ayars, J. E.: A Processing Method for Weighing Lysimeter Data and Comparison to Micrometeorological ETo Predictions, Agricultural Water Management, 88, 141–146, https://doi.org/10.1016/j.agwat.2006.10.008, 2007.

Vialet-Chabrand, S., Matthews, J. S., Simkin, A. J., Raines, C. A., and Lawson, T.: Importance of Fluctuations in Light on Plant Photosynthetic Acclimation, Plant Physiology, 173, 2163–2179, https://doi.org/10.1104/pp.16.01767, 2017.

White, T., Brantley, S., Banwart, S., Chorover, J., Dietrich, W., Derry, L., Lohse, K., Anderson, S., Aufdendkampe, A., Bales, R., Kumar, P., Richter, D., and McDowell, B.: The Role of Critical Zone Observatories in Critical Zone Science, in: Developments in Earth Surface Processes, vol. 19, pp. 15–78, Elsevier, ISBN 978-0-444-63369-9, https://doi.org/10.1016/B978-0-444-63369-9.00002-1, 2015.