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High-resolution carbon cycling data from 2019 to 2021 measured at six Austrian long-term ecosystem research sites

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Abstract. Seven long-term observation sites have been established in six regions across Austria, covering major ecosystem types such as forests, grasslands, and wetlands across a wide bioclimatic range. The purpose of these observations is to measure key ecosystem parameters serving as baselines for assessing the impacts of extreme climate events on the carbon cycle. The datasets collected include meteorological variables, soil microclimate, CO_2 fluxes, and tree stem growth, all recorded at high temporal resolution (15–60 min) between 2019 and 2021 (including 1 year of average climate conditions and 2 comparatively dry years). The DOIs of the dataset can be found in the "Data availability" section. The sites will be integrated into the European Research Infrastructure for Integrated European Long-Term Ecosystem, Critical Zone, and Socio-Ecological Research (eLTER RI). Subsequently, new data covering the variables presented here will be continuously available through the data integration portal. This step will allow the data to reach their full potential for research on drought-related ecosystem carbon cycling.

1 Introduction

Climate change has been affecting ecosystems globally, with serious implications for the terrestrial carbon (C) cycle, which in turn feeds back into the climate system (Heimann and Reichstein, 2008). As an emerging feature of climate change, extreme climate events (ECEs) are expected to occur with increasing frequency and intensity in the coming decades (IPCC, 2021). ECEs are considered to exert higher impacts on ecosystems and the services they provide to humankind than gradual changes in the climate (Frank et al., 2015; Reichstein et al., 2013; Grünzweig et al., 2022; Anderegg et al., 2020). Understanding, predicting, and managing extreme climate events and their consequences for ecosystems and societies will therefore be one of the big challenges in the coming decades. To detect and attribute the impacts of ECEs on ecosystem processes and services, they need to be evaluated against the background of the typical interannual range of these processes (Ciais et al., 2005; Bernal et al., 2012; Fu et al., 2020; Schindlbacher et al., 2012), and analyses of ecosystem resilience to ECEs require robust quantification of baselines of ecosystem functioning (Bahn and Ingrisch, 2018; Ingrisch and Bahn, 2018). To derive such baselines and the interannual variability of ecosystem carbon cycling, coordinated and representative observation networks need to be in place to enable data retrieval and rapid-response scientific campaigns to study the after-effects and post-disturbance trajectories resulting from ECEs (Kulmala, 2018; Mahecha et al., 2017; Mirtl et al., 2018; Dirnböck et al., 2019; Müller and Bahn, 2022). Datasets obtained through such observation networks are also essential for benchmarking models (Futter et al., 2023; Baatz et al., 2021; Wu et al., 2018) and for comparison with ecosystem experiments (Kröel-Dulay et al., 2022).

Within a research infrastructure project focusing on ecosystem carbon, nitrogen, and water fluxes, i.e., Long-Term Ecosystem Research for Carbon, Water, and Nitrogen (LTER-CWN, https://www.lter-austria.at/cwn/, last access: 1 March 2024), we equipped seven long-term observation sites in six regions, which are part of the existing Long-Term Ecological Research Network of Austria (LTER-Austria), with high temporal resolution (30–60 min) C cycle measurements. The sites cover three major ecosystem types occurring across Austria (forests, managed mountain grassland, and wetlands), and most of them are part of socio-ecological research platforms for transdisciplinary studies (Fig. 1). Here, we provide observational ecosystem response data capturing naturally occurring ECEs from the first 3 years after the creation of the infrastructure (2019 to 2021). These datasets include meteorological variables, soil microclimate, CO_2 flux measurements using automated chambers (soil CO_2 efflux), eddy covariance techniques (net ecosystem exchange), and tree stem radial increments and shrinkage in forested plots.

2 Site descriptions

The sites are key research infrastructures for ecosystem-related greenhouse gas observations in Austria. They include forests (Klausen-Leopoldsdorf and Rosalia in Lower Austria, Zöbelboden in Upper Austria, and Stubai in Tyrol), mountain grassland (Stubai and Tyrol), and wetlands (Pürgschachen Moor, Styria and the Lake Neusiedl reed belt, and Burgenland). This network of sites covers typical forest, alpine, and wetland ecosystems of central Europe (Fig. 1). Furthermore, the sites represent different geological characteristics, from crystalline rock in the central Alps to limestone in the northern Alps to unconsolidated Holocene sediments in the lowlands. All of the sites are part of the LTER-Austria network and, once officially launched, will be included in the European eLTER RI (https://elter-ri.eu/, last access: 1 March 2024). For a detailed description of the sites, we refer the reader to the Dynamic Ecological Information Management System – Site and dataset registry (DEIMS-SDR) (Table 1).

2.1 Rosalia Forest Demonstration Centre (mixed beech forest)

The Rosalia Forest Demonstration Centre was established in 1972 as a collaboration between the BOKU University, Vienna, Austria, and Austrian Federal Forests, and it covers approximately 1000 ha on the western slopes of the Rosalia Mountains (Rosaliengebirge) in Lower Austria (Fig. 1 and Table 1). The forest contains all the major tree species occurring in Austria, i.e., European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.), larch (*Larix decidua* Mill.), and fir (*Abies alba* Mill.). The altitude ranges from 320 to 725 m a.s.l., and the mean annual temperature and mean annual precipitation are 6.5 °C and 796 mm, respectively. The substrate is mainly composed of crystalline rocks, and the soils are predominantly Cambisols (Working Group WRB, 2015) sporadically combined with Planosols (in plains and on moderate slopes), Fluvisols (in valleys), or podzolic Cambisols (on steep slopes) (Fürst et al., 2021).

The demonstration forest has several experimental and observation sites distributed along its area, including for water, soil, vegetation, and air observations (e.g., Gillespie et al., 2023). A watershed (220 ha) is subject to hydrological observations (Fürst et al., 2021), and the forest is regularly monitored on permanent plots (Gollob et al., 2020). The meteorological data presented here originate from three stations located at 385 (Mehlbeerleiten), 500 (Kuhwald), and 640 m a.s.l. (Heuberg). The C cycle data were measured at a long-term experimental site launched in 2012. The site is located in a pure mature beech stand at 600 m a.s.l. (47°42′26″ N, 16°17′59″ E). It faces northwest, with a slope of approximately 20 %. This experiment focuses on investigating the effect of changing precipitation patterns on soil nitrogen fluxes, soil microbial changes, greenhouse gas efflux, and soil water processes (Leitner et al., 2017; Liu et al., 2019; Schwen et al., 2015; Gillespie et al., 2024). Monitoring is performed on control and manipulated plots. The data from both natural and manipulated plots are published in this paper. Manipulation involves the use of rainout shelters (for simulating drought periods of different lengths) and an irrigation system (for recreating rainfall events of different intensities). The monitoring infrastructure involves measurements of greenhouse gas (GHG) (N_2O, CH_4, and CO_2) fluxes, soil nutrients (suction cups), and microclimate parameters.

2.2 Klausen-Leopoldsdorf (beech forest)

This site, Klausen-Leopoldsdorf, is located about 40 km southwest of Vienna on a NNE-facing slope and was founded in the 1990s as one of Austria's sites contributing to the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) (Neumann and Starlinger, 2001). The site is divided into four different subareas within a small catchment: (1) the ICP

Forests site, (2) a weather station located 2.7 km from the ICP Forests intensive plots at 398 m a.s.l., (3) a catchment runoff weir (475 m a.s.l.), and (4) the LTER-CWN measurement plot (520 m a.s.l.), where the C cycle data presented here were measured (Fig. 1 and Table 1). The forest within the measurement plot is a pure beech (*Fagus sylvatica* L.) stand. The mean annual temperature is 8 °C, and the mean annual precipitation is 801 mm (2010–2022). The geological substrate is sandstone, and the soil type is mainly stagnic Cambisol or dystric Cambisol (Working Group WRB, 2015). Instruments installed in the LTER-CWN measurement area include a sap flow and dendrometer measurement system on 10 trees, 12 GHG automated measurement chambers for CO_2 respiration, and soil moisture and soil temperature sensors at different soil depths (5–30 cm).

In addition to the data presented here, many other datasets are available. Soil GHG fluxes (manual sampling) were measured starting in the year 2001 (Kitzler et al., 2006). At the ICP Forests site, instruments for long-term monitoring (since 1996) such as soil moisture, air temperature and relative humidity, soil temperature, soil solution with suction cups, throughfall deposition, litterfall traps, stemflow, and manual and automatic dendrometers have been installed, and the data are available at https://bfw.ac.at/lims/level2.daten (last access: 1 March 2024) or the ICP Forests Program Centre.

2.3 Lake Neusiedl (reed belt)

The measurement site is located in the eastern reed belt of this lake and as such is inside the Lake Neusiedl–Seewinkel National Park (Fig. 1 and Table 1). The region (average altitude 120 m a.s.l.) is characterized by a (sub)continental Pannonian climate with a mean annual precipitation of 576 mm (2013–2022). The reed belt is a dynamic ecosystem consisting of a mosaic of reed stocks (*Phragmites australis* (Cav.) Trin. ex Steud.), sediment, and open-water areas. Increasing dry periods and thus successive drying of the reed belt since 2018 have led to an increase in reed stocks within the belt, an increase in the sediment areas, and a sharp decline in the open-water areas, according to a 2021 study that investigated the spatial and temporal variations within the reed ecosystem at Lake Neusiedl (Buchsteiner et al., 2023). Processes driving CH_4 emissions from the reed belt were recently investigated in detail (Baur et al., 2024).

The data presented here stem from devices permanently installed at the site. They include an eddy covariance tower for CO_2, CH_4, water vapor fluxes, and relevant accompanying meteorological parameters as well as soil heat flux, soil moisture, and soil temperature sensors.

2.4 Pürgschachen Moor (peat bog)

The Pürgschachen Moor is located at the bottom of the Styrian Enns Valley at an altitude of 632 m a.s.l. (Fig. 1 and Table 1). It is a pine peat bog with an area of about 62 ha. Thus, it is the largest (by some distance) intact valley peat bog in Austria, with closed peat moss cover and a good example of the formerly widely distributed peatlands of inner-alpine valleys of the European Alps. The mean average temperature is 8.2 °C, and the mean annual precipitation is 1233 mm (2013–2022). The typical vegetation of the peat bog is constituted of three associations of plants, i.e., *Pino mugo-Sphagnetum magellanici* (pine peat bog association), *Sphagnetum magellanici* (colored bog moss association), and *Caricetum limosae* (bog sedge association), depending on the prevailing hydrological site conditions. The current mean water table depth is about 14 cm below the soil surface in the central peat bog area. Peat decomposition and the related CO_2 and CH_4 fluxes were the subject of a series of research studies (Drollinger et al., 2019; Knierzinger et al., 2020; Müller et al., 2022; Glatzel et al., 2023).

The data presented here stem from devices permanently installed at roughly the center of the peat bog. They include an eddy covariance tower for CO_2, CH_4, and water vapor fluxes and the relevant accompanying meteorological parameters as well as for soil heat flux, soil moisture, and soil temperature sensors.

2.5 Stubai (subalpine hay meadow, larch and spruce forest)

The two observation plots used in this study are part of the LTER site Stubai (Table 1), which is located in the Stubai Alps in Tyrol, Austria (Fig. 1). Research at the study site began in 1993. The two observation plots are a mountain grassland and a subalpine forest in an alpine pasture area called Kaserstattalm. The underlying rock is siliceous and calcareous. The average air temperature is about 3 °C, and the precipitation is about 1100 mm. About 35 % of the annual precipitation occurs as snow during the winter months.

The grassland site is located at an altitude of 1810–1850 m a.s.l. on a southeast-facing slope with an inclination of about 20°. The site is an extensively managed meadow that is harvested once a year in early August and grazed lightly in late summer. The soil is a dystric Cambisol (Working Group WRB, 2015). The vegetation type is *Trisetetum flavenscensis* and consists of perennial grasses and forbs dominated by *Agrostis capillaris* L., *Festuca rubra* L., *Anthoxanthum odoratum* L., *Ranunculus montanus* Willd., *Leontodon hispidus* L., *Trifolium repens* L., and *T. pretense* L. (Bahn et al., 2009; Schmitt et al., 2010).

The forested observation plot is located close to the treeline at 1960 m a.s.l. on a slope with an inclination of 20–35°. It is dominated by the two common tree species European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) H. Karst.). In previous years, the plot was a pasture, and it was reforested in the 1980s (Oberleitner et al., 2022).

Both observation plots are equipped with micrometeorological stations, soil environment monitoring (soil moisture and soil temperature), and soil CO_2 devices. At both observation plots, we measured soil CO_2 fluxes with automated chambers during the summer. The forest plot is additionally equipped with tree dendrometers and tree sap flow sensors. In the grassland, land use and drought-related carbon cycle research was carried out over the last 2 decades (Fuchslueger et al., 2014; Hasibeder et al., 2015; Ingrisch et al., 2020; Ingrisch et al., 2018). Research using the forest plot started only recently (Oberleitner et al., 2022).

2.6 Zöbelboden (mixed beech forest)

The LTER Zöbelboden site is located in Kalkalpen National Park in the Northern Limestone Alps, Austria (Fig. 1). Measurements began in 1992 as part of ICP on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM), covering a 90 ha catchment with an elevation range of 550–956 m a.s.l. (Table 1). The main underlying rock type is Norian dolomite (*Hauptdolomit*) partly overlain by limestone (*Plattenkalk*). According to long-term meteorological measurements (1993–2022), the mean annual air temperature and precipitation are 8.2 °C and 1645 mm, respectively. Maximum precipitation occurs in summer and snowfall usually between December and April.

The data presented here were measured at Intensive Plot II, which is located on a steep (36° on average) northwesterly-exposed slope at 880 m a.s.l. The soils of the plot are lithic and rendzic Leptosols (Working Group WRB, 2015). The plot is dominated by beech (*Fagus sylvatica* L.) with intermixed sycamore (*Acer pseudoplatanus* L.), European ash (*Fraxinus excelsior* L.), and spruce (*Picea abies* (L.) H. Karst.). Since the year 1995, this plot has been equipped with a number of field measurement devices for long-term monitoring (throughfall deposition, litterfall traps, lysimeters, soil moisture and temperature sensors, and manual dendrometers) and supplemented by other monitoring characteristics (tree inventory, needle and leaf chemistry, and soil chemistry; see, e.g., Leitner et al., 2020; Kobler et al., 2019; Dirnböck et al., 2016; Dirnböck et al., 2020). Drought impacts on carbon allocation in the forests of the catchment currently form one of the research foci for which long-term observation data exist (see, e.g., Hartl-Meier et al., 2014), together with experimental plots with rainout shelters.

The instruments and data included here are soil respiration automated chambers, soil water potential, temperature sensors, and automated dendrometers. The meteorological data stem from a station in close proximity to the plateau at 890 m a.s.l. The site is also equipped with an eddy covariance tower, but these data will be published elsewhere.

3 Dataset description, measuring methods, quality assurance (QA), and quality control (QC)

We followed routine QA and QC procedures to ensure functionality of the sensors and data quality comprising remote function control, on-site check of sensors and cables, regular sensor calibration, data checks through different quality assurance procedures (e.g., exceedance of thresholds, outlier detection, or deviations from other measurements), and data quality flagging.

3.1 Meteorology, soil temperature, and soil moisture

All the meteorological stations are located within the boundaries of the respective sites, except for Klausen-Leopoldsdorf, where the station is a distance of 2.7 km from the site. Meteorological measurements at the wetland sites were implemented next to the eddy covariance tower. In addition to the routine data checks, we compared the measurements with nearby stations where appropriate. Meteorological measurements were detected at a 1 min interval and averaged over half-hour periods, while the rain data were summed. The measurements include air temperature, precipitation, relative humidity, wind speed and direction, air pressure, and several radiation variables (at least global radiation but also shortwave and longwave radiation and photosynthetically active radiation).

We used different types of soil temperature and soil moisture or soil water potential sensors (PT100 or thermoelements for soil temperature, TDR or FDR sensors for soil moisture, and soil water potential sensors). Before we buried the soil temperature or soil moisture and soil water potential sensors in the soil, they had been calibrated or at least tested for consistency. Mostly, we used gravimetric samples to calibrate the TDR and FDR soil moisture sensors. At Zöbelboden, where stony, organic-rich soils are found, we corrected the TDR values using water potential sensor data installed in the same soil profiles together with soil water retention functions derived from undisturbed soil cores. In addition to the regular QC procedures, we checked the data for consistency of the values across the sensors (e.g., along the soil profiles) and compared them with other measurements (air temperature and precipitation). Half-hourly to hourly values are presented.

3.2 Carbon fluxes

3.2.1 Soil CO_2 efflux

We measured soil CO_2 efflux at five of the seven observation plots. The automated soil CO_2 respiration measurement systems are capable of operating autonomously during the snow-free periods. The measurement chambers and measurement systems collected air continuously from the chamber headspace to determine the exchange of CO_2 between the soil and atmosphere at the observation plots. At all the sites, we used non-steady-state, non-throughflow chambers (Pumpanen et al., 2004). The chambers at each site measured consecutively every half-hour to hour. In addition to the automated systems, manual flux measurements were also performed, which served to validate the automated measure-

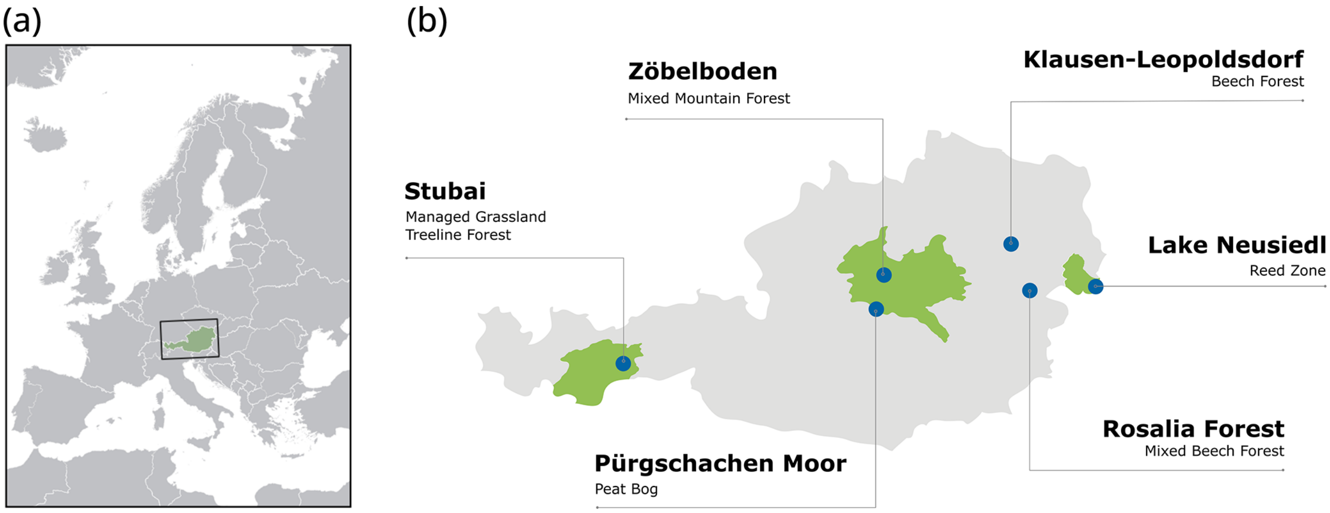

Figure 1. Locations of the sites in **(a)** Europe and **(b)** Austria. The blue dots indicate the sites; the green areas are long-term socio-ecological research platforms (LTSERs) (from left to right: LTSER Tyrolian Alps, LTSER Eisenwurzen, and LTSER Lake Neusiedl) within the LTER-Austria network. For site information about the altitude and climate, see Table 1.

Table 1. Ecosystem type, altitude, climate, and metadata links of the sites and observation plots. Geographic boundaries and linked datasets can be found in the site and dataset registry system (DEIMS-SDR).

Site	Ecosystem type	Altitude (m a.s.l.)	Annual temperature (°C)	Annual precipitation (mm)	Site and observation plot	DEIMS ID
Rosalia Forest Demonstration Centre (ROS)	Mixed beech forest	600	6.5	796	Site	https://deims.org/77c127c4-2ebe-453b-b5af-61858ff02e31*
					Heuberg Meteorological Station	https://deims.org/locations/44854b32-64c3-4c9d-9aec-9b0b74f8ac70*
					Kuhwald Meteorological Station	https://deims.org/locations/1225d57e-02da-47fd-9760-ab39d64999ef*
					Mehlbeerleiten Meteorological Station	https://deims.org/locations/0becf0ce-98d7-4f64-a074-f89046083e5e*
					Experimental station	https://deims.org/locations/b7008603-fca2-452f-9b3d-aad30cdafc7a*
Klausen-Leopoldsdorf (KLL)	Beech forest	520	8	801	Site	https://deims.org/bb472a51-f85f-4de0-8358-f21ecbe2a102*
					Measuring station	https://deims.org/locations/d5cba3ce-7489-46d1-8d97-61641ffb5758*
Lake Neusiedl (NSS)	Reed zone	120	11.5	576	Same as the site	https://deims.org/locations/4234987b-9031-4332-9bdd-f869d503ac51*
Pürgschachen Moor (PUE)	Peat bog	632	8.2	1233	Same as the site	https://deims.org/locations/ab2d021b-f318-487a-a85b-ab34566e4c02*
Stubai (KAS)	Grassland	1830	3	1100	Site	https://deims.org/324f92a3-5940-4790-9738-5aa21992511c*
					Kaserstattalm meadow	https://deims.org/locations/cf7843b7-32d6-44e9-ba82-9a8d915036a7*
	Treeline forest	1960	3	1100	Kaserstattalm forest	https://deims.org/locations/af2afdad-d6fb-4580-b6e3-be7d07b56f8e*
Zöbelboden (ZOE)	Mixed mountain forest	880	8.2	1645	Site	https://deims.org/8eda49e9-1f4e-4f3e-b58e-e0bb25dc32a6*
					Intensive Plot II	https://deims.org/locations/bc96a499-1b20-4da8-be2d-17306d64b788*

* Last access: 1 March 2024.

Table 2. Meteorological parameters measured at the six sites during 2019–2021. Availability is indicated using the ticks. For the parameter names, we refer to the thesaurus at http://vocabs.lter-europe.net/EnvThes/ (last access: 1 March 2024).

Meteorological parameter	KAS	KLL	NSS	PUE	ROS	ZOE
Air relative humidity	✓	✓	✓	✓	✓	✓
Air pressure	✓				✓	✓
Air temperature	✓	✓	✓	✓	✓	✓
Precipitation amount	✓	✓	✓	✓	✓	✓
Global radiation irradiance		✓	✓	✓	✓	✓
Net radiation irradiance			✓	✓		✓
Photosynthetically active radiation	✓		✓	✓		✓
Sunshine duration						✓
Wind direction	✓	✓			✓	✓
Wind speed	✓	✓			✓	✓

ment systems. Table 3 provides detailed information on the measurement systems used at the sites.

Two different automated chamber systems were used: a LI-COR system and custom-made chambers in combination with LI-COR trace gas analyzers (Table 3). The custom-made soil chambers are equipped with a fan and a thermometer. The controlling unit and the gas analyzer (a CH_4 and CO_2 LI-COR 7810, a LI-COR 840, or a LI-COR 8100A; LI-COR Biosciences, USA) are located in already existing measurement containers. Remote access to the devices allows the plausibility of the data and chamber leakage to be checked in real time. We visited the instruments at weekly to monthly intervals, with maintenance and supervision work that included checks of the tightness of the gas lines, connections, and chamber lids; correct closing and opening of the chambers; and the functioning of ventilation fans inside the chambers, the ingrowth of the plants, and the gas analyzers. The gas analyzers were calibrated once a year in the laboratory with calibration gases. We uninstalled and serviced the chambers during winter, but the frames stayed permanently on site to avoid disturbance of the soil.

At Klausen-Leopoldsdorf, the gas fluxes of readings were determined using the R package gasfluxes (Fuss, 2020). At Rosalia, a custom-made Python script was used. Zöbelboden and Kaserstattalm processed the data with SoilFluxPro software (LI-COR Biosciences, 2019). We used the R^2 values of the fitted empirical models to select valid data. We refer the reader to Table 3 and the metadata published with the data for detailed specifications.

3.2.2 Eddy covariance measurements at the wetland sites

At both wetland sites, Pürgschachen Moor and Lake Neusiedl, fully equipped eddy covariance systems are in place. Wind speed and direction were measured using a three-axis ultrasonic anemometer (WindMaster Pro, Gill Instruments; Lymington, UK). CO_2 and H_2O mixing ratios were measured using the closed-path infrared gas analyzer LI-7200, and CH_4 was detected with the open-path gas analyzer LI-7700 (both LI-COR Inc; Lincoln, USA). The measurements were taken with a sampling rate of 10 Hz. We installed the devices at vegetation-dependent heights, i.e., 3.05 m a.g.l. in Pürgschachen Moor and 8.6 m a.g.l. in the reed belt of Lake Neusiedl. The eddy covariance devices were checked daily via remote access and calibrated once a year in the lab and monthly in the field.

The data contain half-hourly eddy covariance flux measurements for CO_2, CH_4, and water vapor. We calculated the fluxes with the EddyPro® software package in express mode with default settings (double rotation, block averaging, and covariance maximization) as part of the SmartFlux® 2 system, providing fully corrected and valid fluxes with quality flags ranging from 0 to 2. The final flags are based on a combination of partial flags accounting for steady-state and turbulent conditions. Only fluxes flagged with 0 (best-quality fluxes) or 1 (fluxes suitable for general analysis, such as annual budgets) are shown in the data. Gaps in the dataset result from missing micrometeorological conditions from data cleaning due to the quality flags or power breakdowns.

3.3 Radial tree stem growth at forest sites

Zöbelboden, Klausen-Leopoldsdorf, and Rosalia used the DR26 sensor (EMS; Brno, Czech Republic), and Stubai used Ecomatic DC2 (Germany) to register the radial stem increment in a 15 to 30 min interval. Maintenance involved avoiding any shift of the sensor during the operation. Concerning data quality and control methods, the Mini32 software (EMS; Brno, Czech Republic) includes graphical features for processing the measured stem increment data. Data processing comprises outlier detection by visual assessment based on expert knowledge. Ecomatic raw data were treated with custom-made R scripts. In both cases, unrealistic values beyond the slowly increasing linear growth rates were assessed visually and deleted.

Table 3. Specifications of the different soil CO_2 flux systems following the standard of Bond-Lamberty et al. (2021).

Field name	Description	Unit	Klausen-Leopoldsdorf	Stubai grassland	Rosalia	Zöbelboden
System			Auto	Auto	Auto	Auto
GHG chambers			Custom-made ($n = 12$)	LI-8100-104 ($n = 4$)	Custom-made ($n = 12$)	LI-8100-104 ($n = 6$)
INSTRUMENT	Measurement instrument model		LI-COR LI-7810	LI-8100A	LI-840	LI-8100A
MSMT_VAR	Type of flux measured		Soil respiration (Rs)			
AREA	Soil surface measurement area	cm^2	2500	317.8	2500	317.8
VOLUME	Volume of the measurement chamber	cm^3	37 500	4076.1	37 500	4076.1
V/A	Volume / area ratio	cm	15	12.83	15	12.83
COLLAR_DEPTH	Depth of collar insertion	cm	5	2	10	2
OPAQUE	Opaque chamber		No	Yes	No	Yes
Chamber system	Static chamber – closed or open		Non-steady state, non-throughflow chambers			
Closing time	Closing time of the chamber (time used for flux calculation)	s	175	Depending on the year	1620	210
PLANTS_REMOVED	Plants removed from inside the collar		No, but hardly any	Yes	No, but hardly any	No plants
flow_rate	Sample flow rate through tubing	$L\,min^{-1}$	1	1 to 2	0.25	1.7
FAN	Mixing fan in the chamber?		Yes	No	Yes	No
CRVFIT_CO2	Flux computation method ("Lin" or "Exp" for linear and exponential; others)		Linear	Automated[1]	Lin or HMR[2]	Automated[1]
R2_CO2	R^2 of flux computation	Fraction	0.90	0.95	0.95	0.99
Calculation of flux			R package gasfluxes	LI-COR Soilflux Pro	Custom-made Python script	LI-COR Soilflux Pro

[1] "Exp" in the data indicates that the exponential fit was better than the linear fit (Exp_SSN < Lin_SSN). "Lin" indicates that the linear fit was better after the maximum number of iterations; the nonlinear coefficients have therefore been derived from the linear fit. [2] Hutchinson and Mosier (1981).

4 Data file structure

We used the eLTER RI data specification that is available on Zenodo (https://www.doi.org/10.5281/zenodo.6373409, Peterseil and Geiger, 2020). Apart from the data files, the measurement locations (station files) and sensors (methods) are included.

5 Data validation

We used the gridded SPEI (Standardized Precipitation Evapotranspiration Index) from the Austrian Meteorological Service (https://data.hub.geosphere.at/dataset/winfore-v2-1d-1km; Haslinger and Bartsch, 2016) to compare the long-term average water availability during the growing season (1980–2010; May to September) with those in the measurement years (Table 4). The advantage of the SPEI is that it accounts for precipitation and temperature via evapotranspiration and integrates this over a given temporal window (we used 30 d) (Vicente-Serrano et al., 2010). Note that the gridded SPEI dataset is based on meteorological data for the period 1960 to 2021. Accordingly, the year 2021 was closest to the long-term average, the year 2020 was a particularly wet year, and the year 2019 was drier than the average. However, there were differences between the sites: in particular, the mountain station in the Tyrolian Alps (Kaserstattalm forest – KAS) did not experience significant deviations from the SPEI compared to the long-term average, apart from a wet growing season in 2021. The SPEI at the site in the Viennese Forest (Klausen-Leopoldsdorf – KLL) does not indicate that, in 2019, the growth period was particularly dry.

The monthly precipitation and temperature patterns are shown in Fig. 2, and the soil water content and soil temperatures are shown in Figs. 3 and 5. Differences in the seasonal precipitation patterns between the measurement years vary a lot between the sites. In summary, lower precipitation occurred in 2019 and 2021 than in 2020 at all the sites. The mean annual temperature maxima (90th percentile) were 0.3 (KAS) and 2.3 °C (ZOE) higher in the year 2019 than in 2020. These differences were lower when comparing the year 2021 with 2019 (≤ 0.6 °C). In accordance with the SPEI, precipitation, and temperature, the soil water content showed the

Table 4. Comparison between the long-term (1980–2010) meteorological drought (SPEI – Standardized Precipitation Evapotranspiration Index) and the measurement years during the growing season (May–September). Significant differences between these years and the long-term averages are shown: *** $p<0.001$, ** $p<0.005$, and * $p<0.01$ according to the Mann–Whitney U test. The SPEI was calculated using a 30 d window at daily resolution using gridded data: https://data.hub.geosphere.at/dataset/winfore-v2-1d-1km (last access: 1 September 2024) (Haslinger and Bartsch, 2016). Negative values indicate dry years.

Site code	1980–2010	2019	2020	2021
ZOE	-0.05 ± 0.94	$-0.49 \pm 1.22^{***}$	$0.42 \pm 0.69^{***}$	-0.02 ± 1.39
KLL	-0.01 ± 0.99	-0.23 ± 1.22	$0.39 \pm 0.86^{***}$	-0.02 ± 1.24
KAS	-0.05 ± 0.97	-0.1 ± 1.17	-0.12 ± 0.78	$0.23 \pm 1.07^{**}$
PUE	-0.02 ± 0.94	$-0.54 \pm 1.26^{***}$	$0.17 \pm 0.59^{**}$	-0.12 ± 1.2
NSS	-0.01 ± 1	$-0.22 \pm 1.13^{*}$	$0.2 \pm 0.87^{**}$	-0.2 ± 1.34
ROS	-0.03 ± 0.98	$-0.34 \pm 1.01^{***}$	0.17 ± 0.83	-0.28 ± 1.08

lowest values during the year 2019, followed by the year 2021, and the soil temperatures were higher during these years (Figs. 3 and 4).

We measured soil CO_2 respiration at four sites (Fig. 4). The complexity of automated chamber measurements resulted in some data gaps at KAS and ROS during the years 2019 and 2021, respectively. At KLL and ZOE, the respiration data cover most of the snow-free period (see Table 2).

At KLL and ZOE, we compared the automatically measured soil CO_2 flux rates with manual measurements. For both sites, we used a portable infrared gas analyzer (EGM-4) connected to a manual soil respiration chamber (SRC) (PP Systems International Inc., Amesbury, MA, USA). The two measurement sites were equipped with permanently installed collars (KLL: randomly distributed within the site in the immediate vicinity of the automated chambers ($n = 12$), area $= 284\,\mathrm{cm}^2$, and insertion depth 2 cm; ZOE: regular grid covering the entire plot ($n = 30$), area $= 78\,\mathrm{cm}^2$, and insertion depth 1.5 cm). The chamber closure times were 60 and 100 s at KLL and ZOE, respectively. Manual measurements were taken in monthly intervals from October 2019 to June 2020 at KLL as well as from June 2019 to October 2019 (monthly interval) and in July 2020 (diurnal variation) at ZOE. Soil respiration (Rs) was calculated automatically by fitting a linear (KLL) or quadratic (ZOE: quadratic fit for flow rates $>0.2\,\mathrm{ppm\,s}^{-1}$, or a linear fit was used) function to the increasing CO_2 headspace concentration.

The mean CO_2 fluxes of the automated chambers correlated well with the manually measured fluxes during the measurement campaigns (Fig. 3). At KLL, the R^2 value was 0.95 (p value < 0.05, t test), and at ZOE it was 0.85 (p value < 0.05, t test). At both sites, neither the intercept nor the slope was significantly different from 0 (p value > 0.2, t test) or 1 (p value > 0.49, t test), respectively. At ZOE, the spatial flux variation was much higher than at KLL (Fig. 3a and b). This reflects the heterogeneity of the soil conditions (shallow rendzic Leptosols with interspersed fine-scale patches of deeper soils), the canopy gaps (with lower root density), and the uneven distribution of litter due to the steep slope of the plot (Kobler et al., 2019). This heterogeneity is more effectively captured by the manual measurement ($n = 30$) than by the automated chambers ($n = 6$). In summary, we conclude that the spatial variation in CO_2 fluxes was higher at both sites than the difference in fluxes caused by the measurement devices (Fig. 3).

Soil CO_2 fluxes are temperature-dependent and thus follow the seasonal changes in soil temperature (Fig. 4). Their additional limitation through soil water availability for plant metabolism and microbial activity is usually much less pronounced in these temperate-zone ecosystems (Bahn et al., 2008; Chen et al., 2014). For a detailed interpretation of the CO_2 respiration fluxes and their limiting factors, we refer the reader to the citations listed in the “Site descriptions” section. Drollinger et al. (2019) provide interpretations of the patterns of CO_2 and CH_4 fluxes, measured using eddy covariance techniques at the bog site Pürgschachen Moor (PUE). Likewise, Baur et al. (2024) provide interpretations for the reed belt of Lake Neusiedl (NSS). Stem growth limitations can, on the other hand, be closely related to soil water content, particularly at sites with relatively low precipitation, such as KLL (Fig. 6). For an in-depth study of drought-related effects on tree growth at the treeline forest at Kaserstattalm (KAS), we refer the reader to Oberleitner et al. (2022).

6 Data availability

6.1 Data access

The data and metadata are accessible at B2SHARE (https://b2share.eudat.eu/, last access: 1 March 2024), a service provided by the EUDAT Collaborative Data Infrastructure. The DOIs of the datasets are listed in Table 5. The site metadata in DEIMS-SDR (Table 1) are part of the data, so the site information can be accessed easily. In chapter 8, we provide a Jupyter notebook to download and merge the single datasets and to visualize the parameters.

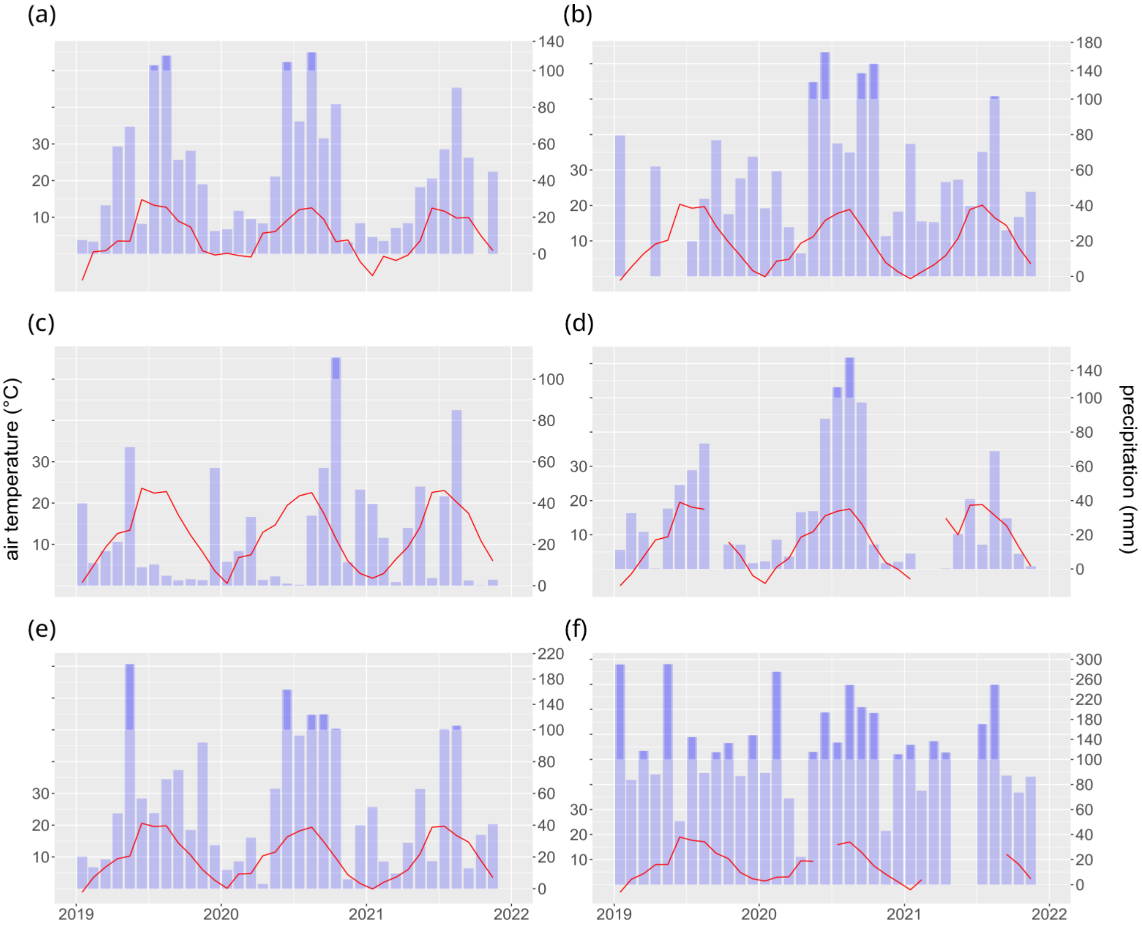

Figure 2. Monthly mean air temperature (red line) and monthly precipitation sums (blue bars; different scales >100 mm) in the six regions.

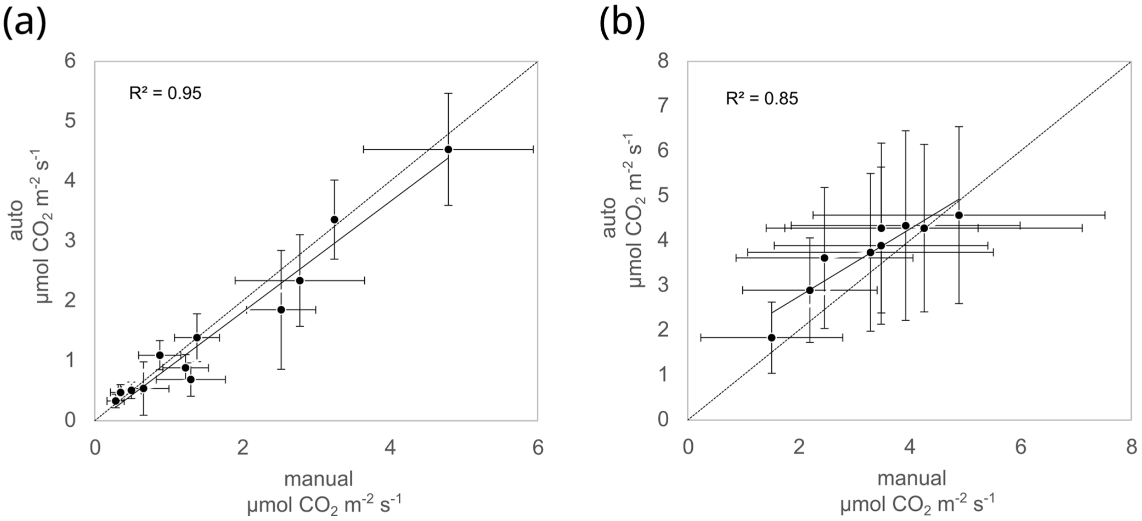

Figure 3. Comparison of automated and manual soil CO_2 fluxes at **(a)** Klausen-Leopoldsdorf and **(b)** Zöbelboden. See Table 3 for the specification of the automated chamber data. The error bars indicate the spatial variation (standard deviations).

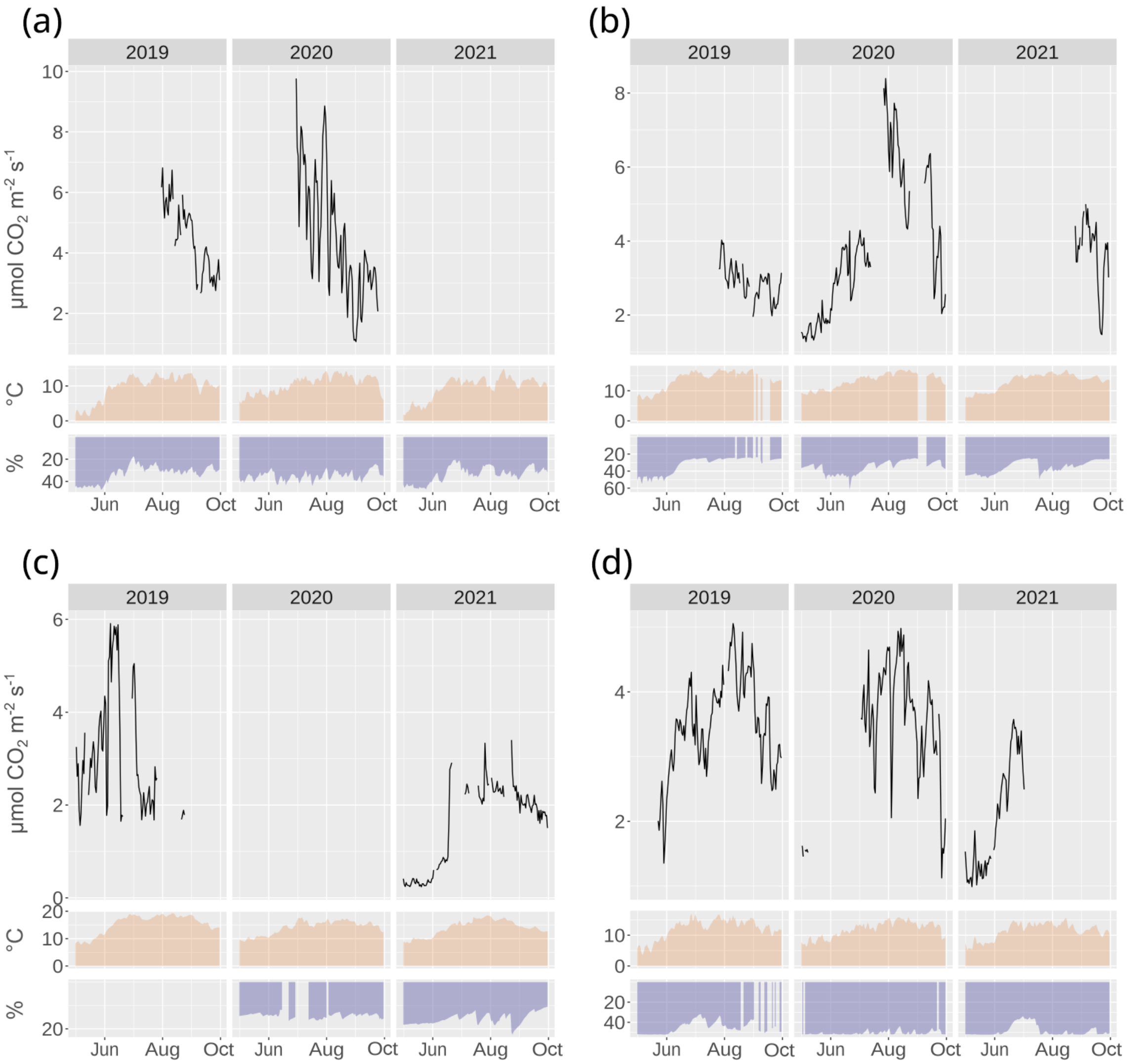

Figure 4. Soil CO_2 respiration (mean of all the chambers), soil temperature (mean of the sensors at 5–15 cm depth), and soil water content (mean of the sensors at 5–15 cm depth) at the forested sites Kaserstattalm forest (KAS), Klausen-Leopoldsdorf (KLL), Rosalia (ROS), and Zöbelboden (ZOE).

6.2 Data visualization and workflow integration

The software stack used to store, import, and quality-control the data provided is built in a PostgreSQL database with a post-GIS extension. The database structure is derived from the Time Series Management (TSM) system developed by the Research Center Jülich (Wohner et al., 2021) and was originally deployed within the LTER-CWN project, but it was re-purposed to better fit the needs of the data management and working group. Now, to import and quality-control the data, a number of Python scripts deployed in a Jupyter environment are used. This also includes scripts for visualizing the data on the fly in Jupyter.

7 Discussion

We provide baseline ecosystem data related to the carbon cycle and capture naturally occurring ECEs across various ecosystem types typical of Austria and other regions of central Europe. Such datasets are scarce because the measurements are demanding in terms of maintenance and funding. Automated soil respiration data at a high temporal resolution, as we report here, are rare too owing to a lack of dedicated monitoring or research infrastructures (Bond-Lamberty et al., 2021). However, soil CO_2 respiration constitutes the second-largest flux in the global carbon cycle and hence is key in estimating ecosystem responses to ECEs (Bond-Lamberty and Thomson, 2010). In addition, we provide soil temperature and moisture measurements at the same resolution, these being key variables determining soil respiration

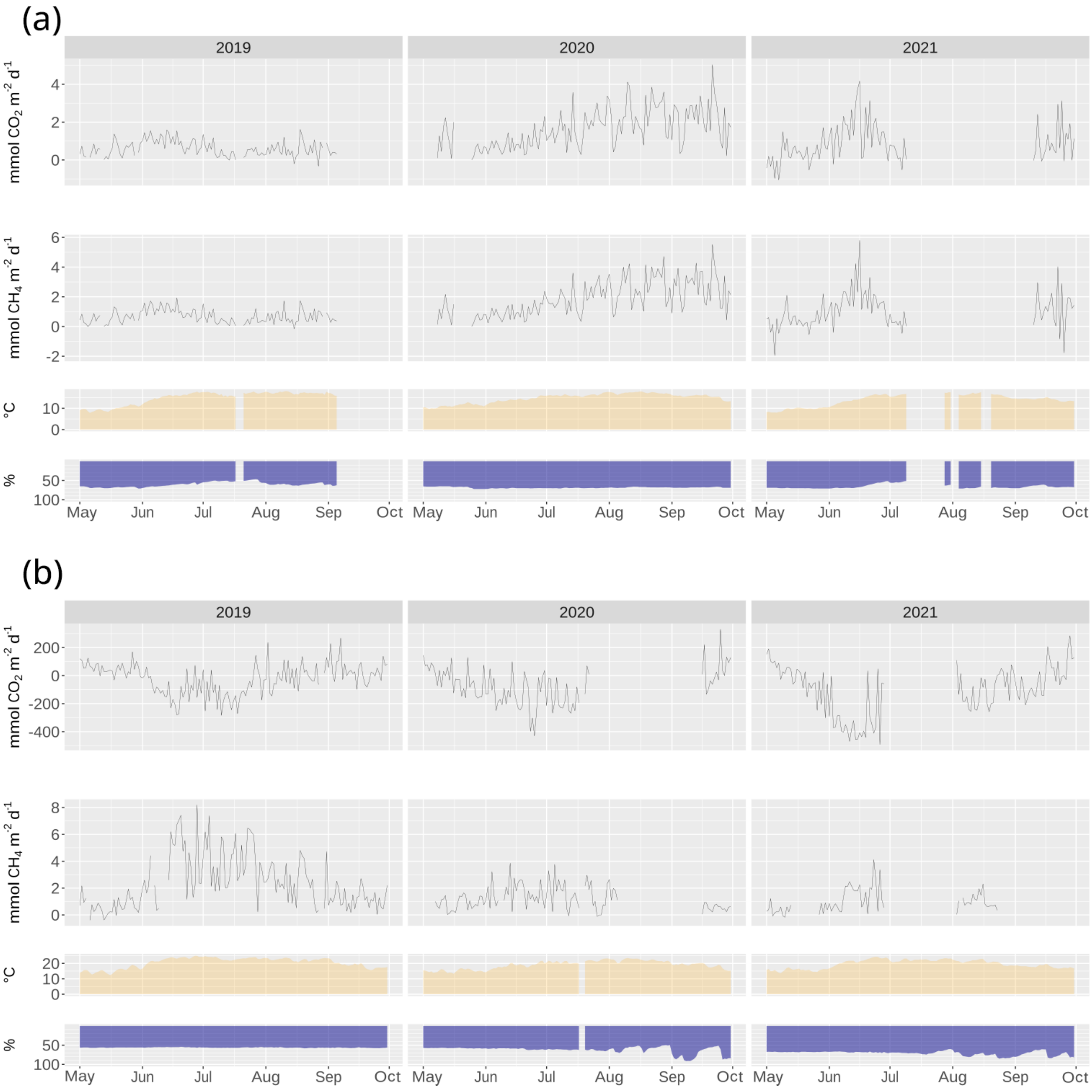

Figure 5. CO_2 and CH_4 fluxes at the sites Pürgschachen Moor peat bog (PUE) and Lake Neusiedl reed zone (NLL), together with their temperature and soil water content.

(Pumpanen et al., 2015). High-resolution measurements of tree stem circumference have been developed as complementary data to relate drought stress to changes in carbon allocation in trees (Zweifel, 2016; Zweifel et al., 2021). The microclimatic, soil, and tree physiological data are complemented by CO_2 and CH_4 fluxes between the vegetation and the atmosphere measured with eddy covariance techniques of the two wetland sites.

Our data are particularly useful for drought-related research. Triggered by the pan-European drought of 2003 (Ciais et al., 2005), a key scientific question has been how droughts affect greenhouse gas sinks and sources in ecosystems (Rödenbeck et al., 2020; Reichstein et al., 2013; Anderegg et al., 2020). Droughts usually reduce soil respiration due to the decrease in autotrophic respiration but also because soil microbial activity drops due to water limitation (Grünzweig et al., 2022). Furthermore, rewetting can result in pulses of high soil respiration (Borken and Matzner, 2009). Drought effects on the ecosystem C cycle can persist for years (Kannenberg et al., 2020; Müller and Bahn, 2022), and novel approaches are being developed to assimilate high-resolution data for understanding and quantifying such legacies (Yu et al., 2022; Fu et al., 2020). In this context, the availability of long-term, high-resolution measurements of key ecosystem parameters is key to understanding and quantifying the effects of recurrent droughts (Oberleitner et al., 2022). While the 3-year data with the usual measurement gaps occurring in field campaigns in rather difficult

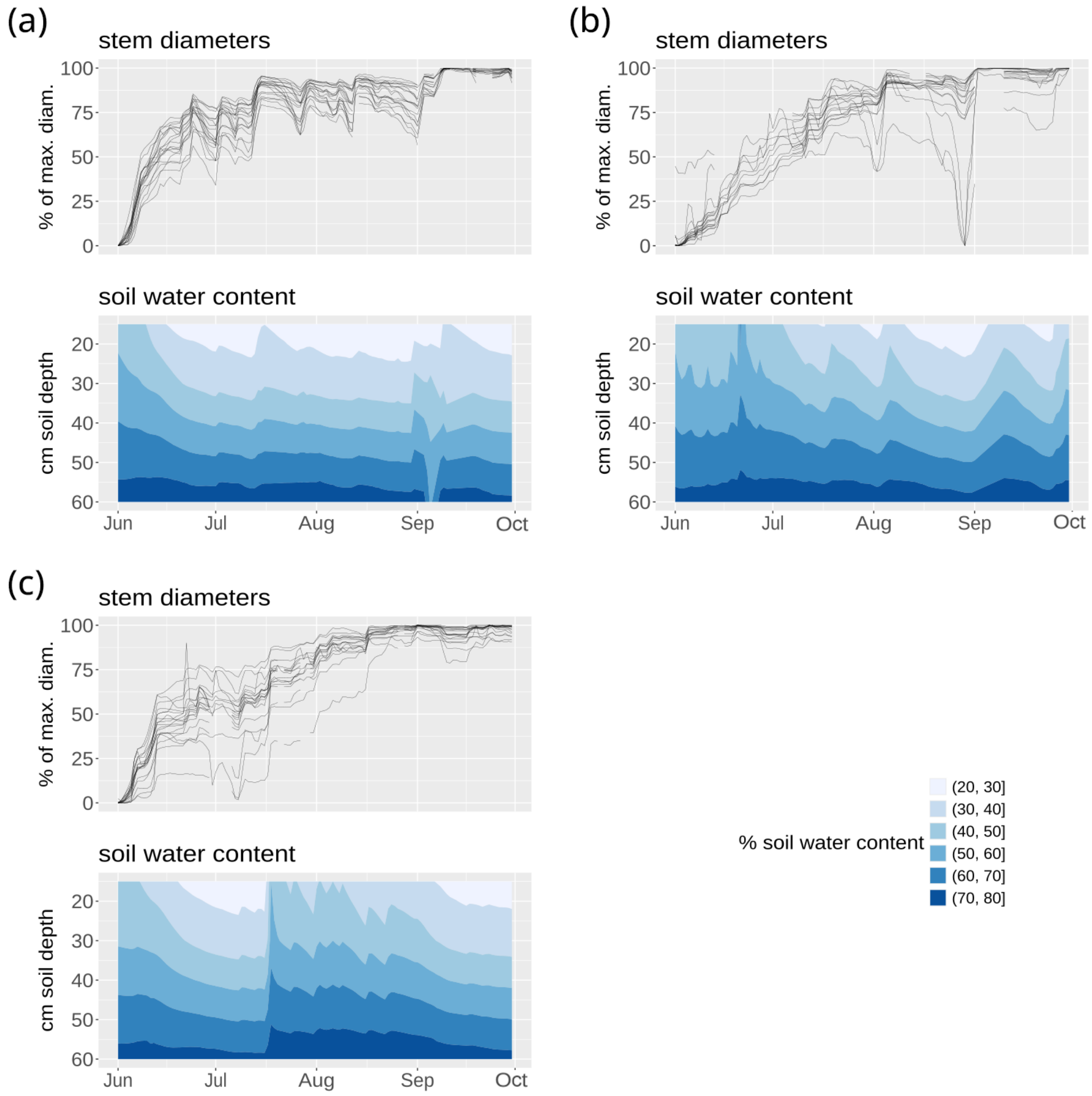

Figure 6. Relative stem diameters and soil moisture at the site Klausen-Leopoldsdorf (KLL) during the years 2019–2021. Stem diameter values were scaled to an annual amplitude of 100.

terrain can only capture aspects of drought-related effects to some extent, they represent a valuable baseline.

The sites presented here are currently being upgraded for implementation in the European Research Infrastructure for Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER RI), together with another ∼ 200 sites in Europe (Mirtl et al., 2018). Climate change impacts on ecosystem processes, including the carbon cycle, are among the targeted research areas that eLTER RI will focus on. The measurements resulting in the data presented here will continue in the future under the umbrella of eLTER RI. Compiling longer-term data series depends on the availability of already validated datasets – as presented here – before eLTER RI is operational. Furthermore, long-term ecosystem observations already exist at these sites with regard to water and the nitrogen cycle, allowing for a contextual interpretation of the trends seen in C-related parameters.

Combining several research and monitoring activities at already heavily instrumented sites not only saves money but also enlarges the data analysis portfolio (Futter et al., 2023; Kulmala, 2018). Even though we provide eddy covariance data for two of our sites, Austria is not part of the Integrated Carbon Observation System (ICOS). A combination of data capturing long-term boundary layer exchange of C with soil C fluxes, microclimate, and, in forests, tree physiological data obviously has great potential (Zweifel et al., 2023; Ramonet et al., 2020). Hence, using the sites simultaneously with other research infrastructures such as ICOS that

Table 5. Dataset DOIs.

Site	Dataset	DOI	Reference
Klausen-Leopoldsdorf	Meteorology	https://doi.org/10.23728/b2share.8f872a37513c4768b16ce755eca4bb57	Gartner et al. (2024a)
	Soil climate	https://doi.org/10.23728/b2share.8d49c0b557f1455a9e66689e035b8cce	Gartner et al. (2024b)
	Soil CO_2 respiration	https://doi.org/10.23728/b2share.5286bd1bc6aa491f874b9bb12d1c5673	Kitzler and Hofbauer (2024)
	Stem increment	https://doi.org/10.23728/b2share.68d84a913f0c4875be5c680ad4d6959e	Gartner and Gollobich (2024)
Rosalia Forest Demonstration Centre	Meteorology	https://doi.org/10.23728/b2share.96c52c247eb846deb2a3ec5e2c27b4f1	Diaz-Pines (2024a)
	Soil climate	https://doi.org/10.23728/b2share.c68143fc11224c44ae5529bd6a35a76d	Diaz-Pines (2024c)
	Soil CO_2 respiration	https://doi.org/10.23728/b2share.d167e727abe947abbc8efc04057557f6	Diaz-Pines (2024b)
	Stem increment	https://doi.org/10.23728/b2share.d0d185f1eb184ae48f6d06ea9aa8dbdf	Diaz-Pines (2024d)
Zöbelboden	Meteorology	https://doi.org/10.23728/b2share.762e665273234b129d09ef017416bcfb	Kobler et al. (2024a)
	Soil climate	https://doi.org/10.23728/b2share.46e19191ce9c427d90f48ce38f56a0e1	Kobler et al. (2024c)
	Soil CO_2 respiration	https://doi.org/10.23728/b2share.4f44006b932142e68981106a016f1f56	Kobler et al. (2024b)
	Stem increment	https://doi.org/10.23728/b2share.2de5b37a0cad4f82a19f477531d6af24	Pröll et al. (2024)
Stubai–Kaserstattalm	Meteorology	https://doi.org/10.23728/b2share.77462914dc0b43cb8c24a967e6851665	Ingrisch and Bahn (2024c)
	Soil climate	https://doi.org/10.23728/b2share.026d76094e8f4512b09b35b7a0d2a9d7	Ingrisch and Bahn (2024d)
	Soil CO_2 respiration	https://doi.org/10.23728/b2share.cfe8c7ad1965433484650ea9026512ca	Ingrisch and Bahn (2024a)
	Stem increment	https://doi.org/10.23728/b2share.0e3eed54ff30418f8720806b5f05cca9	Ingrisch and Bahn (2024b)
Pürgschachen Moor	Meteorology	https://doi.org/10.23728/b2share.5442510ad03e4968afb4e2108e85a64d	Maier and Glatzel (2024e)
	Soil climate	https://doi.org/10.23728/b2share.9380364098d14978b876a87517652d62	Maier and Glatzel (2024f)
	Eddy covariance	https://doi.org/10.23728/b2share.4f783e3ff2884abca5c59960db0b7955	Maier and Glatzel (2024d)
Lake Neusiedl	Meteorology	https://doi.org/10.23728/b2share.f7176c9ee982464f947d2fe9fb8f389d	Maier and Glatzel (2024b)
	Soil climate	https://doi.org/10.23728/b2share.4e6474cd55f9487d97e3d31e83baa530	Maier and Glatzel (2024c)
	Eddy covariance	https://doi.org/10.23728/b2share.b83caca3efe44868a1ed49129b4a576a	Maier and Glatzel (2024a)

provide high-quality eddy covariance measurements would obviously be ideal, the more so because European research infrastructures follow findable, accessible, interoperable, and reusable (FAIR) data principles (Wilkinson et al., 2016).

While the eLTER RI data infrastructure is still in development, we comply with the standards already implemented. We used DEIMS-SDR (https://deims.org/, last access: 1 March 2024) as the catalog documenting the sites (Wohner et al., 2019, 2022). It issues persistent identifiers for sites (see Table 1) that allow us to uniquely identify sites across research projects and networks. Tools are being developed to query available information about sites programmatically (Oggioni et al., 2023; Wohner, 2023), thus providing contextual ecosystem information.

8 Interactive computing environment

A Jupyter notebook for accessing, merging, and visualizing the data from all the sites is available at https://gist.github.com/1O/9bbe44a03f12801c6c742202b005db57 (Offenthaler, 2024).

Author contributions. TD, MB, EDP, ID, ME, KG, GG, AnM, JI, BK, JK, ArM, GP, SV, SZB, AZ, and SG designed the measurements and carried them out. CW and JP designed and constructed the database. KK, SV, and GP customized and filled the database. IO developed the Jupyter notebook. TD prepared the manuscript with contributions from all the co-authors.

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