Ref. Ares(2023)2259609 - 29/03/2023

European long-term ecosystem, critical zone and socio-ecological systems research infrastructure PLUS

Report on key parameters influencing biogeochemical processes and appraisal of related eLTER RI services and tools

Deliverable D8.2

02/02/2023

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Prepared under contract from the European Commission
Grant agreement No. 871128
EU Horizon 2020 Research and Innovation action

Project acronym:	**eLTER PLUS**
Project full title:	**European long-term ecosystem, critical zone and socio-ecological systems research infrastructure PLUS**
Start of the project:	Feb 2020
Duration:	60 months
Project coordinator:	Professor Jaana Bäck University of Helsinki, Finland https://www.lter-europe.net/projects/elter-plus
Deliverable title:	Report on key parameters influencing biogeochemical processes and appraisal of related eLTER RI services and tools
Deliverable n°:	D8.2
Nature of the deliverable:	Report
Dissemination level:	Public
Citation:	Gillespie, L. & Díaz-Pinés, E. (2023). *Report on key parameters influencing biogeochemical processes and appraisal of related eLTER RI services and tools*. Deliverable D8.2 EU Horizon 2020 eLTER PLUS Project, Grant agreement No. 871128.

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Deliverable status:

Version	Status	Date	Author(s)
0.1	Draft	13th Nov 2022	Lauren M. Gillespie (BOKU)
0.5	Draft	12th Dec 2022	Gillespie, L., Díaz-Pinés, E.
1.0	Draft review	23rd Jan 2023	Gillespie, L., Díaz-Pinés, E., (Pasi Kolari for Material and Methods review)
1.0	Internal review	27th Jan 2023	Dirnböck, T
1.0	Final	2nd Feb 2023	Gillespie, L., Díaz-Pinés, E.

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Glossary

B2DROP	EUDAT B2DROP service, based on NextCloud
B2SHARE	EUDAT B2SHARE publication service, based on Invenio issuing DOIs
BGC	Biogeochemical
DataLabs	eLTER Data Laboratory, a collaborative platform for eLTER members to share data, work, code, and more
DEIMS-SDR	Dynamic Ecological Information System - Site and Dataset Registry, being the central site catalogue for eLTER
eLTER	Integrated European Long Term Ecosystem, critical zone and socio-ecological Research
RI	Research Infrastructure

Summary

The eLTER network offers large amounts of long-term monitoring data from many ecological variables across Europe, potentially enabling the detection of slowly-occurring changes in European ecosystems. However, much of this data has not yet been consolidated and analysed across sites, which impedes a full understanding of ongoing trends. Long-term changes in biogeochemical processes in many habitats across Europe are still a black box even though these processes determine the exchange of carbon (C) and nitrogen (N) between the geosphere, biosphere, hydrosphere, and atmosphere, which has considerable consequences for and influence on on-going climate change.

Within the eLTER PLUS project, the primary objective of Task 8.2 was to increase process understanding of the impact of climate change and extreme weather events on C and N cycling and feedbacks in a broad range of ecosystems. To achieve this, biogeochemical legacy data from eLTER sites were collected, homogenised, cleaned, gap-filled, and analysed, leading to the development of multiple products. This process was not straight-forward and multiple difficulties were encountered, such as missing metadata and a large variety of data structures. A general workflow was developed that outlined methods used, elaborated on issues encountered, and suggested steps forward to facilitate future data analysis efforts in the frame of the eLTER RI.

The scientific product produced from this work explored soil drought event effects on soil greenhouse gas fluxes (GHG, i.e. CO_2, CH_4, and N_2O) over time in two different sites: a boreal, coniferous forest, Hyytiälä SMEAR II, and a temperate, broadleaf forest, Rosalia Lehrforst. Soil moisture and soil temperature data were used to identify soil drought events. Then data from GHG flux chambers were analysed using generalized additive models (GAM) to see whether gas fluxes differed before and after the identified drought events and whether there was an overall temporal trend. Due to the data structure, it was not possible to clearly distinguish between changes caused by the drought events themselves or by in-direct climate change effects, e.g. via on-going decreased soil moisture or increased soil temperatures. Regardless, there were clear and significant temporal changes in soil CO_2, CH_4, and N_2O fluxes over the measured timeframes at both sites. Preliminary results underline Hyytiälä as a potential important sink for CH_4 and may become more so as time goes by.

1 Introduction

1.1 Task objective

The eLTER PLUS Task 8.2 aims to increase process understanding of the impact of climate change and extreme weather events on carbon (C) and nitrogen (N) cycling and feedbacks in a broad range of ecosystems. To this purpose, data on C and N fluxes were analysed. Further, extreme weather events (i.e. drought) were characterised. It was the goal of the task to facilitate a) identification of critical environmental thresholds and tipping points in C and N turnover and fluxes across the eLTER spectrum of ecosystems, climate zones and socio-ecological contexts and b) improvement of our understanding of the impact of extreme weather events and climate change on ecosystem processes.

1.2 Deliverable context

The exchange of materials, energy, and nutrients between the geosphere, biosphere, hydrosphere, and atmosphere is an elaborate interplay of processes occurring over both small and large spatial and temporal scales (Hedges 1992). The discipline of biogeochemistry is devoted to the investigation of these processes (Schlesinger and Bernhardt 2013), which are not stagnant in time and evolve with changing conditions (Costa et al. 2021). Indeed, the current climate crisis will shift biogeochemical (BGC) processes in directions yet unknown as these processes are just now becoming elucidated (Costa et al. 2021). Climate scenarios that were considered pessimistic when created are now looking to be ever more realistic with an already 1.1°C increase in global temperatures (IPCC 2022). Alongside global warming, weather patterns are predicted to become more erratic and extreme (Jansson and Hofmockel 2020). More frequent and severe drought, for example, is becoming an ever more common feature of climate change (IPCC 2022). This could be seen with the 2022 droughts in Europe where some major rivers dried to critical levels, notably in France, Germany, and Italy (Henley 2022). Understanding BGC processes under current and historic conditions is imperative to predict future trends and be able to make calculated mitigation efforts.

Soils are a central playing field where many BGC processes occur and soils act as important sources or sinks for elements. Indeed, soil is the largest terrestrial repository of organic carbon (~1500 Gt carbon; Crowther et al. 2019). While soils are the field, soil microorganisms are the central players driving BGC processes, including bacteria, fungi, archaea, viruses, and protozoa. Plant litter, for example, is decomposed by microorganisms, transforming dead plant material into organic products, which liberates elements into the soil that can be taken up by decomposers and plants, stored in the soil, released into the atmosphere in a gaseous form, or leached from the soils (Kozlowski et al. 1991; Thomas and Packham 2007; Coleman and Wall 2015; Lladó et al. 2017). This elemental recycling plays a critical role in ecosystem functioning. In temperate and boreal forests, for example, N fixing bacteria and mycorrhizae fungi are responsible for up to 80% of N and 75% of phosphorus (P) plants acquire (van der Heijden et al. 2008). Whether elements are retained or released by the soil depends on a multitude of factors, but notably on microbial activity, microbial community composition, the form the element is presented, and environmental conditions (Paul 2007; Wall 2014). For example, the balance between atmospheric N uptake through microbial N fixation/nitrification processes and N efflux through denitrification can determine the N source/sink nature of system (Kozlowski et al. 1991; Schulze 2000). Furthermore, because soil microorganisms largely regulate the rate of element exchange between terrestrial and atmospheric pools, including the release or uptake of greenhouse gases (CO_2, N_2O, CH_4), their activity has major implications for climate feedback effects (Crowther et al. 2019). Indeed, soil N_2O emissions represent 56–70% of all global N_2O sources (Syakila and Kroeze 2011), and the CO_2 exchanged between the soil and the atmosphere exceeds by one order of magnitude the anthropogenic CO_2 emissions (Friedlingstein et al. 2020).

Soil microorganisms are reciprocally influenced by changing climatic and water regimes that have so far unknown consequences on their stability and resilience (Jansson and Hofmockel 2020). It is now well established that soil microbial activity and community taxonomic composition is influenced by decreased soil moisture availability, by the severity and duration of these drought events, as well as by soil re-wetting (Schimel 2007, 2018; Bardgett and Caruso 2020; Jansson and Hofmockel 2020). Microbially-driven BGC cycling, for example, ceases under severe water stress, and this suppressed microbial activity leads to reduced C and N loss (Heimann and Reichstein 2008; Schimel 2018). Microbial responses to drought and rewetting are influenced by the drought duration, severity, and frequency, which affect the diffusion rate and availability of resources to microorganisms, the microbial recovery pattern (linear or exponential), and the scale of microbial mortality (Göransson et al. 2013; Kakumanu et al. 2013; Meisner et al. 2015, 2017). Alongside extreme drought events, extreme precipitation events are also predicted, which present an equally large challenge for microbial survival and activity. Rapid re-introduction of water into the soil forces microorganisms to quickly re-establish osmotic equilibrium to avoid cell lysis and mortality (Schimel 2007). A high influx of water could also lead to inundated and therefore anaerobic soil conditions, which decreases microbial access to gaseous and volatile solutes (Schimel 2018) and could increase denitrification activity (Schulze 2000). N_2O having ~300 times the global warming potential compared to CO_2 makes increased emissions a real concern. Moreover, there is a large pool of substrate that suddenly becomes available after rewetting, which can lead to a large pulse in microbial activity (Borken and Matzner 2009; Schimel 2018). Thus, the overall effect of a larger heterogeneity in precipitation distribution on the soil GHG balance will depend on the magnitude of the GHG pulses following rewetting (Birch 1958; Schimel 2007; Xiang et al. 2008) as well as the plant and microbial adaptations during drought (Bardgett and Caruso 2020).

Effects and responses of the soil upon water availability disturbances also differ depending on the time scale you consider. Changes to BGC processes are oftentimes non-linear in time, and the result of accumulated effects only become apparent after long time scales (Wollast and Mackenzie 1989; Schlesinger and Bernhardt 2013). Long-term monitoring of these processes is therefore paramount to identifying and understanding current and changing patterns. Most research projects are funded for short periods (3-5 years), meaning measurements are only conducted at most for a couple of years. However, this is often too short to observe significant or long-lasting responses to climate change (Shaver et al. 2000) or potentially identify tipping points for ecosystems (Reyer et al. 2015). This is a key reason why eLTER is important; it is a source of invaluable, long-term ecological records that permit such temporally extensive pictures. Furthermore, different ecosystems and geographical locations, with their varying nutrient cycles, will not necessarily be affected to climate change the same (Shaver et al. 2000; Griffiths and Philippot 2013). The wide geographical distribution of eLTER sites along with a diverse representation of habitat types (e.g. forest, grassland, moor, montane) further adds to its value as it enables a wider view of what has occurred in the heterogeneous patchwork of European natural habitats and be able to make predictions for future occurrences as climate change continues to change ecosystem landscapes.

Here, we sought to use eLTER BGC legacy data to understand historical drought effects on BGC processes. This knowledge is imperative to understanding potentially accumulated effects on processes and predicting future changes.

1.3 Workflow

1.3.1 Step-by-step workflow

0. Identification of data needs, data availability, and data calls

Data used in task 8.2 was retrieved from data collection activities in collaboration with several WPs from the eLTER PLUS project: WP4, WP7, WP8, WP9, WP10. One aim of the data retrieval included the collection of legacy data[1] to run science cases, including the biogeochemistry science case described in this report. For this, Task Leads and their collaborators were inquired about their data needs (e.g. variables, methods, time range, time range, temporal or spatial resolution; D8.5 and D9.5; see below for link). Once a list of potentially interesting variables was constructed, a data availability survey was implemented to get an idea of the potential availability of data across all LTER Europe sites. A total of 420 LTER site managers in Europe were contacted asking for information about the number of variables, the temporal resolution, length of observations, etc. they may have available. After this, a data request was sent, including specifications on how to report the data (Peterseil and Geiger 2020) and how to upload it (Peterseil et al. 2020).

It should be noted that the data formats the sites could use were very flexible in order to keep their workload low. The site manager's contribution was on a voluntary basis. They could deliver already published data using DOIs, other online sources, or via a specific format developed for LTER data reporting where no online sources were available. ICP Forests data was retrieved centrally with a data request to the program centre. Although site managers were asked to also provide metadata via DEIMS-SDR along with data, they often did not.

Additional information on the abovementioned process (data requirements, site surveys, data retrieval) can be found in the deliverable reports:

- D4.1 – *Workflow for retrieval and harmonization of legacy data*
- D8.5 – *Report on data requirements (CS1-4) to be used in VA and WP10*
- D9.5 – *Report about data requirements (CS1-4) to be used in VA and WP10*
- D10.2 – *Data and ICT needs from the RCs to be used in VA*.

1. Data identification

In order to explore the effects of drought on BGC processes, the data needs for Task 8.2. included time-series data for BGC variables that captured multiple drought events and was long enough to show potential changes in BGC processes (ideally >10 years). Soil moisture and soil temperature data that overlapped temporally the aforementioned variable were also required to be used to identify drought events. Then important auxiliary data (climate, vegetation, plot and soil characterization, etc.) was needed to potentially help explain findings and/or differences between sites. It was also desired to have a homogenous distribution of sites to cover the maximum of habitat types and climatic, pedological, environmental, and social conditions across the European continent. However, it became clear that only a very limited subset of sites was in a position to potentially deliver the data in the frequency and duration required to answer the scientific questions posed in the case study. There was notably a lack of representation in Southern and Eastern Europe and for non-forest habitats.

Using a document that compiled data availability survey and data delivery status, among other information (document described in section 2.1), a heatmap was created that listed the sites and the BGC variables measured at each site that had been indicated as delivered (Fig. 1.1). It was color-coded to identify the sites that had the most measured variables and the variables measured at the most sites. The measurement frequency was included on the cells, but this was only as accurate as the information provided in the survey; there were inconsistencies found between the survey information

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[1] Legacy data - old information that an organization has, especially information stored in an old-fashioned way (https://www.ldoceonline.com/dictionary/legacy-data)

and the data delivered. For example, the soil K, N, and P variables were oftentimes indicated as having a ‘yearly’ or ‘decadal’ measurement frequency, but when the delivered data was explored, the site only had a couple datapoints from a single year. Further details are provided in the section 1.3.2 “Difficulties encountered”.

With the assistance of WP7, a BGC-specific data call was made where we targeted the sites that had indicated having certain BGC variables in the data availability survey but had not delivered them. This resulted in some additional BGC data to be delivered.

For our analysis, we sought to prioritize and select the BGC variables that were measured at the greatest number of sites. Once a sub-selection of sites was identified, the delivered data for the target variables were homogenized. From the data delivered following the eLTER PLUS 2020 and 2021 data calls we assembled three time-series datasets: a soil greenhouse gas (GHG) flux dataset, a soil water chemistry dataset, and a ‘complete’ soil moisture and soil temperature dataset. The workflows for the three datasets were the same for the first steps (data retrieval, trimming, harmonisation, gap-filling, etc.). Thus, the GHG dataset is used as a primary example elaborating this process. Following this, differences for the soil water chemistry dataset and ‘complete’ soil moisture and soil temperature dataset are explained.

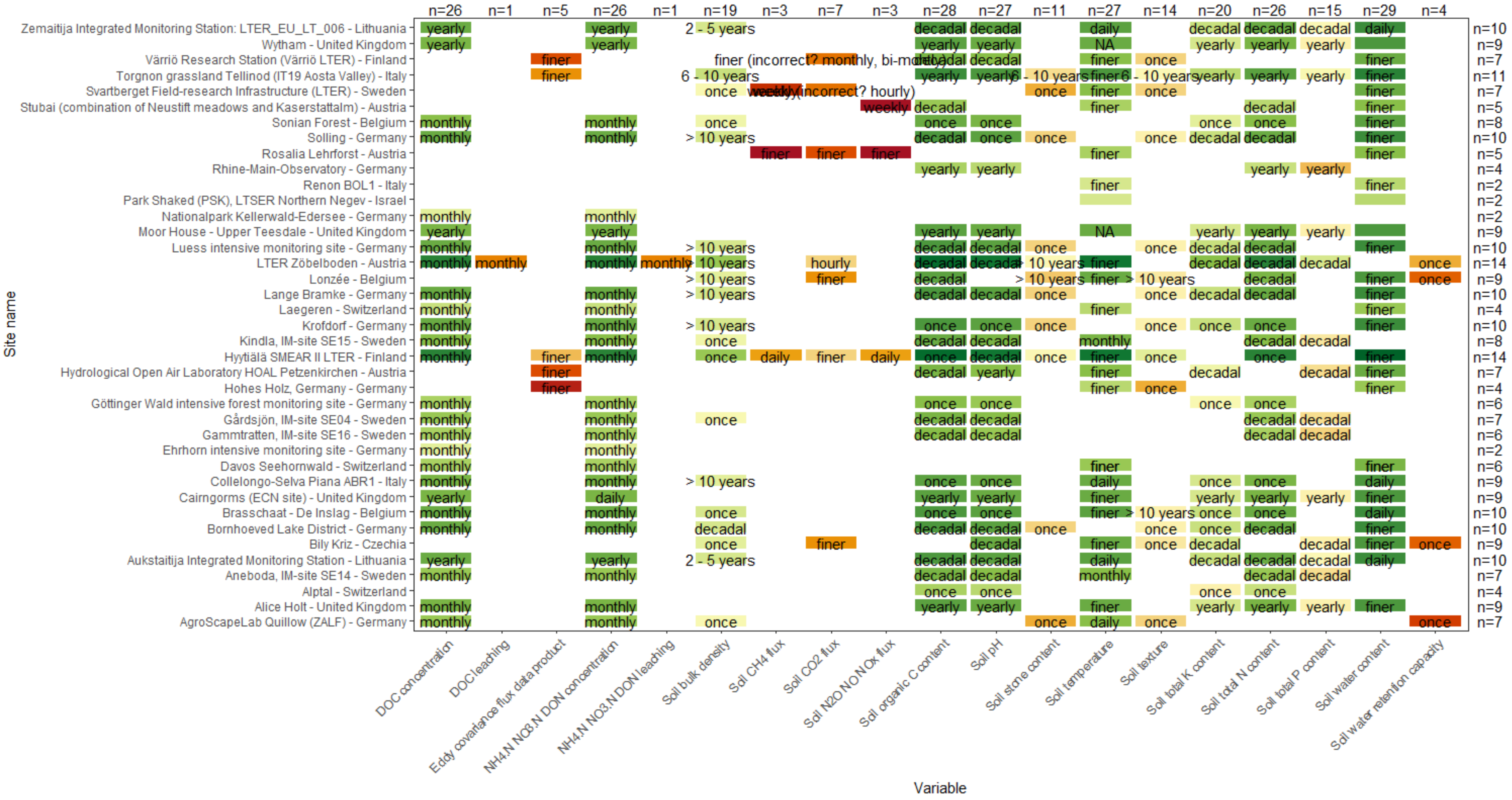

Fig. 1.1. Heatmap of what sites measure what biogeochemical target variable. Values above the map indicate the number of sites that measure the associated variable and values to the right of the map indicate how many variables are measured at the associated site. The cells are color-coded to indicate maximization of number of sites and number of variables, measured by the addition of number of sites that measure the variable plus the number of variables measured at that site. Dark green indicates high site + variable numbers and red indicates low numbers. The text on the cells is the data frequency as indicated by the site manager.

Workflow for soil GHG flux, soil moisture, and soil temperature data

2. Data retrieval and selection of LTER sites

The R function '*Function to download B2Drop files directly into R*', described in Section 2.2, was used to import the data directly from B2Drop into R. All soil GHG data was from individual data files not associated with larger networks (e.g. FLUXNET, ICOS). There were four sites that delivered soil GHG flux data (Hyytiälä SMEAR II, Rosalia Lehrforst, Svartberget, and Zöbelboden), but only two that had >2 years of measurements. These two forest sites, Hyytiälä SMEAR II and Rosalia Lehrforst, provided data for soil CO_2, CH_4, and N_2O fluxes as well as soil moisture and soil temperature data that was measured within the vicinity of the GHG flux measurements. Therefore, only Hyytiälä SMEAR II and Rosalia Lehrforst were selected for further analysis. That means that of the 217 sites that responded to the survey indicating their data availability, our selection process resulted in a subset of two sites (Fig. 1.2).

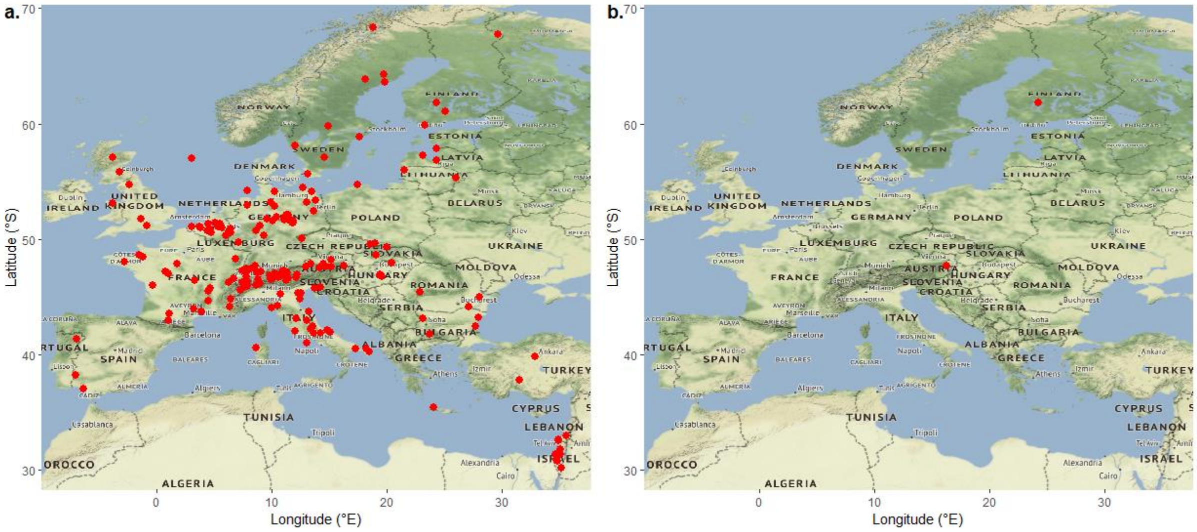

Fig. 1.2. (a.) Sites that responded to the data availability survey (217 sites responded; sites in Antarctica were excluded from this map) and (b.) sites in the final GHG subset (Hyytiälä SMEAR II, Finland and Rosalia Lehrforst, Austria).

3. Data trimming

Since soil moisture and soil temperature data that temporally overlapped the soil GHG flux data was required to identify drought events, soil GHG flux measurement periods without this additional data were not used. Additionally, the models used for data analysis (generalized additive models) required a minimum number of observations per month and no missing years. After trimming, Hyytiälä CO_2 flux data spanned nine years and CH_4 and N_2O data spanned seven years (Table 1.1). For Rosalia, CO_2, CH_4, and N_2O gas fluxes spanned three years. The soil moisture and soil temperature data were trimmed to match these durations.

Table 1.1. Duration of the time-series data from the two soil GHG flux sites.

	Hyytiälä SMEAR II	**Rosalia Lehrforst**
Soil CO_2 flux	2009 - 2017	2013 - 2015
Soil CH_4 flux	2007 - 2013	2013 - 2015
Soil N_2O flux	2007 - 2013	2013 - 2015

4. Data harmonization, standardization, and transformation

Dataset structure was harmonized to a long-format and all data was averaged by day to resolve different measurement frequencies; for example, soil GHG fluxes at Rosalia were measured every 3 hours while soil moisture and soil texture were measured every 30 minutes. An effort was made to consolidate equivalent columns when merging datasets. However, whether certain columns were exact equivalents was not always evident. Unless the columns were the same with 100% certainty, columns were left separate. This led to many dataset-specific columns, but the risk of miss-labelling was strongly reduced. Variable names were standardized and the data transformed to have the same units (e.g. from µmol to mg, m^3 m^{-3} to %). Additional columns were added to the homogenized dataset to include important metadata not in the original datasets, e.g. units, site name, DEIMS-SDR URL, GPS coordinates, habitat type where the measurements were taken, sample depth, soil type, soil texture, etc.

Data originated from measurements in the field which were considerably different in terms of methodological details. This however, did not imply significant issues with regard to the data homogenization. Some soil GHG flux data was measured using transparent chambers and other using opaque chambers (the transparent chambers allowing continued photosynthesis of contained plants), but these chambers were at the same site and when compared, did not show a significant difference in soil GHG fluxes.

5. Gap filling

Some soil moisture data had problematic data gaps, and we explored different options to fill them. First, we sought to gap-fill *in-situ* soil moisture data with soil moisture satellite data from two models ERA5L and GLEAM (3 km horizontal resolution). However, it became quickly apparent that due to differences in scale and variation, simple correction and insertion of satellite data was not possible (Fig. 1.3). Moreover, satellite data did not cover dates after 2018, which were a large part of the missing *in-situ* data.

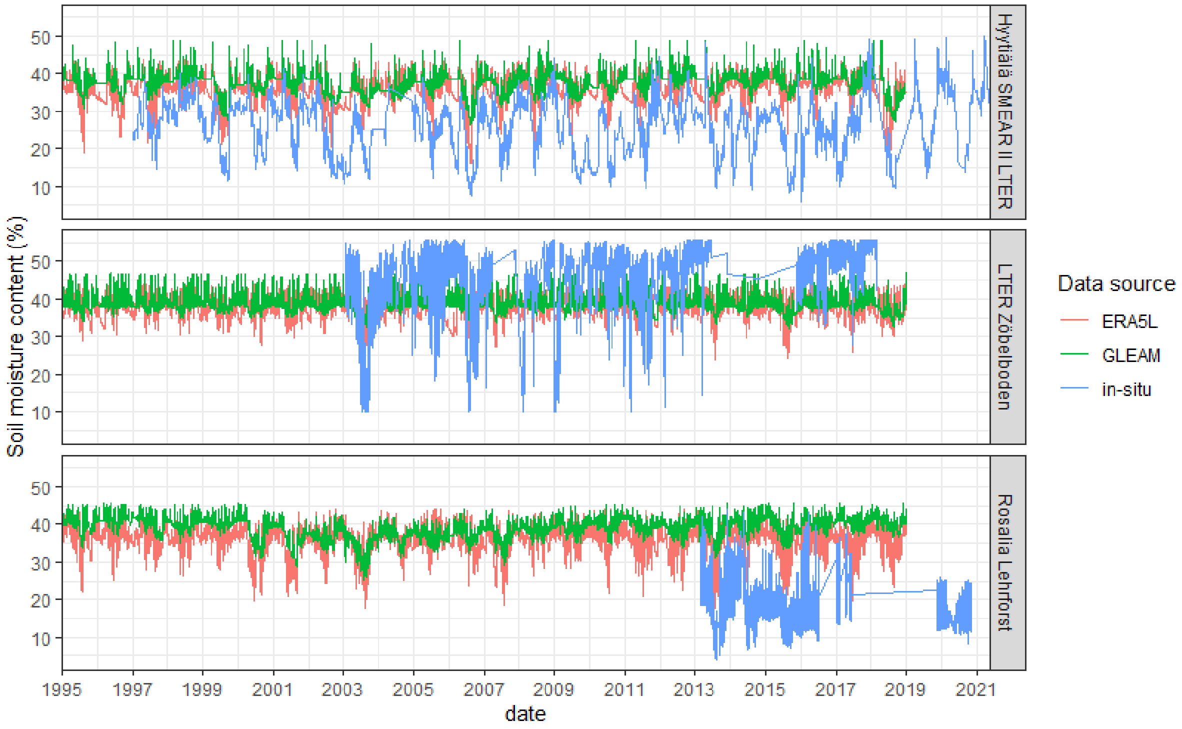

Fig. 1.3. Soil moisture data (%) from *in-situ* data (blue) and satellite data from two models: ERA5L (pink) and GLEAM (green) with a 3 km horizontal resolution. The *in-situ* data for Zöbelboden and Rosalia Lehrforst shows the results from multiple chambers.

Instead of using satellite data, data was gap-filled using the interpolation 'na_kalman' and 'na_seadec' functions in the imputeTS package (version 3.3, Moritz and Bartz-Beielstein 2017). The data was not gap-filled before or after the first and last measurements of the year (i.e. non-measurement season in winter) or at the peak or valley of curves. This was done because there was no way to verify function extrapolations during these periods.

6. Quality control and outlier detection

The data had already gone through data quality filters before being delivered by the site managers to eLTER. However, there were still values that appeared odd (impossible values, appeared to be caused by machine malfunction, etc.). Site managers were contacted to verify that these values were indeed incorrect and give the green light to remove them.

7. Dataset availability

The dataset, including the soil GHG fluxes, soil moisture, soil temperature, precipitation, air temperature, soil characteristic (soil texture, soil type, etc.), site information, and additional metadata for the two sites analysed, will be made publicly available online (B2Drop or B2Share) with documentation including data sources, column descriptions, how data was transformed from original data delivered, etc.

Workflow for soil water chemistry, soil moisture, and soil temperature data

The BGC time-series variables related to soil chemistry that were measured and available at the most sites were dissolved organic carbon (DOC), ammonium (NH_4^+-N), nitrate (NO_3^--N). We therefore went through the same data retrieval, homogenization process as described for the soil GHG dataset for a subset of ten sites with this soil water chemistry data and overlapping soil moisture and soil temperature data (Table 1.2). The data for the UK sites all came from the ECN repository from two datasets: ECN soil solution chemistry and ECN meteorology. For Brasschaat, Collelongo-Selva, Davos Seehornwald, and Laegeren, DOC, NH_4^+-N, and NO_3^--N data came from ICP Forests soil solution dataset, and the soil moisture and soil temperature data came from FLUXNET. For Zöbelboden and Aukstaitija, all data came from individual files delivered to the B2Drop. Collelongo-Selva also delivered an individual file containing DOC, NH_4^+-N, NO_3^--N, soil moisture, and soil temperature data, which did not appear to be the same Collelongo-Selva data obtained from ICP Forests and FLUXNET and therefore was also included.

Table 1.2. Sub-selection of ten sites with DOC, NH_4^+-N, NO_3^--N, soil moisture, and soil temperature data.

County	Site name	Habitat	DEIMS-SDR URL
AT	LTER Zöbelboden	Forest	https://deims.org/8eda49e9-1f4e-4f3e-b58e-e0bb25dc32a6
BE	Brasschaat - De Inslag	Forest	https://deims.org/68e6a8e5-d6d2-4c8c-91c4-10e7f87ac556
IT	Collelongo-Selva Piana ABR1	Forest	https://deims.org/9b1d144a-dc37-4b0e-8cda-1dda1d7667da
LI	Aukstaitija Integrated Monitoring Station	Forest	https://deims.org/fad7f221-25f3-4286-a1b3-43a5f010a3e3
CH	Davos Seehornwald	Forest	https://deims.org/a547dab2-859a-414c-b148-0e7df8de5773
CH	Laegeren	Forest	https://deims.org/7b4d8b76-1c6d-410c-998c-f9c56b2f7347
UK	Alice Holt	Forest	https://deims.org/d47ec839-5d20-4315-9f88-1e9edbab22e8

UK	Cairngorms	Moor	https://deims.org/5a04fee1-42aa-47e9-abfc-043a3eda12ac
UK	Moor House Upper Teesdale	Moor	https://deims.org/bf78c96f-0763-4b31-b1a6-6eccef19edd1
UK	Wytham	Forest	https://deims.org/16dcd0c3-a114-412c-9f01-8c1af292ba69

Once the data was homogenized and cleaned, a GAM was run on each variable for each site (GAM structure and application is described in detail in section 4 “Scientific product: Drought effects on soil GHG fluxes in a boreal and a temperate forest”). This initial attempt helped identify what sites were too data-deficient for GAM analyses and were thus removed. The sites may have had many observations, but data was usually from multiple depths and sensors. Once these dependent data groups were taken into account as random variables, there were too few observations per month. This left only Brasschaat, Belgium and Moor House Upper Teesdale, United Kingdom. Upon talking with the site manager of Moor House however, it was explained that the soil moisture and soil temperature data were not measured in the same location as the soil water chemistry variables (different habitat and soil type). This therefore disqualified Moor House as a usable site, leaving just Brasschaat. Discussion with the Zöbelboden site manager revealed that there were additional years of soil water chemistry data that could potentially make it a usable site. This is to be explored, but the DOC, NH_4^+-N, NO_3^--N dataset will not be further discussed in this report due to its current incomplete state.

Workflow for the dataset with all delivered soil moisture and soil temperature data

Soil temperature and soil moisture data were the two most delivered BGC variables and generally had a long measurement duration and frequency. A homogenized soil temperature and soil dataset was created with all delivered data, which ultimately including data from 79 sites in 15 countries (see Table 1.3 for complete site list). Some of the data originated from individual files delivered from sites (the case for sites: Aukstaitija Integrated Monitoring Station, Lithuania; Brasschaat - De Inslag, Belgium; Collelongo-Selva Piana ABR1, Italy; Hyytiälä SMEAR II LTER, Finland; Rosalia Lehrforst, Austria; and Zöbelboden, Austria). The rest of the data came from platform repositories: ECN, FLUXNET, ICOS, and ICP Forests. The workflow for this dataset was more or less the same as for the soil GHG dataset, with some deviances described in the next paragraph.

Many files had columns with codes that were not explained in the dataset. The definition or description of theses codes was hunted down and added after an underscore (e.g. "1_Data measured on plot as described under location in form PLM"; 1 being the code). Additional columns were added to include metadata (e.g. method, unit, depth, metadata source). However, this metadata was oftentimes difficult to find or not explicitly clear, and so important information was missing for certain sites, e.g. method, depth, equipment. It will be necessary to reach out to the site manager of each site where this information is missing to obtain it. This homogenized dataset has not yet been cleaned (although most datasets delivered had already gone through a quality control check) and has not been checked for duplicates.

The homogenized dataset has been made available on the B2Drop accompanied by a READ.ME document providing information about the file. The datafile is too large to open with MS Excel; it needs to be downloaded and then opened using another software (e.g. R or Python). There may be issues with replicate rows when importing into R; 'row.names=NULL' needs to be included in the read.csv script, e.g. read.csv("Homogenized_SWC_ST_data_20221205.csv", header=T, row.names=NULL , fileEncoding = "latin1").

This data will be used in collaboration with WP9.3 to evaluate continental scale land-surface model outputs of ecosystem processes and enhance ecosystem model parameters through assimilation of these observed *in-situ* soil moisture and soil temperature time series.

Table 1.3. List of countries and sites included in the homogenized soil temperature and soil moisture dataset.

Country	Site name	DEIMS-SDR url
Austria	LTER Zöbelboden	https://deims.org/8eda49e9-1f4e-4f3e-b58e-e0bb25dc32a6
Austria	Rosalia Lehrforst	https://deims.org/77c127c4-2ebe-453b-b5af-61858ff02e31
Austria	Stubai	https://deims.org/324f92a3-5940-4790-9738-5aa21992511c
Belgium	Brasschaat - De Inslag	https://deims.org/68e6a8e5-d6d2-4c8c-91c4-10e7f87ac556
Belgium	Lonzée	https://deims.org/c3c8a84f-ff66-4d19-8c28-42c7ed63b43d
Belgium	Sonian Forest	https://deims.org/0fa0d44f-5314-405f-a647-a7dda423031f
Belgium	Vielsalm	https://deims.org/c4c1c0ca-5a43-4d19-ab50-34dad0af44e8
Czech Republic	Bily Kriz 1	https://deims.org/a61dd7df-5fd7-47b4-8172-b7dfaf969748
Czech Republic	Bily Kriz 2	https://deims.org/a61dd7df-5fd7-47b4-8172-b7dfaf969748
Czech Republic	Lanzhot	
Czech Republic	Rajec	https://deims.org/4934a491-fa10-4b79-a460-4c82f6d43eec
Czech Republic	Stitna	
Czech Republic	Trebon (CZECHWET)	
Denmark	Soroe	
Finland	Hyytiälä SMEAR II LTER	https://deims.org/663dac80-211d-4c19-a356-04ee0da0f0eb
Finland	Lettosuo	
Finland	Siikaneva	
Finland	Varrio	https://deims.org/b471311f-e819-4f6f-bbae-1ac86cd9777f
France	Bilos	
France	Hesse	https://deims.org/b47f5a24-2f3f-4ffb-8a16-76b011aa8569
Germany	Anklam	
Germany	Bornhoeved Lake District	https://deims.org/2aedc444-7007-4d07-877c-0abf528b0ecd
Germany	Ehrhorn intensive monitoring site	https://deims.org/8849988d-762f-475b-98d6-ab08b29645ab
Germany	Gebesee	
Germany	Grillenburg	
Germany	Hainich	https://deims.org/5b409a72-2a45-4238-a501-e24f1a2900db
Germany	Hetzdorf	
Germany	Hohes Holz	https://deims.org/ddd2e8d2-44db-420e-8fa4-6b4fe1b00c78
Germany	Huetelmoor	
Germany	Klingenberg	
Germany	Krofdorf	https://deims.org/f73a0f95-8fb0-4755-92fc-f4b0207f5fe4
Germany	Lange Bramke	https://deims.org/8e24d4f8-d6f6-4463-83e9-73cac2fd3f38
Germany	Luess intensive monitoring site	https://deims.org/050e88fa-06e7-43e5-8dcc-6b75a549cb09
Germany	Nationalpark Kellerwald-Edersee	https://deims.org/5c11903f-9b21-47ee-a72b-13d5ef4b7db7
Germany	Oberbärenburg	
Germany	Rollesbroich	https://deims.org/356417de-5a3c-429d-82c1-08a4e924ab3b
Germany	Selhausen	https://deims.org/0a006b69-5134-4c0a-864c-f86c0c61288f
Germany	Selhausen Juelich	https://deims.org/0a006b69-5134-4c0a-864c-f86c0c61288f
Germany	Solling	https://deims.org/2d55b484-2a89-4023-be00-49829ab327f9
Germany	Tharandt	
Germany	Wustebach	https://deims.org/9fe5a5d1-ccc0-41ab-b555-5ca44da24cd8
Italy	Borgo Cioffi	

Country	Site name	DEIMS-SDR url
Italy	Castelporziano2	
Italy	Collelongo-Selva Piana ABR1	https://deims.org/9b1d144a-dc37-4b0e-8cda-1dda1d7667da
Italy	Lison	
Italy	Renon BOL1	https://deims.org/5d32cbf8-ab7c-4acb-b29f-600fec830a1d
Italy	San Rossore 2	
Italy	Torgnon Larch forest Tronchaney	https://deims.org/4312983f-c36a-4b46-b10a-a9dea2172849
Lithuania	Aukstaitija Integrated Monitoring Station	https://deims.org/fad7f221-25f3-4286-a1b3-43a5f010a3e3
Netherlands	Loobos	
Russia	Fyodorovskoye	
Russia	Fyodorovskoye dry spruce	
Spain	Albuera	
Spain	Majadas del Tietar North	
Spain	Majadas del Tietar South	
Sweden	Degero	
Sweden	Hyltemossa	
Sweden	Lanna	
Sweden	Norunda	
Sweden	Rosinedal-3	
Sweden	Svartberget	https://deims.org/c0705d0f-92c1-4964-a345-38c0be3113e1
Switzerland	Alp Weissenstein	
Switzerland	Chamau	
Switzerland	Davos Seehornwald	https://deims.org/a547dab2-859a-414c-b148-0e7df8de5773
Switzerland	Früebüel	
Switzerland	Laegeren	https://deims.org/7b4d8b76-1c6d-410c-998c-f9c56b2f7347
Switzerland	Oensingen crop	
United Kingdom	Alice Holt	https://deims.org/d47ec839-5d20-4315-9f88-1e9edbab22e8
United Kingdom	Cairngorms	https://deims.org/5a04fee1-42aa-47e9-abfc-043a3eda12ac
United Kingdom	Drayton	https://deims.org/00eb83ef-c965-462d-8022-7f7ff75ccd14
United Kingdom	Glensaugh	https://deims.org/1c4d454d-0c00-49f9-a7fe-3a3e596c3648
United Kingdom	Hillsborough	https://deims.org/371c5259-6f38-4aa7-9517-c56f608c62cc
United Kingdom	Moor House Upper Teesdale	https://deims.org/bf78c96f-0763-4b31-b1a6-6eccef19edd1
United Kingdom	North Wyke	https://deims.org/4fbe4bf9-e342-4412-8f0c-c75aff08a8ca
United Kingdom	Porton	https://deims.org/0f05a86f-0f7a-4b81-8268-6818a6064428
United Kingdom	Rothamsted	https://deims.org/cb340d4c-e6e5-465a-b0cb-d6c613fa5541
United Kingdom	Sourhope	https://deims.org/125d4667-0fae-418d-88ff-7d9930809d12
United Kingdom	Wytham	https://deims.org/16dcd0c3-a114-412c-9f01-8c1af292ba69
United Kingdom	Yr Wyddfa/Snowdon	https://deims.org/8b5da977-eed8-459f-b663-f3835aa0b356

1.3.2 Difficulties encountered

The workflow was complex and involved several steps, and a number of obstructions were encountered during the process. After the data delivery request was made by WP10, the delivery response was relatively slow for many sites. Multiple data calls were made, include one BGC-specific data call, and although this resulted in some additional data being delivered, some sites never responded. One issue included **site managers needing to find/retrieve the data**, which oftentimes required finding and contacting the relevant person who had or was knowledgeable about the data.

Another component **compounding delivery delay was the need to reshape data** into the eLTER format or a “recognized format” per the eLTER PLUS request. Some sites did deliver the data in the eLTER structure, while other sites delivered the data in a “recognized” format which was notably the case when the data was already stored in platforms, such as ICP Forests, ICOS, and FLUXNET. Data reshaping is compulsory when working with non-homogenized data but can be very time consuming. It goes without saying that as an operating platform, eLTER will receive the data of the standard observations in a standardized eLTER format. This will be the case with future collection and delivery of eLTER Standard Observations but the legacy data remains an issue. However, in the present context of pre-existing legacy data, many site **managers are already overburdened** and may not have the time to dedicate to reformatting. There also may **not be a clear enough benefit** for them or for their site to use already limited time to do so. Moreover, **not all site managers are well acquainted with software programs** (e.g. R and Python) that can facilitate and expedite the reshaping process and oftentimes concurrently reduce human error. This potentially led to some data never being delivered. It then raises the question concerning legacy data, is it better to receive the data in a non-eLTER format, which requires time and effort on eLTER’s side to reshape, or to potentially not receive the data at all? The development of tools or workflows to automate reshaping of delivered datasets, alleviating this work from both sides, was impeded by the sheer diversity of data structures (e.g. long or wide format), file types (e.g. CSV, Excel, TXT, DAT), storage methods (e.g. zipped folder, data in multiple files or excel tabs). In an effort to remediate this issue, an R script was created to facilitate downloading files from the eLTER B2Drop data storage location and directly importing them into R without storing the memory-demanding data on the computer itself and able to handle many data types and storage methods (see section 2.2 for more details).

The **lack of a detailed inventory of delivered data and associated metadata** made it challenging for data users to quickly identify sites with the desired variables and data requirements (e.g. timeseries length, measurement frequency, method). DEIMS-SDR (Wohner et al. 2019) is a very useful source of metadata, but sites need to add more detail, notably at a variable level. Indeed, in the metadata provided by sites, it was often not clear where within a site measurements were taken. Site managers needed to be contacted to verify whether two variables had been measured in the vicinity of one another and could be logically related (same habitat, same soil conditions, etc.). Ideally, a GPS location should be provided for each sensor. The existing possibility to define “observation locations” within DEIMS-SDR, which allow relating various measurements, should be explored as an additional option. Moreover, the metadata provided by sites, usually via links, was oftentimes distributed throughout multiple documents, in both written text and datafiles, and not always straightforward to understand. The survey results (elaborated in eLTER PLUS D10.2 report “Data and ICT Requirements”) provided some guidance for potentially existing data, but there were discrepancies between what sites indicated as existing in the survey and what was delivered. Certain requested information in the survey, such as measurement frequency and duration, appears to have been interpreted differently by different site managers. It was therefore necessary to manually evaluate each data document and metadata file, which was very slow and labour intensive. A compiled document with the survey results, the results from an initial inventory effort for BGC variables, and additional site metadata (e.g. GPS location, habitat, associated platforms, etc.) was created to consolidate information; this is detailed in section 2.1. Ideally, from our data user perspective, **datasets should contain the measured data and associated metadata (e.g. units, methods, plot information) in a single file** (in a single sheet if using excel). This would reduce the risk of metadata becoming separated from the data and the need for the user to find and add this information themselves. Data in a long format would be most conducive to achieving this. In addition, there was overall not enough metadata provided to write a complete material and methods section, and the data user was heavily dependent on the person/the people who took the measurements to fill in information gaps. If the person/these people were not available, a sufficiently detailed material and methods section required for a peer-reviewed publication would not be possible.

The **data level** (data levels defined in 2.3.2 Data levels in eLTER PLUS D10.2 report "Data and ICT Requirements"; e.g. raw data, gap-filled data, etc.) was often **not overtly indicated for delivered data**. Some data had 'quality flag' indicators with various coding; coding explanations were often hard to find or the site manager needed to be contacted. Even in data with quality controls, there were still odd values (outliers, flat-lined data, impossible values). So, contact with the data collector was still required to verify values.

Other issues were associated with the **lack of a sustained long-term experimental approach and design**. In some cases, measurement methods and/or sample locations within a site changed every couple of years breaking continuity. This is probably due to the lack of a long-term, coordinated scientific approach and standard observations and methods; this situation is to be changed in the frame of the eLTER RI. One additional reason for this pattern is that measurements are often associated with projects of limited duration, so that it was common to **cease variable measuring when the funding was over**. Finally, ancillary critical **soil characteristics were missing** (e.g. soil texture and bulk density data) for many sites. A Remote Access project proposal was written and executed to obtain this information for certain target sites (eLTERSoilPara Project); this is explained in section 2.3.

2 Supporting products created

2.1 Document compiling site and variable information and initial data inventory

During the initial phase of the eLTER PLUS project, a suite of documents was created in the process of accumulating information about the variables measured at eLTER sites (survey documents), how to prioritize sites based on WP8 and WP9 task requirements, and what sites had delivered what data type (e.g. timeseries, biodiversity, or plot data). In addition to these documents, the online catalogue DEIMS-SDR (Wohner et al. 2019) is an important repository of eLTER site, platform, and measurement metadata. However, the dispersal of information both online and offline, in multiple documents, and in multiple excel tabs hindered the ability to quickly filter for sites that fulfilled target conditions, for example, measured certain variables or variable groups, habitat, geographical location, whether this data was delivered to eLTER PLUS WP10, and data measurement frequency and duration.

A compiled document was thus created to consolidate this information into a single MS Excel file, facilitating finding and filtering information. First, in the data availability survey results document "*eLTER_Survey_20200915_1700.xlsx*", the individual tabs for time-series, plot, and biodiversity data were consolidated. The site prioritization score (ranging from 0 to 3; 3 being the highest) was also included; this originated from the document "*eLTER_Survey_Results_Prioritization-of-sites.xlsx*" that calculated site prioritization based on measured variables (relying on survey results for this information) and on homogeneous distribution across ecosystems and climatic zones. Second, key information was retrieved from the DEIMS-SDR json files and incorporated into the document including site GPS location, eLTER parent site name and URL, habitat(s) found at the site, and whether the site was associated with different platforms or projects (e.g. ICP Forests, ICOS, FLUXNET). When the site was associated with external platforms and/or networks, an effort was made to find and include the associated site code, for example, '50_19' and 'CH-Lae' being the site codes for the Swiss site Laegeren for the ICP Forests and FLUXNET platforms, respectively. Third, WP7 provided an updated site manager contact list "*ContactList_eLTERPLUS_20210510.xlsx*" and a document indicating data delivery status “*Overview_20210715.xlsx*”. Fourth, a key was included that explained each column header, information source (e.g. file name, DEIMS-SDR json file), and whether the information is at the site, data type (i.e. timeseries, plot, or biodiversity), or variable level. File names in the source column indicated the date the file was created when relevant (YYYMMDD format). The compiled document also included the date it was updated (both in the key tab as well as in the file name); this ensured a trace of how recent the information was, which is notably important for information such as delivery status and site manager contact information. It would be useful to include information from the data submission report “*_DataSubmissionReport_Summary_20211021(newestversion).xlsx*” document, such as the metadata link, but this has not yet been done. At the time of the publication of this report the compiled file is called “*eLTER_Compiled_Survey_Overview_Information_20221214*”.

An initial issue confronted when working with the compiled document was that the much site information and the data delivery status were at the site or data type level (i.e. time-series, plot, or biodiversity; abiotic ecosystem data or biodiversity data) and not the variable level (e.g. soil moisture content, soil temperature). A user could filter the survey information (the variables the site indicated it had data for) and delivery status (at the data type level), but the user was still required to look through the delivered datafiles themselves to see whether the desired variable was in fact delivered. This is a shared issue with the data submission report document. A full inventory of all delivered variables was missing. An effort to conduct such an inventory was started for the task 8.2 potential target sites and target datasets, and additional columns were added to the compiled document (column headers starting with ‘SITE_’) to include what was found in the delivered documents and metadata: variable name in the dataset, unit, sample depth, method, measurement frequency, measurement start and end dates, data location in the B2Drop, and the data B2Drop link. However, a full inventory of all data on the eTLER B2Drop would be a massive undertaking and well beyond the aims and capacities of this task. Another issue encountered with the compiled document is not knowing the exact location of the point observation data, e.g. geographical location within the site, the habitat at that location, slope, aspect. Indeed, the site habitat list retrieved from DEIMS-SDR was not in a particular order, i.e. habitat order does not indicate habitat dominance, and it was unclear what habitat the measurements originated from. This information is sometimes available in the delivered metadata or on DEIMS-SDR but not always and not yet included in this compiled document.

2.2 R script to download B2Drop files directly into R

To facilitate and expedite the direct importation of a datafile or multiple datafiles from the eLTER B2Drop into Program R (version 4.2.1; R Core Team 2022) the R script “Function to download B2Drop files directly into R” was created and made available on the eLTER DataLabs platform, a collaborative platform for the eLTER community to share data, work, code, and more.

The function was designed to read the "share link" URL that can be obtained from the B2Drop data page. Non-B2Drop data URLs sometime work, but this is a case-by-case situation. To find the "share link" url, right click the file or folder name, choose "Details", then in the right-hand menu that appears, choose "Sharing", then "Share link" "copy to clipboard".

Once the URL is entered into the function, in the console, the function asks the user to indicate how the file(s) is/are stored (i.e. as an independent file, as a zipped file, or in an un-zipped folder). If the URL links to a single file, the user enters the file name as indicated on B2Drop including file type, and the file is imported into R. The dataset name in the R environment is the file name excluding problematic symbols such as periods. The function can currently import the following data types: CSV, Excel, text, and DAT.

If an excel (.xlsx) document is detected, the excel file sheet names will be printed in the console, and the user will need to choose which sheet to download. The function does not currently support the download/importation of multiple sheets simultaneously. In order to download several sheets from the same excel document, the function will need to be run one time per sheet. Since the dataset is named after the file and not the sheet, the dataset name will need to be changed before running the function another time to download another sheet. Otherwise, the newly downloaded sheet will override the preceding sheet downloaded. If a CSV or DAT file is detected, the user will be given the option to choose the separator (e.g. a comma or a semi-colon). If no separator is indicated, the function defaults to using a comma. A column titled 'file_name' including the name of the file imported is automatically to the dataset.

If the URL links to a zipped file or a non-zipped folder, then the file names will be printed in the console, and the user can choose whether one file is to be imported or multiple. If 'multiple' is selected, the user will then indicate the common pattern between the desired file names. Once the function downloads the files containing the common pattern, it asks the user whether the files should be combined into a single dataset or left as independent datasets stored in a list. Regardless of whether the files are combined or left as a list, a column titled 'file_name' is added to indicate the file origin of the data.

Future improvements could include adding loops for when the user enters incorrect information. Currently, the function aborts and the user needs to restart. An occasional issue is that the file(s) is/are sometimes downloaded to the working directory, when one is set (i.e. 'setwd') as well as imported into R. This issue needs to be resolved with future versions of this function.

2.3 eLTERSoilPara Project: filling soil characteristics data gaps

One central aim of the task was to explore the effects of extreme weather events, namely drought, on BGC processes. However, the definition of drought is not straightforward and several approaches can be used. While meteorological drought is considered the lack of precipitation, soil drought occurs when there is a water deficit in the soil creating plant (and microbial) stress. Two important variables to define and characterize soil drought are soil texture and bulk density, which influence soil water retention. However, these variables are not consistently measured as standard methods are time-consuming. Therefore, this critical information is missing for many eLTER sites.

An eLTER PLUS remote access (RA) proposal, eLTERSoilPara, was therefore written to request topsoil soil samples from twelve key sites targeted by Task8.2 to measure and gap-fill this missing soil parameter data in order to better define extreme weather at the site-level.

The soil samples were taken by the site personnel and shipped to BOKU where the bulk density (volumetric cylinder method; Al-Shammary et al. 2018) and soil texture (particle size analysis; sedimentation method, Robinson 1922) were conducted. The standard methods used here were chosen to remain consistent with the methods used by most of the eLTER sites that had already delivered soil texture data. Soil sampling location was within the vicinity of and under similar soil conditions as where the soil temperature, soil moisture, soil dissolved organic carbon (DOC), soil nitrogen in the form of ammonium (NH_4^+-N), and nitrogen in the form of nitrate (NO_3^--N) concentration measurements were taken. This was imperative as to be able to explore relationships between these variables. Soil samples from the same site were distributed in a manner that best represents the location.

This call also revealed that some sites already had this information, but the data was not yet available on the B2Drop. All sites responded positively to the call and were happy to participate. As an outcome of the project, we generated information on soil texture and soil bulk density from 12 targeted eLTER sites. The information generated is valuable and can be used by the sites themselves as well as other researchers.

3 Steps forward

The eLTER PLUS Task 8.2 aimed to increase process understanding of the impact of climate change and extreme weather events on carbon (C) and nitrogen (N) cycling and feedbacks in a broad range of ecosystems. It was the goal of the task to facilitate a) identification of critical environmental thresholds and tipping points in C and N turnover and fluxes across the eLTER spectrum of ecosystems, climate zones and socio-ecological contexts and b) improvement of our understanding of the impact of extreme weather events and climate change on ecosystem processes.

Not all of these goals were achievable with the eLTER data that currently was made available, e.g. identify critical environmental thresholds and tipping points across a spectrum of ecosystems and geographic distribution or reanalysis to establish climate change mitigation measures. However, a better understanding of plot-scale ecosystem processes was achieved for soil GHG fluxes in two forest types in two contrasting climatic regions. Furthermore, the undertaking of Task8.2 underlined key areas where improvement is needed and where future effort and resources can be placed. Specifically, we identified potential for improvement with regard to (meta)data reporting, standardization of methods, and representativity of selected habitats and pedo-climatic conditions across Europe.

Inventory of existing legacy data

A critical key step forward is creating a reliable inventory of what sites measure what variables, whether this data has been delivered and is accessible, and all possible metadata (unit, method, measurement/sensor location, metadata source and location, etc.). This inventory should be updated at least yearly. The compiled document described in section 2.1 could provide a foundation or starting point towards this effort. DEIMS-SDR is the logical front end for this effort.

Metadata included in the datafiles

As a guiding principle, as much of the metadata as possible should be included in the datafiles themselves. Ideally, there should be sufficient metadata to write a complete material and methods section with minimum or no input from site managers. As a minimum, there should be at least a set that allows the user to understand and further process the data, so that the user should not have to search elsewhere to find the units, methods, code explanations, etc. A good deal of time is lost searching for critical information. Data in a long format allows additional metadata columns to be included, have metadata change over time, and data can be quickly filtered based on metadata (filter for certain habitats, data measurement frequencies, or methods). This facilitates quick and easy access and limits metadata becoming separated from the data.

Soil characterization

Many sites are missing critical soil characteristic data that hinders fully exploring or explaining patterns found. This soil characterization data-gap could be easily filled, as was shown with the eLTER SoilPara project. A new eLTER TA/RA-funded project could try to address this problem for the remaining eLTER sites where this information is missing. A more permeant solution would be to have a central service that tries to develop guidelines on how to characterize the sites. This should be linked with the eLTER Standard Observations.

Standardize methods and measured variables between eLTER sites

Standardizing methods and variables between sites are of utmost importance; unfortunately, this issue cannot easily be solved. Not all sites have the same resources, notably financial support, to use the same methods. Requiring more accurate but more expensive methods could hinder certain sites, and potential habitat types as well, from participating in the eLTER network. As a minimum, standardizing the variables that are measured at each site would permit a better understanding of BGC processes over a wider geographical distribution and in more ecosystems. These issues are dealt within the development of the eLTER Standard Observations, which are described in the deliverables of WP3.

Increased eLTER representation of southern and eastern Europe and of non-forest habitats

For BGC data, there is a clear underrepresentation of eLTER sites in southern and eastern Europe and of non-forest habitats. In Eastern Europe, the few sites that delivered data had relatively few variables measured, which means they are less likely to be included in analyses. Southern Europe will be highly affected by climate change, notably for diminishing water resources, (IPCC 2022), so it is important that they be represented and surveyed long-term. WP9 in cooperation with WP3 are analysing the network of sites regarding representativeness and will address these issues. Their work is based on already existing assessments (Mollenhauer et al. 2018; Wohner et al. 2021).

Site funding

As mentioned earlier, some sites had to stop measuring certain variables due to lack of continued funding. Some of these measurements had been going on for >10 years, and with ongoing climate change, current and future measurements are critical to understand how ecosystem processes are changing under increasing climatic, biologic, and anthropogenic pressures. Funding is difficult to obtain for many sites and even more so with the current, global economic difficulties. Within the eLTER RI, implementation and operation of sites will still be funded through national sources, but eLTER has already and will continue to significantly improve opportunities and competitiveness for receiving research funding. For now, a list of European calls on the eLTER website or a forum where questions and advice could be obtained for grant writing would be helpful. The Site and Platform Forum (SPF), for example, could also be in charge of supporting/guiding the sites in the acquisition of funds. With the final implementation of eLTER these services will be made available through the head office.

Automated data updating

Since eLTER focuses on long-term, ongoing research, it is necessary to frequently update datasets with newly acquired data. B2Drop was never intended as a permanent solution for eLTER data storage, and its replacement needs to incorporate this ongoing influx of new data. Constant maintenance is also required and data quality controls if the data did not already go through one or perhaps a second filter to ensure odd data did not get through, as was seen in Task8.2. The development of these workflows is a central part of WP10 and WP11 in cooperation with WP3, where the eLTER Standard Observations are being defined together with their methods and protocols.

Moreover, it will be necessary to link legacy data with newly acquired data. The Standard Observations will be measured with harmonized protocols, but this may differ from those applied in the past. Therefore, it is important to come up with ideas and methods how to link these data sets.

4 Scientific product: Drought effects on soil GHG fluxes in a boreal and a temperate forest

4.1 Methods

Site descriptions

The SMEAR II LTER site (Station for Measuring Ecosystem-Atmosphere Relations; https://deims.org/locations/499ec663-5d9b-42c4-a248-593199e78ea3) is situated in the managed Hyytiälä Forestry Field Station of the University of Helsinki in southern Finland (Fig. 4.1). The site is dominated by *Pinus sylvestris* L. (Scots pine) with other prevalent species include *Picea abies* (L.) H. Karst. (Norway spruce), *Betula pendula* Roth (silver birch), and *Betula pubescens* Ehrh. (downy birch) and some *Juniperus communis* L. (common juniper), *Salix* sp. L. (willow), and *Sorbus aucuparia* L. (mountain ash) (Ilvesniemi et al. 2009) The study locations (Toheli for CO_2; MaSa for CH_4 and N_2O fluxes) are in an even-aged Scots pine stand established by sowing after clear-felling, prescribed burning, and light soil preparation in 1962 (Hari et al. 2013). The understory plant species composition consisted of *Vaccinium myrtillus* L. (European blueberry), *Vaccinium vitis-idaea* L. (lingonberry), *Polytrichum commune* Hedw. (common haircap moss), *Pleurozium schreberi* (Brid.) Mitt. (red-stemmed feathermoss), *Hylocomium splendens* (Hedw.) Schimp (mountain fern moss), and *Deschampsia flexuosa* (L.) Trin. (wavy hair-grass). Further site characteristics can be found in Table 4.1.

The Rosalia Lehrforst LTER site (https://deims.org/77c127c4-2ebe-453b-b5af-61858ff02e31) is located in the eastern part Austria (Fig. 4.1) and is investigated by the University of Natural Resources and Life Sciences, Vienna. All major tree species and forest types in Austria are present at the site: *Picea abies* (L.) H. Karst., *Abies alba* Mill. (European silver fir), *Larix decidua* Mill. (European larch), *Pinus sylvestris* L., *Fagus sylvatica* L., *Quercus* sp. (oak), etc. The site has been forested since at least the end of the 19th century, probably for longer. The study location (DRAIN; https://deims.org/locations/b7008603-fca2-452f-9b3d-aad30cdafc7a) is in a mature *F. sylvatica* stand aged between 90-110 years. There is no understory beyond a small amount of *Rubus*. Further site characteristics can be found in Table 4.1.

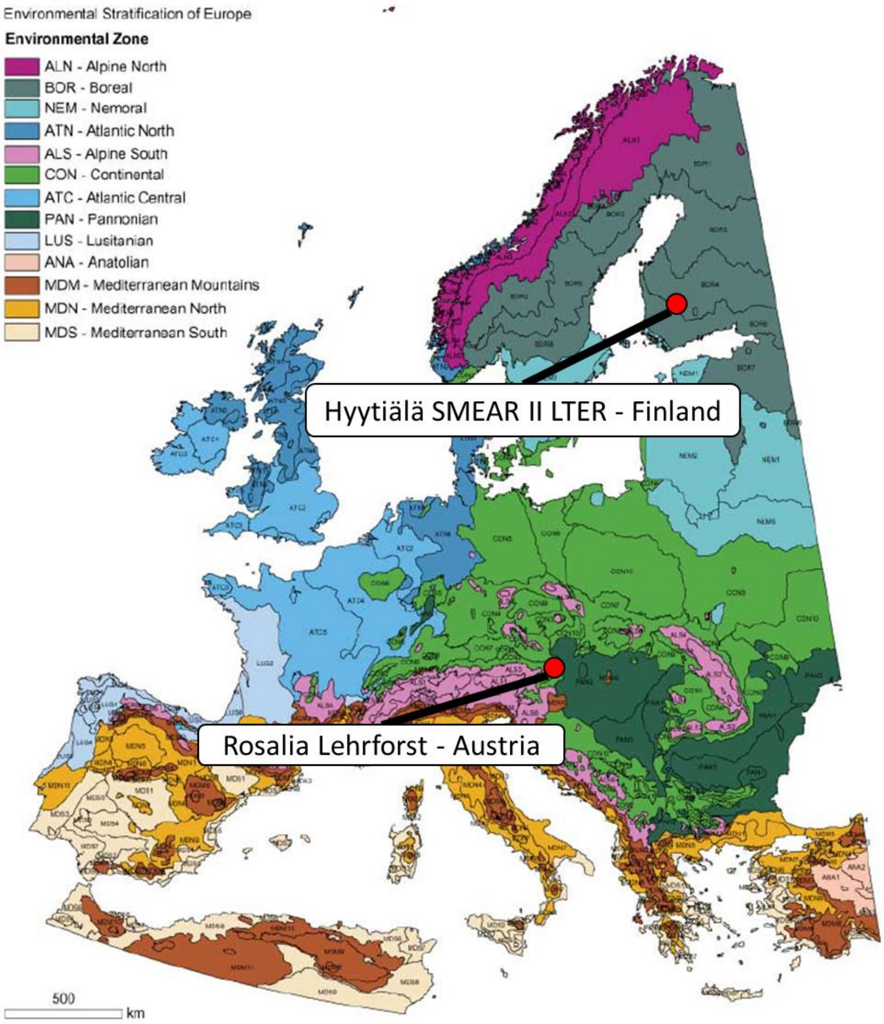

Fig. 4.1 Location of the two soil GHG flux data sites: Hyytiälä SMEAR II in Finland and Rosalia Lehrforst in Austria. The gas flux measurements were conducted in a forest at both sites. Map taken from Metzger et al. (2005).s

Table 4.1. Site characteristics.

	Unit	Hyytiälä SMEAR II	Rosalia Lehrforst
Country		Finland	Austria
Coordinates		61°51’N, 24°17’E	47°42’N, 16°17’ E
Elevation range	m a.s.l.	140-200	300-720
Elevation of measurements	m a.s.l.	181	600
Annual precipitation	mm	711	785
Mean annual air temperature	°C	3.5	6.5
Slope	°	0	14
Orientation		Not applicable	west-facing
Bedrock		Granite	metamorphic crystalline
Soil type*		Haplic Podzol	pseudo-gleyic Cambisol
Clay†	%	9	7
Silt†	%	40	47
Sand†	%	52	46
Bulk density	g cm^{-3}	0.74	0.60

pH		3.41	3.84
Soil C	%	3.89	4.55
Soil N	%	0.12	0.25

*according to WRB classification

†percent weight; FAO classification (Jahn et al. 2006)

Soil Greenhouse Gas flux measurements

At Hyytiälä SMEAR II, soil CO_2 fluxes were measured with three (2009-2014; see Pumpanen et al. (2015) for additional set-up details) or two (2015-2017) automatic, static chambers (total chamber volume 10 L, enclosed soil surface area 0.05 m^2) placed on an aluminium collar inserted into the soil 5 cm deep to avoid cutting tree roots and minimize sideways diffusion in the soil that could influence measured fluxes (Hutchinson and Livingston 2001). On the collar was a chamber made of acrylic glass that could close. The soil chamber was equipped with a fan to ensure mixing of the headspace air and a small vent hole to minimize pressure disturbances in the chamber headspace. During measurement, the chamber closed for 3.5 min every 30 min during which CO_2 fluxes were measured using a GMP343 diffusion type CO_2 probe (Vaisala Oyj, Vantaa, Finland, NDIR sensor), and the data were recorded at 5-second intervals by AD converters (Nokeval, Nokeval Oy, Nokia, Finland). Headspace temperature and relative humidity were measured using a thermocouple type K sensor and a semiconductor sensor (HIH-4000, Honeywell International, Inc.), respectively. The fluxes (mg CO_2 m^{-2} h^{-1}) were calculated using concentration change over time from outlier-filtered raw data collected between 40 s and 170 s from chamber closing using linear fit and corrected for air temperature and atmospheric pressure (Metcalfe et al. 2007). The chambers were initially transparent and later covered with aluminium foil for darkening. Measurements at night and with dark chambers were included in this dataset. In a previous study at the same location, no flux difference was found between transparent and opaque chambers, transparent chambers permitting photosynthesis of ground vegetation, and therefore, the presence of ground plants should not greatly influence CO_2 flux results (Vainio et al. 2021). The CO_2 fluxes from the different chambers were averaged to have a single flux estimate.

Hyytiälä SMEAR II soil N_2O and CH_4 fluxes were measured from 2007 to 2014 with one stainless steel, automated, static chamber, consisting of a permanent collar installed in the soil and a chamber that was closed on top of the collar (total volume 83 L, enclosed soil surface area 0.32 m^2). The chamber was equipped with a fan to ensure mixing of the headspace air and a vent-tube to minimize pressure disturbances. The gas concentrations were sampled during a 45-min closing time once per day. Fluxes were then calculated from the concentration change from outlier-filtered raw data collected using linear fit for N_2O fluxes (µg N_2O m^{-2} h^{-1}) or exponential fit for CH_4 fluxes (µg CH4 m^{-2} h^{-1}) and corrected for air temperature and atmospheric pressure. Negative values of exchange rates denote net GHG uptake by the soil from the atmosphere.

At Rosalia Lehrforst, soil CO_2, CH_4, and CH_4 fluxes were measured with an automated soil-atmosphere GHG flux detection system (Butterbach-Bahl et al. 1998), constructed by the Karlsruhe Institute of Technology, Institute of Atmospheric Environmental Research (KIT-IFU, Garmisch-Partenkirchen, Germany) (Díaz-Pinés et al. 2017; Dannenmann et al. 2018). The system encompasses 12 automated chambers and is part of a climate manipulation experiment (Leitner et al. 2017). For this work we included data from four automatic, static flux chambers, corresponding to the environmental control (no manipulation of the precipitation). The chamber had a total volume 37.5 L (enclosed surface area 0.25 m^2) made of transparent acryl glass with a stainless-steel frame installed on a stainless-steel frame inserted 5 cm into the ground. The chambers were equipped with fans to ensure homogeneous air mixing and with a non-force open vent for pressure equilibration in the headspace. Four chambers closed for 45 min during which the air in each chamber was sampled four times. The gas samples were transported from the chambers via stainless-steel tubes to a central valve switching unit using a gas pump (flow rate 250 ml min^{-1}, NMP 830 154 KNDC, KNF Neuberger GmbH, Germany). A gas aliquot was then transferred to a non-dispersive infrared CO_2 analyser (LI-840A CO2/H2O analyser, LI-cor, NE, USA) and another aliquot was derived to a SRI 8610 Gas Chromatograph (SRI Instruments Europe GmbH, Bad Honnef, Germany) for estimation of the CH_4 and N_2O concentrations, which were measured with a Flame Ionization Detector (FID) and a ^{63}Ni Electron Capture Detector (ECD), respectively. CO_2 was removed from the gas aliquot measured in the Gas Chromatograph with an Ascarite (sodium hydroxide-coated silica) Column. Calibration gas (400 ppb N_2O, 3 ppm CH_4 and 400 ppm CO_2 in N_2, Linde Gas GmbH, Stadl-Paura, Austria) was added every 45 minutes by duplicate. The four air samples taken during a chamber closure created a linear change of gas concentrations, the slope of which was used to calculated the gas flux rates (mg CO_2-C m^{-2} h^{-1}, µg CH_4-C m^{-2} h^{-1}, µg N_2O-N m^{-2} h^{-1}) which were corrected for air temperature and atmospheric pressure (Metcalfe et al. 2007). Gas flux measurements with a regression coefficient (R^2) <0.9 were discarded. Each chamber was measured roughly every 3 hours, thus eight flux measurement per chamber per day were produced. The GHG fluxes from the different chambers were averaged to have a single flux value data. Soil CO_2 efflux included respiration of ground vegetation, but very few plants were present on the forest floor at the site, and the influence of plants on the estimated CO_2 fluxes is therefore considered to be negligible.

The fluxes for all three GHG at both sites were averaged by day. At both sites, low temperatures, and/or snow cover prevented the continuation of the measurements during winter. Measurements were usually conducted from April to November at Hyyitiälä and from March to December in Rosalia.

Soil moisture and temperature measurements

At Hyytiälä SMEAR II, soil water content was measured between 2 and 6 cm depth with a Time Domain Reflectometer (TDR, Campbell Scientific TDR-100) connected to datalogger (Campbell 21X), multiplexers (SDMX50), and probes. The 15 cm-long, two-rod type probes were installed vertically but slightly descending deeper into the soil and were chosen to able to install them in the stony soil. The datalogger controlled the measurement sequence and applied algorithms that determined the apparent probe length and soil water content (Ledieu et al. 1986). The datalogger memory was transferred automatically daily to the main computer through a modified RS232/485 line. Soil temperature was measured between 2 and 5 cm depth using silicon temperature sensors (Philips KTY81-110) connected to serial data transmitters (Nokeval 5020) and then to the main computer through a RS232 line, where the temperature channels were read at 15-min intervals. Matlab scripts and functions were used to remove periods of instrument malfunctions or other known severe quality issues in the data, signal conversion from mV to appropriate physical units, and calibration correction. A basic quality check was also conducted to remove unrealistic values and of spikes by running mean or median filter below-canopy PAR by sensor location and soil variable (temperature and water content). The discontinuity in soil moisture time series caused by 2011–2012 pit renovation was corrected by adjusting the signals of the channels consistent with pre-2011 data using the continuous time series of soil temperature and moisture at the location of automated CH_4 chamber (site MaSa) and soil water potential data as the baselines.

In Rosalia Lehrforst, soil moisture (time-domain reflectometry; theta.ML2x probes, METER ENVIRONMENT, Munich, Germany) and soil temperature (thermistor Th2-f probes, METER ENVIRONMENT) were measured at 10 cm depth every 30 minutes. Probes were located within the same plot <2 m from the chamber measurements, and data was visually inspected and quality controlled.

All soil temperature and soil moisture measurements were averaged by day to correspond with the daily gas flux measurements.

Meteorological data

Hyytiälä SMEAR II precipitation measurements were the precipitation (liquid water equivalent) accumulated (mm) during previous 1 min using a Vaisala FD12P weather sensor at 18 m height. Air temperature (°C) measurement were made at 4.2 m height with a Pt100 sensor (platinum resistance thermometers) protected from solar radiation and ventilated by fans.

Rosalia Lehrforst air temperature and precipitation data were obtained from the nearby Heuberg Meteorological Station (~500 m away). Precipitation was measured by weight with a Sartorius QS8 (precipitation collected in 200 cm^2 collector) at 1.50 m height with a 30 min sum value. Air temperature was measured with an UMS RFT-2 at 2 m height with an average from 1-minute resolution measurements

Statistics

All statistical analyses and figures were run or created using R (version 4.2.1; R Core Team 2022) and RStudio (version 2022.7.2.576, RStudio Team 2015). Removal of unrealistic data or with issues was conducted with the quality checks described above. Data was then gap-filled using interpolation ‘na_kalman’ and ‘na_seadec’ functions in the imputeTS package (version 3.3, Moritz and Bartz-Beielstein 2017). This was done only for the measuring season, that is to say, data was not gap-filled before or after the first and last measurements of the year. This was done because there was no way to verify function extrapolations during these periods.

The permanent wilting point (PWP) was used as the threshold indicating a drought event, because it is the soil water potential threshold below which microbial activity is limited (Skopp et al. 1990; Davidson et al. 1998) and a plant wilts permanently (measured at 4.2 pF, -15 bar). So, in this study, when the soil water potential dropped below this threshold, concurrently with relatively high soil temperatures (i.e. above the annual average; as to filter out winter droughts), the soil was considered in a drought. Winter droughts were not considered since biogeochemical activity is already very low due to low soil temperatures. The duration was the number of consecutive days the PWP was reached. Severity was the percent the soil water content dropped below the threshold. The period before the first measured drought was labelled the ‘initial period’, each period below the PWP was labelled a ‘drought period’ and numbered consecutively, the period following a drought period was labelled a ‘post-drought period’ and again labelled consecutively. This factor variable, termed ‘soil moisture status’, was then included in the statistical models described below to compare the initial period with subsequent periods. At Hyytiälä SMEAR II, the PWP was obtained by laboratory measurement. In Rosalia Lehrforst, the PWP was estimated using the Saxton-Rawls method (Saxton and Rawls 2006). Palmer’s Drought Severity Index (PDSI; Heim 2002), which uses air temperature and precipitation data to estimate relative dryness, is frequently used in studies exploring soil drought (Dai 2013). However, it was not used here, because it did not capture the same drought dynamics as the soil moisture content and soil temperature measurements (example Fig. 4.2). Indeed, the soil moisture and soil temperatures are measured directly in the soil and therefore can better indicate soil moisture conditions making the PWP, which is a soil moisture threshold, a more accurate drought indicator.

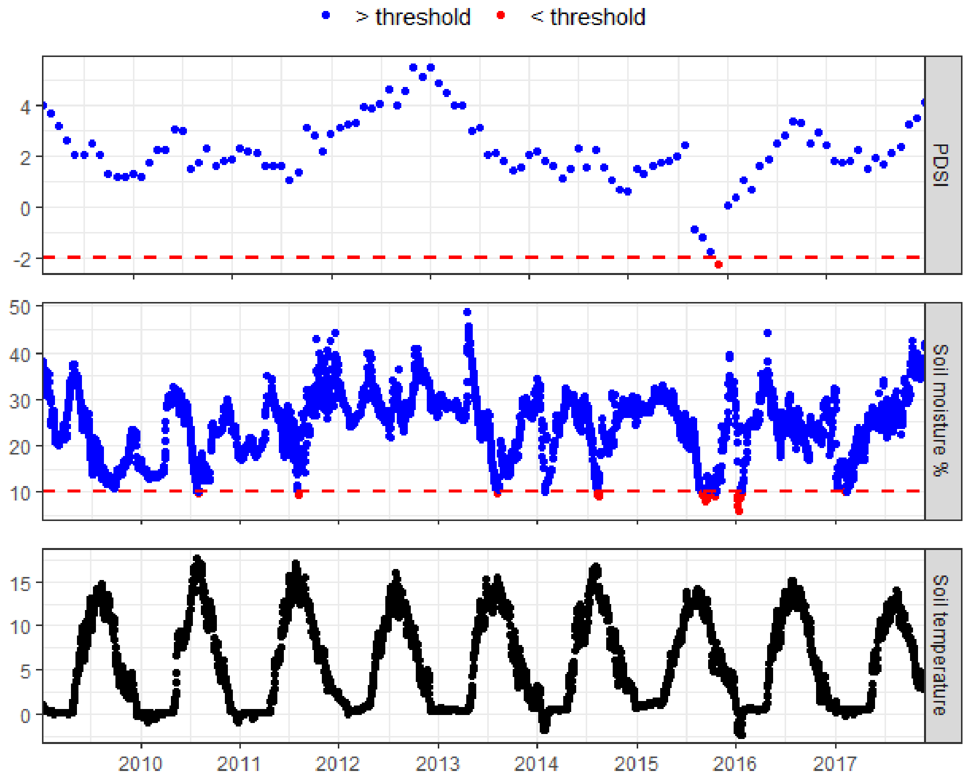

Fig. 4.2. Hyytiälä SMEAR II comparison between drought events identified by PDSI and soil moisture content. The drought threshold, under which the system is considered in drought stress (indicated by red), is defined as -2 for PDSI and as 10% (the permanent wilting point for the associated soil) for the soil moisture content. The soil temperature was used to verify the soil moisture drought stress.

Generalized additive models (GAM) were run, using the ‘gam’ function in the mgcv package (version 1.8.40; Wood 2011), to analyse the changes of the GHG fluxes (CO_2, CH_4, NO_2), soil moisture content, and soil temperature variables over the measured period. GAM was chosen to take into account the seasonal variability of these data (Wood 2017). In the GHG flux models, the moisture status was included as a categorical explanatory variable to see whether the fluxes were different between the ‘initial period’ and the ‘drought periods’ and ‘post-drought periods’, i.e. before, during, and after drought events. Smooth functions were applied to month and time individually, with month having a *cyclic* cubic spline and the number knots equalling the number of measured months. At Hyytiälä SMEAR II, CO_2 was measured nine months per year over nine years and CH_4 and N_2O for eight months per year over seven years, missing months being the winter months not measured. At Rosalia Lehrforst, CO_2 was measured ten months per year over three years and CH_4 and N_2O for nine months per year over three years.

Model structure:

gam(gas flux ~ moisture status + s(month, bs = "cc", k = number of months) + s(time, bs="cr"))

When there was autocorrelation, determined by visual inspection of auto-correlation function (afc) and partial auto-correlation function (pafc) graphs created using the stats package (version 4.2.1), generalized additive mixed models were run using the gamm() function (mgcv package) with the addition of the correlation function ‘corAR1’ with a form of ~1|month. Model assumptions and fit were verified using the ‘gam.check’ function (mgcv package), plotting the residuals, and R^2 were used to check model fit following the process described in Zuur and Ieno (2016). Soil moisture and soil temperature were analysed using the same model structure but excluding the soil moisture status.

4.2 Results

Using the drought threshold defined here (i.e. soil moisture content percent < permanent wilting point, PWP), five drought periods were identified for Hyytiälä SMEAR II (Table 4.2). The CO_2 flux measurement period overlapped all five droughts, while CH_4 and N_2O flux measurement periods overlapped the first three droughts. In Rosalia Lehrforst, three drought periods were identified, and all three GHG measurement periods overlapped these three droughts. Figure 4.3 shows daily precipitation and air temperature values during these drought events.

Table 4.2. Soil moisture status periods, including period duration in days and the severity of the drought, i.e. the soil moisture percent below the PWP threshold, during the drought period. When the three gases have different measurement durations, durations are separated by a semi-colon: CO_2;CH_4;N_2O.

	Hyytiälä SMEAR II			**Rosalia Lehrforst**		
	Year	**Duration (days)**	**Drought severity (%)**	**Year**	**Duration (days)**	**Drought severity (%)**
initial		469;1209;1209			119	
drought 1	2010	3	0.2	2013	103	5.2
post-drought 1		365	NA		235	NA
drought 2	2011	3	0.5	2014	8	2.0
post-drought 2		733	NA		20	NA
drought 3	2013	4	0.4	2015	100	3.9
post-drought 3		368;115;115	NA		85;54;46	NA
drought 4	2014	5;NA;NA	0.9			
post-drought 4		381;NA;NA	NA			
drought 5	2015	19;NA;NA	1.8			
post-drought 5		803;NA;NA	NA			

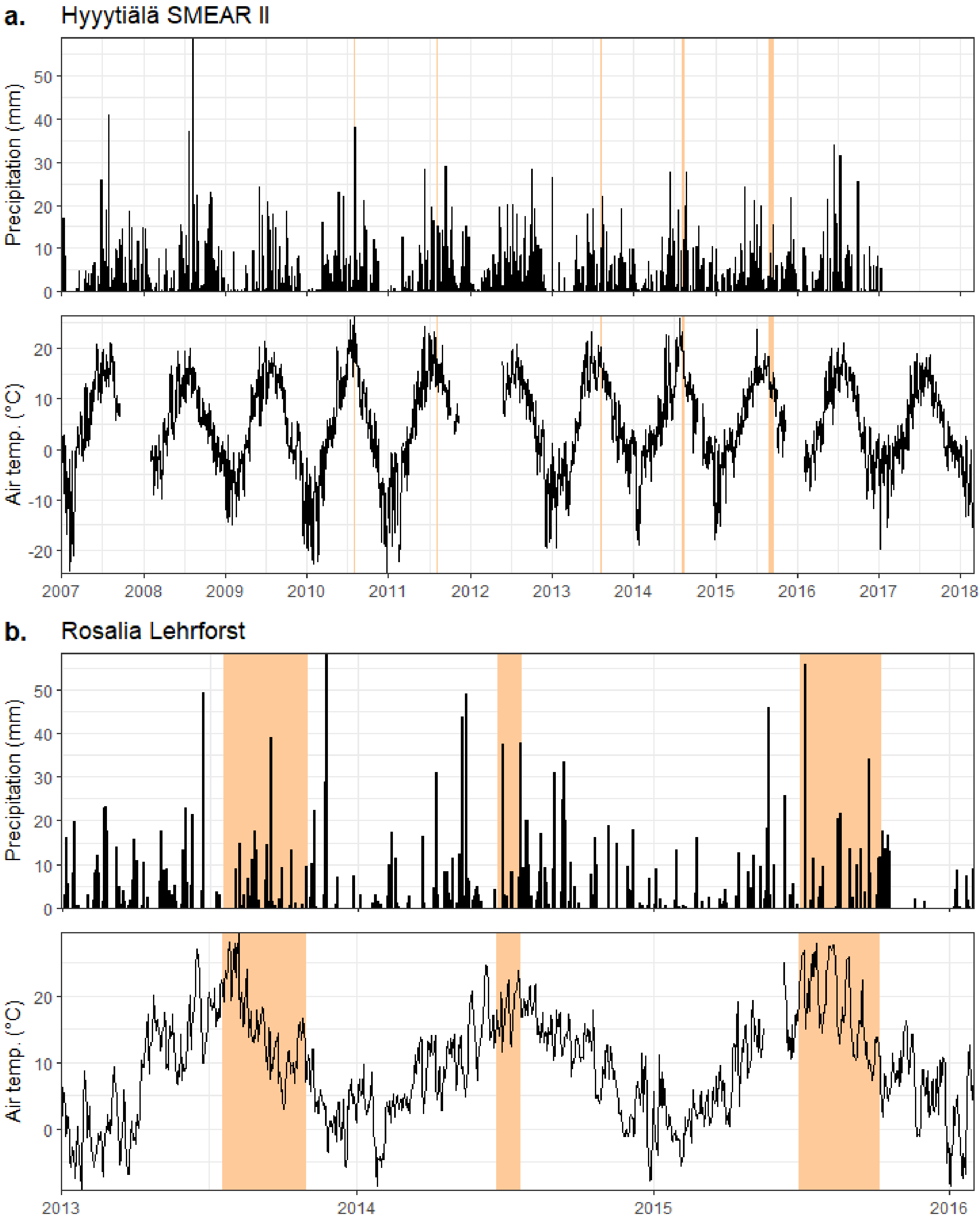

Figure 4.3: Precipitation (mm) and air temperature (°C) at (a.) Hyytiälä SMEAR II and (b.) Rosalia Lehrforst. Orange shaded periods indicate when the soil system was considered in a drought.

<u>Hyytiälä SMEAR II LTER</u>

Over the measurement period, soil moisture was 24.8 ± 6.9% on average. Moisture content was 4% higher in the post-drought 5 period as compared to the initial period (Fig. 4.4a), but this did not translate to a significant increase over time ($p > 0.05$; Table 4.3). Soil moisture content was highest post-drought 2 (9% higher than initially), but CO_2 fluxes were not significantly higher during this period. Soil temperature was 8.4 ± 4.2°C on average over the measurement period, and showed a strong significant temporal trend (Fig. 4.4b), with post-drought periods having higher soil temperatures than the initial period (0.2 to 1.1°C higher).

Over the nine years measured, the soils emitted an average of 120.0 ± 71.6 mg CO_2-C m^{-2} h^{-1}. There was a 13% increase in CO_2 emissions between the initial period (i.e. before drought 1) and last post-drought period (i.e. post-drought 5; from 109.0 ± 70.1 up to 123.0 ± 70.7 mg CO_2-C m^{-2} h^{-1}, respectively; Fig. 4.4c), with a significant time smooth effect, and a 2.8% increase between the first and last years 2009 and 2017 (from 107.0 ± 69.0 to 110 ± 69.8 mg CO_2-C m^{-2} h^{-1}, respectively). Supporting this, there was a significant difference between the initial flux period and the final post-drought period (post-drought 5; Table 4.3). No other period, drought or non-drought, was significantly different after autocorrelation was taken into account.

Over the seven years measured, the soils took up a net average of 139.0 ± 78.2 µg CH_4-C m^{-2} h^{-1} with a 76% increase in uptake between the initial and final moisture status periods (from 115.0 ± 40.5 µg CH_4-C m^{-2} h^{-1} to 202.0 ± 145 µg CH_4-C m^{-2} h^{-1}) and 114% increase between the first and last years 2007 and 2013 (from 87.6 ± 11.8 µg CH_4-C m^{-2} h^{-1} to 188 ± 136 µg CH_4-C m^{-2} h^{-1}; Fig. 4.4d). During the initial period, all soil CH_4 fluxes were uptake (average 115.0 ± 40.5 µg CH_4-C m^{-2} h^{-1}). As time progressed, the soil progressively started to emit CH_4 but also concurrently took up more CH_4, leading to an overall increase in variability in observations. In the final year, the soil emitted an average of 126.0 ± 190 µg CH_4-C m^{-2} h^{-1} and took up an average 205.0 ± 109 µg CH_4-C m^{-2} h^{-1}. The model results supported the significant difference between the initial fluxes and most subsequent periods, with a continuous increase in CH_4 uptake (Table 4.3). Even though the occurrence of soil CH_4 emissions increased with time, there was still a net CH_4 uptake as indicated by a significant time smooth effect and a strongly significant ($p = 0.0001$) negative decrease between the initial and final periods (initial period and post-drought 3, respectively). Overall, time and soil moisture status period (i.e. drought, post-drought, etc.) explained relatively little of the CH_4 flux variance ($R^2 = 0.26$).

Over the seven years, the soils emitted a net average of 0.6 ± 1.1 µg N_2O-N m^{-2} h^{-1} with a decrease between the initial and final soil moisture periods (from 0.82 ± 1.1 down to 0.14 ± 1.3 µg N_2O-N m^{-2} h^{-1}, respectively; Fig. 4.4e). Soil N_2O emissions decreased and uptake increased over time; the first, year soils emitted 0.93 ± 0.45 µg N_2O-N m^{-2} h^{-1} and took up 0.28 ± 0.0 µg N_2O-N m^{-2} h^{-1}, while in the last year soils emitted 0.52 ± 0.52 µg N_2O-N m^{-2} h^{-1} and took up 0.63 ± 1.36 µg N_2O-N m^{-2} h^{-1}. This trend was supported by the significant time smooth effect in the model results (Table 4.3). There were also significant declines between the initial period and all post-drought periods, with what appears to be stronger effects (estimate value) with each subsequent drought. Overall, like CH_4 fluxes, time and soil moisture status explained relatively little of the N_2O flux variance ($R^2 = 0.15$).

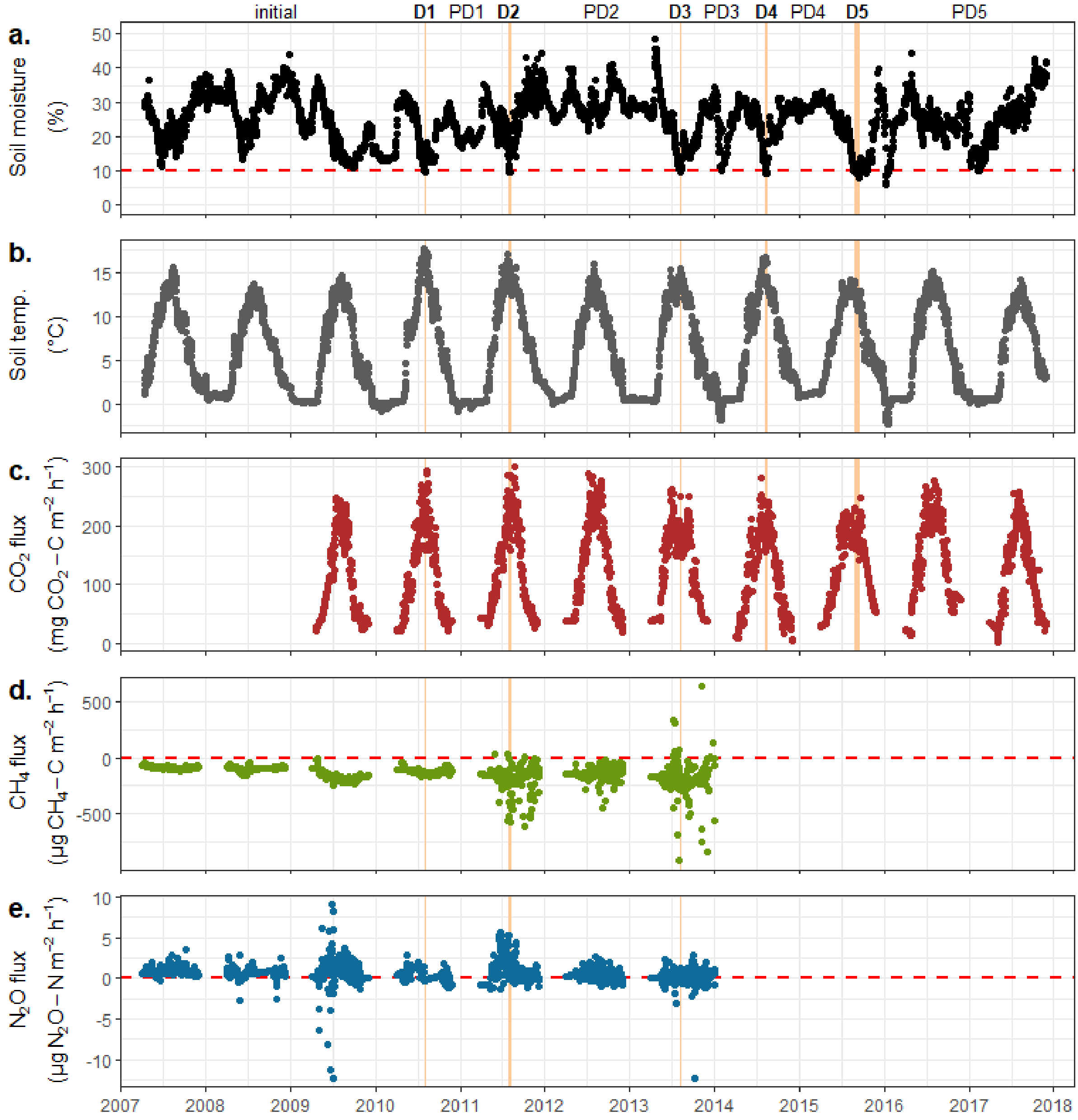

Figure 4.4: Hyytiälä SMEAR II (a.) soil moisture content (%), (b.) soil temperature (°C), (c.) CO_2 fluxes (mg CO_2-C m^{-2} h^{-1}), (d.) CH_4 fluxes (µg CH_4-C m^{-2} h^{-1}), and (e.) N_2O fluxes (µg N_2O-N m^{-2} h^{-1}) over time. Orange shaded periods indicate when the soil system was considered in a drought (winter 'droughts' were not considered here), and soil moisture status periods are labelled above (D = drought period, PD = post-drought period). The red, dashed line on the soil moisture figure indicates the PWP.

Table 4.3: Hyytiälä SMEAR II GAM results for the soil moisture, soil temperature, CO_2 fluxes, CH_4 fluxes, and N_2O fluxes.

Soil moisture content	**edf**	**Ref.df**	**F**	**p-value**		**R-sq.(adj)**
s(month)	2.07	6.00	0.92	0.03	*	0.08
s(time)	1.00	1.00	0.21	0.64		
Soil temperature	**edf**	**Ref.df**	**F**	**p-value**		**R-sq.(adj)**
s(month)	4.90	6.00	77.77	< 0.0001	***	0.83
s(time)	7.78	7.78	18.12	< 0.0001	***	

Soil CO2 flux	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**		**R-sq.(adj)**
(Intercept)	107.08	12.17	8.80	< 0.0001	***	0.83
drought 1	-7.69	12.80	-0.60	0.55		
post-drought 1	2.60	7.74	0.34	0.74		
drought 2	-15.80	15.92	-0.99	0.32		
post-drought 2	13.85	12.27	1.13	0.26		
drought 3	-36.07	18.39	-1.96	0.05	*	
post-drought 3	-7.98	14.88	-0.54	0.59		
drought 4	-25.92	20.55	-1.26	0.21		
post-drought 4	-9.05	18.30	-0.49	0.62		
drought 5	25.56	21.83	1.17	0.24		
post-drought 5	43.25	21.44	2.02	0.04	*	
	edf	**Ref.df**	**F**	**p-value**		
s(month)	5.39	6.00	207.97	< 0.0001	***	
s(time)	4.77	4.77	8.27	< 0.0001	***	
Soil CH4 flux	**Estimate**	**Std. Error**	**t-value**	**p-value**		**R-sq.(adj)**
(Intercept)	-111.52	9.58	-11.64	< 0.0001	***	0.26
drought 1	-32.81	67.92	-0.48	0.63		
post-drought 1	-38.72	16.45	-2.35	0.02	*	
drought 2	-120.14	51.08	-2.35	0.02	*	
post-drought 2	-45.37	20.22	-2.24	0.03	*	
drought 3	-99.14	53.07	-1.87	0.06	.	
post-drought 3	-125.25	28.34	-4.42	< 0.0001	***	
	edf	**Ref.df**	**F**	**p-value**		
s(month)	2.80	6.00	10.51	< 0.0001	***	
s(time)	8.76	8.98	27.06	< 0.0001	***	
Soil N2O flux	**Estimate**	**Std. Error**	**t-value**	**p-value**		**R-sq.(adj)**
(Intercept)	1.52	0.18	8.50	< 0.0001	***	0.15
drought 1	-1.02	0.96	-1.06	0.29		
post-drought 1	-1.25	0.24	-5.14	< 0.0001	***	
drought 2	-1.55	0.86	-1.81	0.07	.	
post-drought 2	-2.06	0.40	-5.21	< 0.0001	***	
drought 3	-1.58	0.91	-1.74	0.08	.	
post-drought 3	-2.01	0.50	-4.01	0.0001	***	
	edf	**Ref.df**	**F**	**p-value**		
s(month)	3.45	6.00	11.38	< 0.0001	***	
s(time)	5.62	5.62	6.65	< 0.0001	***	

Rosalia Lehrforst

Over the three years measured, the soil moisture content averaged 17.8 ± 6.1% with a 40% decline between the initial and last periods (from 23.8 ± 3.7 to 14.2 ± 1.0%, respectively) and an 18% decline between the first and last year (from 18.0 ± 6.8 to 14.5 ± 4.0%, respectively; Fig. 4.5a). Model results supported a significantly declined in soil moisture over the measured period (Table 4.4). Soil temperature averaged 10.2 ± 4.1°C with a decrease between initial and final periods (from 9.0 ± 4.0°C to 8.0 ± 1.6°C, respectively; Fig. 4.5b) but an increase between the first and last years (from 9.9 ± 4.4°C to 10.3 ± 4.2°C, respectively). Indeed, there was no significant temporal effect on soil temperature according to model results (Table 4.4).

The soils emitted an overall average of 71.7 ± 36.1 mg CO_2-C m^{-2} h^{-1}. There was a 50% decrease between the initial and last post-drought period (from 83.9 ± 36.7 to 41.5 ± 15.4 mg CO_2-C m^{-2} h^{-1}, respectively), whereas the second post-drought period showed a 22% increase (from 83.9 ± 36.7 to 102.0 ± 5.1 mg CO_2-C m^{-2} h^{-1}; Fig. 4.5c). Between the first and last years, 2013 and 2015, there was a 13% decrease in CO_2 fluxes. During the first and third drought, there was a decline in CO2 emissions, while during the second, and shorter drought, there was just an increase then a plateau. Although, fluxes appeared more influenced by seasonal trends than by drought periods. Model results did not show a significant soil CO_2 flux trend between the initial period or any subsequent drought or post-drought periods (Table 4.4).

Overall, soils had a net uptake of 44.9 ± 18.3 µg CH_4-C m^{-2} h^{-1} with a 33% increase in uptake between the initial and the last post-drought period (from 33.4 ± 13.9 to 44.7 ± 6.5 µg CH_4-C m^{-2} h^{-1} respectively) but a 20% decrease between the first and final years (53.8 ± 22.3 and 43.0 ± 16.1 µg CH_4-C m^{-2} h^{-1} in 2013 and 2015, respectively; Fig. 4.5d). The soil did not emit any CH_4 during the measurement period. CH_4 uptake was 38% higher during drought periods compared to non-drought periods (average 62.3 ± 5.1 µg CH_4-C m^{-2} h^{-1} vs. 45.2 ± 11.8 µg CH_4-C m^{-2} h^{-1}, respectively), with the increase starting before the drought period, i.e. before the soil moisture reached the permanent wilting point. Uptake decreased when the soil moisture content increased again. Model results showed significantly lower initial CH_4 uptake than most of the drought or post-drought periods (Table 4.4). The first drought and the last period (post-drought 3) were not significantly different from the initial period. The time smooth showed a significant change in CH_4 fluxes over the measured period.

Soils emitted an overall average of 3.8 ± 3.4 µg N_2O-N m^{-2} h^{-1} with a decrease in emissions between the initial and last post-drought period (from 7.1 ± 3.7 to 0.7 ± 1.3 µg N_2O-N m^{-2} h^{-1}, respectively) and between the first and last years (4.6 ± 3.7 and 1.4 ± 1.4 µg CH_4-C m^{-2} h^{-1} in 2013 and 2015, respectively; Fig. 4.5e). The first and second droughts appear to coincide with a decrease in N_2O emissions (average 1.8 ± 1.7 and 2.7 ± 0.6 µg N_2O-N m^{-2} h^{-1}, respectively), with a subsequent increase after the end of the drought. Fluxes appear less affected by the third drought but generally had lower emissions. N_2O uptake occurred during the first and last drought periods as well as during the last post-drought period (average 1.3 ± 1.2, 0.5 ± 0.5, and 0.3 ± 0.3 µg N_2O-N m^{-2} h^{-1}, respectively). There appears to be a general decrease in emissions and increase in uptake over time, but this is not supported by the GAM results (Table 4.4). There were no significant differences between N_2O fluxes during the initial period and any other period, and there was no significant time smooth effect.

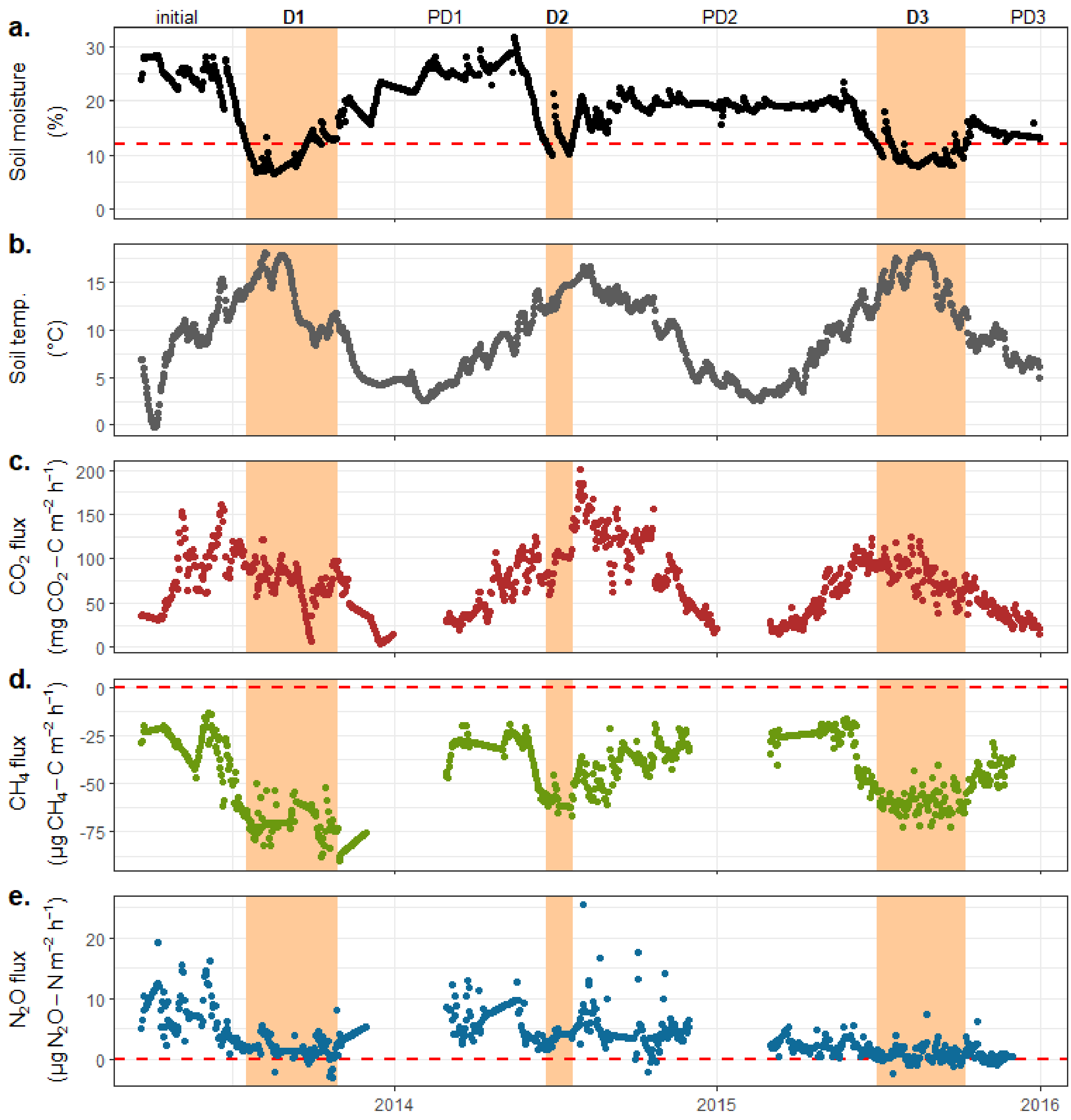

Figure 4.5: Rosalia Lehrforst (a.) soil moisture content (%), (b.) soil temperature (°C), (c.) CO_2 fluxes (mg CO_2-C m^{-2} h^{-1}), (d.) CH_4 fluxes (µg CH_4-C m^{-2} h^{-1}), and (e.) N_2O fluxes (µg N_2O-N m^{-2} h^{-1}) over time. Orange shaded periods indicate when the soil system was considered in a drought (winter 'droughts' were not considered here), and soil moisture status periods are labelled above (D = drought period, PD = post-drought period). The red, dashed line on the soil moisture figure indicates the PWP.

Table 4.4: Rosalia Lehrforst GAM results for the soil moisture, soil temperature, CO_2 fluxes, CH_4 fluxes, and N_2O fluxes.

Soil moisture content	**edf**	**Ref.df**	**F**	**p-value**		**R-sq.(adj)**
s(month)	2.72	8.00	2.68	< 0.0001	***	0.60
s(time)	2.00	2.00	162.78	< 0.0001	***	
Soil temperature	**edf**	**Ref.df**	**F**	**p-value**		**R-sq.(adj)**
s(month)	3.98	8.00	12.82	< 0.0001	***	0.84
s(time)	1.62	1.62	1.30	0.16		
Soil CO_2 flux	**Estimate**	**Std. Error**	**t-value**	**p-value**		**R-sq.(adj)**

(Intercept)	53.05	13.08	4.06	< 0.0001	***	0.65
drought 1	-10.37	7.67	-1.35	0.18		
post-drought 1	8.31	9.76	0.85	0.40		
drought 2	11.17	14.44	0.77	0.44		
post-drought 2	25.09	16.18	1.55	0.12		
drought 3	37.13	27.14	1.37	0.17		
post-drought 3	42.69	29.47	1.45	0.15		
	edf	**Ref.df**	**F**	**p-value**		
s(month)	4.30	8.00	9.52	< 0.0001	***	
s(time)	1.00	1.00	3.15	0.08	.	
Soil CH_4 flux	**Estimate**	**Std. Error**	**t-value**	**p-value**		**R-sq.(adj)**
(Intercept)	-36.4	6.2	-5.9	< 0.0001	***	0.80
drought 1	-4.4	3.9	-1.1	0.27		
post-drought 1	-12.9	5.7	-2.3	0.02	*	
drought 2	-23.6	7.4	-3.2	0.001	**	
post-drought 2	-17.2	8.2	-2.1	0.04	*	
drought 3	-34.2	14.8	-2.3	0.02	*	
post-drought 3	-24.9	16.9	-1.5	0.14		
	edf	**Ref.df**	**F**	**p-value**		
s(month)	4.43	7.00	9.14	< 0.0001	***	
s(time)	2.83	2.83	6.05	0.0004	***	
Soil N_2O flux	**Estimate**	**Std. Error**	**t-value**	**p-value**		**R-sq.(adj)**
(Intercept)	6.08	1.76	3.46	0.0006	***	0.57
drought 1	-1.19	1.08	-1.11	0.27		
post-drought 1	-1.44	1.43	-1.01	0.31		
drought 2	-2.04	2.10	-0.97	0.33		
post-drought 2	-1.03	2.31	-0.45	0.65		
drought 3	-5.09	3.87	-1.32	0.19		
post-drought 3	-6.66	4.18	-1.59	0.11		
	edf	**Ref.df**	**F**	**p-value**		
s(month)	2.87	7.00	2.41	0.0002	***	
s(time)	1.00	1.00	0.39	0.53		

4.3 Preliminary conclusion

In this study, we sought to identify the effects of soil drought events on soil GHG fluxes and general temporal trends at a boreal forest and a temperate forest site. Results showed significant changes for most GHG fluxes at both sites over the periods measured. Drought effects appeared more GHG-specific, but post-drought CH_4 uptake was consistently affected by soil moisture dynamics. In Rosalia, this CH_4 uptake sensitivity was visible well before soil moisture content dropped to drought conditions. Drought events also consistently, negatively affected N_2O fluxes in Hyytiälä. One caveat with *in-situ* measurements is the inability to control environmental factors and disentangle potential drivers of observed trends. Indeed, here, it is not possible to clearly distinguish between changes caused by the drought events themselves or by indirect climate change effects, e.g. via on-going decreased soil moisture, increased soil temperatures, or variables not measured here such as increased atmospheric CO_2 levels or N deposition. At Hyytiälä SMEAR II, for example, differences between initial and post-drought periods were found for all three GHG, but these results appear to be part of a larger, general trend oppose to a direct drought effect, notably for CH_4 and N_2O fluxes where there were measurements years before a drought event. At Rosalia Lehrforst, the limited 3-year measuring period also hindered a larger view of temporal trends. Although it is not possible to say with one hundred percent certainty the driver, there were nonetheless clear and significant temporal changes in soil CO_2, CH_4, and N_2O fluxes over the measured timeframes. This underlines the importance of long-term measurement networks such as eLTER to be able to detect and understand changes to BGC processes. These preliminary results also underline Hyytiälä as an important, large carbon sink for CH_4 and may become more so as time goes by. Indeed, the CH_4 sink strength of this site could outweigh the warming effects of its N_2O emissions (Skiba et al. 2009). Rosalia as well acts as a CH_4 sink, although to a lesser degree.

5 Acknowledgements

The deliverable presented here was performed within the project eLTER PLUS funded under the Horizon 2020 research and innovation programme under grant agreement No 871128 (eLTER PLUS) with the assistance of the project eLTER PPP No 871126 (eLTER PPP). Thank you also to site managers and all associates for their support in answering the survey, delivering data, providing data user assistance, and participating in the eLTERSoilPara project. Thank you to all collaborating WP for all support provided.

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