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# Impact of various flood conditions on the $CO_2$ ecosystem exchange as a component of floodplain grassland restoration

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ABSTRACT

Beyond flood protection to prevent severe damage, the restored floodplain grassland in Austria provides ecosystem services in terms of carbon balance. Net ecosystem exchange (NEE), gross primary productivity (GPP), and ecosystem respiration ($R_{eco}$) were quantified by the eddy covariance (EC) method before, during and after a severe flooding event. Our results show that the carbon balance is heavily influenced by water level in the study site. The diurnal variations influenced by various degree from the flood are analysed, showing the average daily GPP of the floodplain grassland in Marchegg dropping from 1.048 g C $m^{-2}$ $day^{-1}$ before the flood, down to 0.470 g C $m^{-2}$ $day^{-1}$ during the flood. The study demonstrates that the restored floodplain grassland in Marchegg functions as a robust CO2 sink with a cumulative NEE of 38.8 g carbon per m2 over the three-month study period, despite temporary disruptions caused by flooding events. The findings emphasise the considerable potential of floodplain grassland restoration for carbon storage and climate change mitigation, with the new data from the EC station offering valuable insights for future restoration projects. Finally, this supports the adoption of the new EU Nature Restoration Law and the need for restoring wetlands, floodplains and rivers to secure water availability and biodiversity in these unique ecosystems. NBS and more specifically as Soil and Water Bioengineering (SWBE) are methods with ecological advantages and a huge potential for sustainable recreation of near-natural ecosystems. It is of crucial importance to prove these beneficial effects, and to quantify them transparently in terms of quality assurance and use of resources in a sustainable and eco-friendly way.

## 1. Introduction

Wetlands are crucial ecosystems, covering only 5–8 % of Earth's surface but providing essential ecosystem services, including carbon sequestration, thus wetland restoration can contribute to mitigate climate change (Mitsch et al., 2013). Wetlands act as natural buffers between land and water, absorbing and slowly releasing surface water, rain, snowmelt, and floodwaters, which helps reduce flood heights and erosion (Gibbens, 2024; EPA, 2024). Their ability to provide ecosystem services, such as flood mitigation, water quality improvement, and climate regulation, underscores the urgency of wetland restoration. This is supported by initiatives like the EU's Nature Restoration Law, adopted in June 2024. Restoring wetlands through nature-based solutions (NBS) enhances both biodiversity and human well-being (IUCN, 2020).

Restoring wetlands through techniques such as Soil and Water Bioengineering (SWBE) can enhance their ability to provide a wide range of ecosystem services, including provisioning (e.g. biodiversity, biomass), regulating (e.g. mitigate disturbances, improving water balance and soil structure, filtering pollutants, climate regulation), cultural (recreation, aesthetics, education) and supporting services (e.g. nutrient cycles, primary production). A key service of SWBE measures is their role in absorbing and storing carbon, contributing to climate mitigation efforts. SWBE combines natural materials and biological components to improve both ecological and engineering outcomes (Bischetti et al., 2014; Evette et al., 2009). SWBE has been extensively studied, with numerous technical guidelines developed (Begemann and Schiechtl,

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1994; Florineth, 2012; Gray and Sotir, 1996; Rey et al., 2019; Schiechtl, 1980; Schiechtl and Stern, 1994; Zeh, 2007). Unlike conventional engineering, SWBE integrates biological components, emphasizing ecological and aesthetic values alongside technical functions (Rauch et al., 2014; Rauch et al., 2022). Numerous real-world applications have demonstrated the successful implementation and advantages of SWBE, highlighting its potential to enhance biodiversity, sustainability and resilience in various environments (Kettenhuber et al., 2023; Preti et al., 2022; Rey et al., 2019). SWBE structures, which rely on living plant material, are generally considered environmentally friendly due to their ecological value. However, there is a growing need to further develop SWBE, particularly to address climate change challenges. Optimizing these structures to enhance benefits like carbon storage and urban heat island reduction, while minimizing negative effects such as greenhouse gas emissions and energy use, is crucial (von der Thannen et al., 2021; von der Thannen et al., 2020). Assessing the ecological success of SWBE structures is essential for their future use in NBS for river and wetland restoration. This necessitates a clear delineation between coastal and inland wetlands. Inland wetlands, such as swamps, bogs, and floodplains, can act as both carbon sinks and sources, depending on factors such as vegetation, hydrology, and management practices (Valach et al., 2021). This study aims to assess the effect of SWBE, particularly in restoring the hydrological conditions of a grassland floodplain, which play a key role in controlling carbon fluxes by influencing the balance between carbon dioxide ($CO_2$) and methane ($CH_4$) (Temmink et al., 2022; Wang et al., 2024; Wei et al., 2022). Changes in water levels or flooding regimes can significantly alter a wetland's carbon budget (Bohn et al., 2007; Christensen et al., 2003). Understanding the carbon sequestration potential of restored wetlands is vital for mitigating climate change (Dalmagro et al., 2018; Pugh et al., 2018; Scheingross et al., 2021, yet many wetland types, such as floodplain grasslands, remain understudied in this context (Helbig et al., 2022; Mander et al., 2024; McDonald et al., 2023).

Thus, this study aims to address this research gap by exploring how restored hydrological regimes via SWBE influence carbon exchange in floodplain grasslands. Using the eddy covariance method, which provides direct measurements of the metabolic responses of ecosystems to ecological and biological influences (Baldocchi, 2020), we measure the effects of floodplain grassland restoration on ecosystem carbon fluxes over three months, particularly focusing on the impact of severe flooding in June 2024. This will investigate the effect of sudden flooding on ecosystem greenhouse gas (GHG) budgets. This study contributes to the understanding of how floodplain grassland restoration can optimise carbon storage and support climate change mitigation efforts.

## 2. Material and method

### 2.1. Study site description and restoration process

The study site is located in the floodplain of the Morava River, in the nature reserve “Untere March Auen”, in the very east of Austria, between the municipalities of Marchegg and Zwerndorf (Fig. 1). In addition to near-natural riparian forests meadows and water meadows characterise the 1100 ha nature reserve. The site in this study is owned partly by the World Wide Fund for Nature (WWF Austria) and partly by a private family. Access to the site was provided by them with legalisation by the nature conservation department of the province of Lower Austria.

Originally owned by a family, the area was acquired jointly by the WWF and the municipality of Marchegg in 1970. In 1972, the Völkl family bought their share from the municipality of Marchegg. The area was finally designated a nature reserve in 1978. Since then, WWF has managed the area as a model farm for sustainable forestry and agriculture. Eyrie protection zones and natural forest reserves form core zones where nature is left to its own devices. For about 15 years, forest

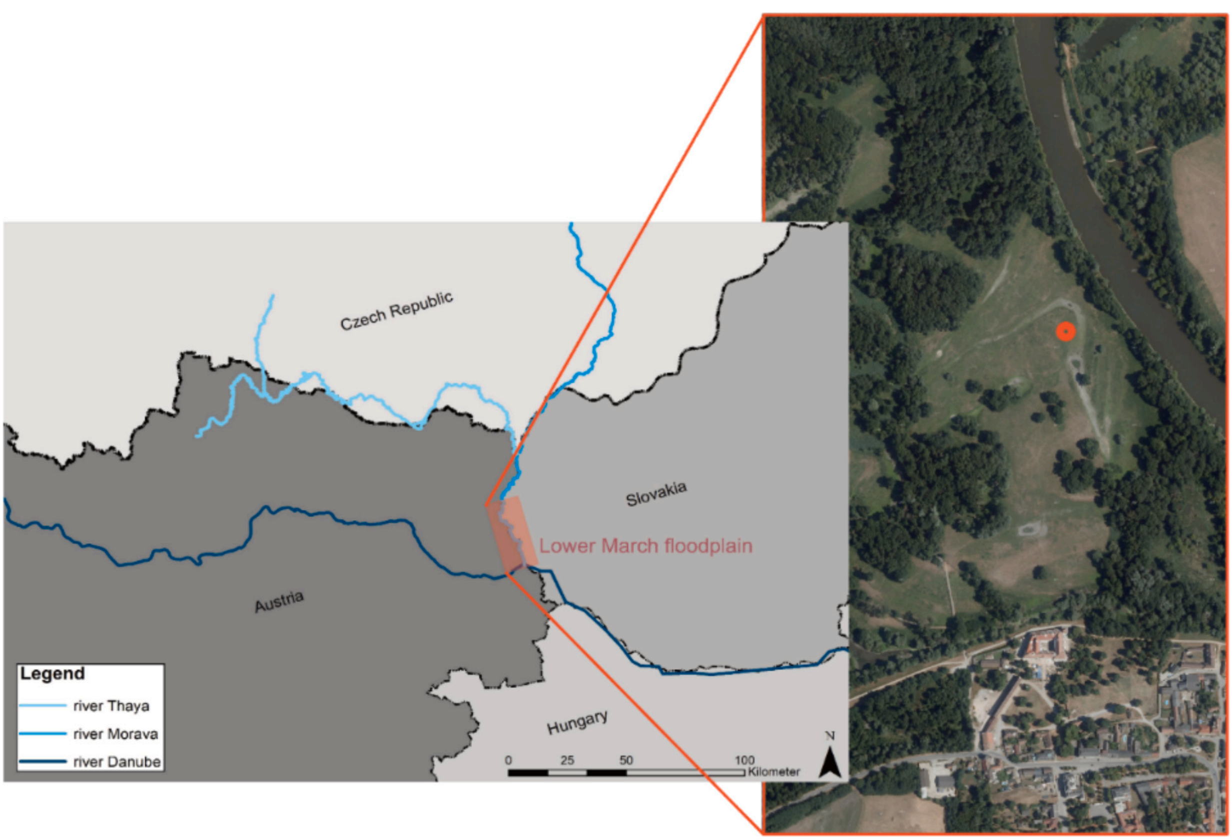


**Fig. 1.** Location of the study site at the border of Austria and Slovakia in the nature reserve near Marchegg, Lower Austria. The red dot marks the location of the EC station. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

management activities have been kept to a minimum, limited mostly to tasks like removing invasive species. Meanwhile, the open grassland continues to be mown, and for the past nine years, a portion of this grassland has been designated for year-round grazing.

The Morava River is the largest left-bank tributary of the upper Danube and a Pannonian lowland river in Austria. Typical of this type of river, it used to flow slowly in meandering, sometimes wider, sometimes narrower, through a landscape of extensive floodplain forests, riparian forests and meadows. Frequent flooding (typically in early spring due to snowmelt) is essential for the meadows and forests of the floodplain and its species. The soil is typical of a floodplain and is characterised by a gleyed grey soil of fine alluvial material. As a result of regulation and intensification in the last century, the river is now only of moderate status (according to the European Commission's Water Framework Directive) and habitats for endangered species of flora and fauna are limited.

In the course of the regulation of the Morava River in the 20th century, all meanders and tributaries were cut off. 75 % of the banks were stabilized with heavy armor stones and a uniform width and course was created, i.e. the Morava was canalised. The course of the river was straightened and shortened from 80 to 69 km. Since then, the river has dug up to 1.5 m into its bed. The river, its surroundings and large parts of the floodplain have been drained more and more. In addition, a large part of the floodplain meadows disappeared because of the industrialization of agriculture and other land use - and with them large areas of habitat for many rare animals and plants. The first recognizable consequences of the climate crisis are enhancing the negative effects of the interventions in nature, e.g. lack of snow in winter and increasing drought in spring and summer. As part of the EU-funded LIFE project "Renaturierung Untere March-Auen", the project partners viadonau - Österreichische Wasserstraßen-Gesellschaft mbH, WWF Austria and Niederösterreichischer Landesfischereiverband carried out ambitious renaturation and species protection measures from October 2011 to October 2019. The aim of the project was the extensive restoration of near-natural river dynamics in the Lower Morava floodplains, the extensification of management, as well as targeted measures to safeguard the populations of endangered species. The LIFE project has succeeded in dynamising and enhancing this habitat in a sustainable way (Egger et al., 2022).

### 2.2. Hydrological conditions

In light of the restoration process that took place between 2011 and 2019, it is imperative to consider the unique characteristics of the study site. The study site is situated on a floodplain meadow, that is part of an all-year grazing project. It is located within a flood protection dike, so it is linked to the main flow conditions of the Morava River by an ox-bow (the river itself is still heavily regulated), which permits regular flooding as a result of high-water levels in the Morava River, either caused by flood events of the Morava River (e.g. snowmelt, heavy rain etc.) or the backwater effect of the Danube (15 km downstream). So, the study site shows near natural floodplain habitat conditions, despite the still restricted hydromorphological conditions of the river. In order to ensure the protection of the local population, the Federal Ministry Republic of Austria – Agriculture, Forestry, Regions and Water Management in the department HORA (Natural Hazard Overview & Risk Assessment Austria) has conducted flood modelling for the entire area. Water levels of up to 3 m may be reached in the grassland of the study site. Following a flood, the water level recedes at a gradual pace, resulting in the formation of standing water bodies in lower areas. The water subsequently evaporates and leaches away over time. Following the restoration process, the area is subject to periodic flooding. The recurrence of flooding is dependent on the frequency of extreme weather events, with the area experiencing 15 cm of flooding annually, 38 cm every two years, and 1.38 m every 30 years. The most recent extreme flooding event occurred on 6th July 2013, with a recorded depth of 2.67 m, while the most recent significant flooding event was in 2020.

### 2.3. Eddy covariance station in a floodplain grassland

The EC system was installed in October 2023 in a clear-cut area within the floodplain of the WWF - alluvial reserve at Marchegg. Due to unforeseen flooding concerns (see Chapter 2.2), the EC system was installed on a self-sufficient floating platform to safeguard the measurement instruments from the effects of water level fluctuations and larger flood events (see Fig. 2). The construction and design were based on the approach outlined by Dušek et al. (2009), for the ecosystem station in Třeboň.

To calculate the flux exchange from the ecosystem to the atmosphere a 3D-sonic anemometer (Gill Instruments Ltd., Lymington, Hampshire, UK) with a sampling frequency of 20 Hz frequency was installed to measure continuously the three wind components, and thus the vertical wind component of the eddies. Simultaneously, $CO_2$ and $H_2O$ concentrations were monitored using an open path gas analyser (LI-7500 DS, LI-COR Biosciences, Lincoln, NE, USA), collecting continuously data with a frequency of 10 Hz. This study analysis the data collected from 1st of May until the end of July 2024.

Additionally, meteorological parameters were measured in a one second interval by the EC tower. Solar radiation data were obtained from a radiometer (Kipp&Zonen B.V., The Netherlands). Rainfall was recorded using a tipping bucket rain gauge (Texas Electronics, USA), and photosynthetic photon flux density was measured using a Quantum Sensor (LI-COR, USA). Microclimate data, including air temperature, air humidity, soil temperature and soil heat fluxes (Hukseflux Thermal Sensors B.V.) (measured at three locations along a transect), and soil

**Fig. 2.** EC station in the WWF- alluvial reserve at Marchegg on the grassland in March 2024 (upper), and flooded in February 2024 (lower). To solve power issues a second solar panel was added end of February 2024.

water content (measured at two sensors), were collected every 5 s and averaged over 30-min intervals using a data logger (Sutron Xlite, Germany).

In order to select an appropriate measurement height, it is necessary to ensure that the sensors are positioned at a sufficient height to enable the well-mixed surface layer above the plant canopy to be measured, while also avoiding disturbances to the measurements caused by the roughness layer. Conversely, the sensors should be positioned at a sufficiently low level to ensure that the footprint expansion does not extend beyond the boundaries of the designated study area. Accordingly, for the floodplain grassland under study, with a mean canopy height ($h_c$) below 1.75 m, the measurement height must be within the range of 1.67 $h_c$ to 6 hc (Rebmann et al., 2018). In consideration of the mentioned criteria, the measurement height was determined to be 2.7 m, with a vegetation height of between 0.1 and 0.5 m, contingent upon the point of the growing season.

The footprint modelling was conducted in accordance with the methodology proposed by Kljun et al. (2015). As a result of the footprint analysis conducted over the initial four-month period after set up, the station was relocated end of January 2024 towards the northwest to facilitate the acquisition of a more expansive field with an undisturbed upwind direction and at the same time to reduce an insufficient wind fetch in the east to only 45–115°. Fig. 3 illustrates the wind rose and analysis of the footprint in January 2024, prior to the relocation, and in March 2024, following the relocation. It is evident that the relocation has reduced the disturbance of the wind due to the presence of higher vegetation from the main wind directions of northwest and southeast. Consequently, the data set can be expanded for subsequent analysis

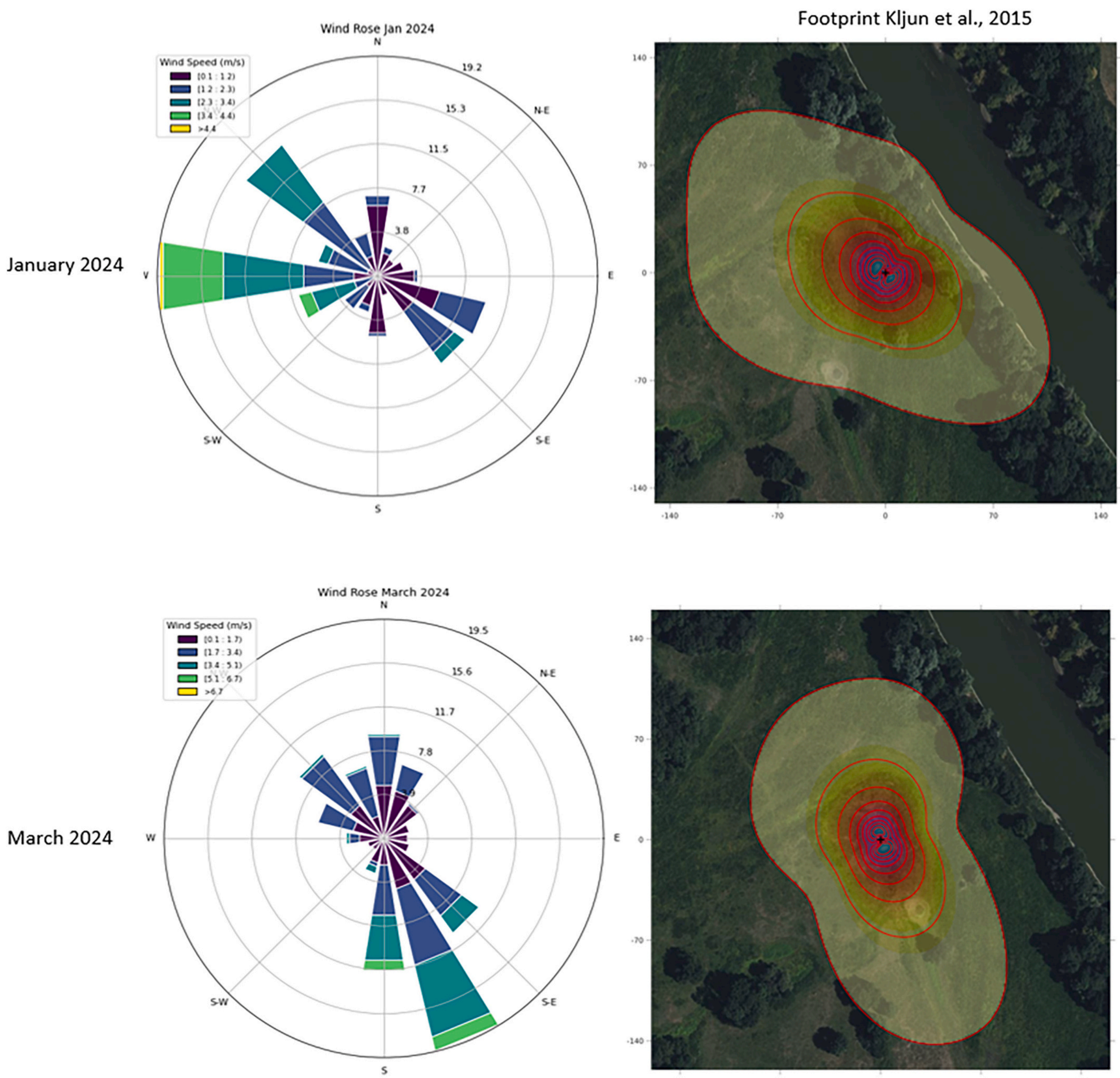


**Fig. 3.** Footprint analysis of the EC station after Kljun et al., 2015 before the measures to reduce interference of the EC measurements in January 2024 (upper) and after in March 2024 (lower).

following the relocation. Thus, after the relocation only data with wind direction from the river and the neighbouring trees must be excluded from the footprint area. The final coordinates of the EC station after the relocation are 48.28677842376566°N, 16.906963932173966°E on an altitude of 131 m. However, the availability of an adequate upwind fetch with minimal interference does not guarantee the representativeness of the footprint for the entire restored area. The site exhibits considerable heterogeneity, encompassing forest areas, grassland, and water channels with varying extents of open water over time due to flooding.

Following the resolution of issues pertaining to the utilisation of disparate measurement instruments and power supplies, the EC system has been capable of measuring $CO_2$ concentration and vertical wind, thereby enabling the continuous calculation of the $CO_2$ flux between the ecosystem and the atmosphere since March 2024. This has facilitated the quantification of ecosystem services pertaining to a restored floodplain area in terms of carbon balance. This study analyses data collected between 1st May and 31st July 2024, which encompasses the period of severe flooding along the Danube catchment area in early June 2024.

### 2.4. Flux calculation and quantification of NEE, GPP, $R_{eco}$

The exchange rate of $CO_2$ and $H_2O$ between atmosphere and plant canopy is quantified by measuring the covariance between fluctuations in vertical wind velocity of air eddies and $CO_2$ or $H_2O$ mixing ratio by the eddy covariance (EC) method (Aubinet et al., 2012; Baldocchi, 2003). The flux can be described as (Burba, 2013)

$$F = \overline{p_d ws} \tag{1}$$

with ρd as dry air density, w is the vertical wind speed, and the dry mole fraction of the gas of interest (s). The theory with physical equations and limitations of the EC method are descibed in detail in Aubinet et al. (2012), Burba (2013), Foken (2008). The EC method is an accurate and widely used method for measuring fluxes from the surface to the atmosphere, ecosystem gas budgets, and emissions from different ecosystems, including agricultural and urban areas, forests, and wetlands (Baldocchi, 2020; Kowalska et al., 2013). In order to obtain precise carbon flux calculations, the EC method is predicated on the assumption of unchanging atmospheric conditions with regard to wind, temperature, humidity and $CO_2$. Furthermore, the terrain should be relatively flat, with homogeneous vegetation at the study site, and no significant wind disturbances due to changes in roughness (Baldocchi, 2003).

The partitioning of night-time data to obtain gross primary production (GPP), ecosystem respiration ($R_{eco}$) and net ecosystem exchange (NEE) was conducted using micrometeorological data, in accordance with the methodology described by Reichstein et al. (2005) with

$$NEE = GPP - R_{eco} \tag{12}$$

Positive and negative NEE values represent sinks and sources of atmospheric $CO_2$, respectively.

### 2.5. Instrument precision and quality control

The LI-COR LI-7500 DS provides fast response measurements, with a frequency of 10 Hz used to collect the data for this study. This allows the vertical fluxes of $CO_2$ in the ecosystem to be calculated. With an instrument accuracy within 1 % of reading and an RMS noise of 0.11 ppm at 10 Hz, the instrument provides reliable data. To ensure comparability with international standards, the guidelines established by Rebmann et al. (2018) were strictly followed. However, a quality check is necessary as certain factors can affect the measurements and lead to measurement errors. The raw data of the $CO_2$ and $H_2O$ densities, measured with an infrared gas analyser at a frequency of 10 Hz, and the 3D wind data were processed every 30 min. The data were processed using the EddyPro v 6.1.0 software (LI-COR Inc., USA), which is recommended for obtaining more comparable results of fluxes and quality flags (Fratini and Mauder, 2014). To calculate the 30-min EddyPro output the despiking method as described by Mauder et al. (2013) was employed. The Tovi™ software (LI-COR Inc., USA) was used for quality screening according to the methodology proposed by Isaac et al. (2017). A reduction in signal strength has a detrimental effect on the reliability of the data obtained, so for the LI-7500DS used to measure $CO_2$ and $H_2O$ concentrations, the data set was filtered to exclude measurements with a signal strength of less than 93 %. In addition, Foken flags (ranging from 0 to 2, with 2 representing the lowest quality) were applied using only values of 0 and 1 for the calculated fluxes (Mauder and Foken, 2006). In addition, any data points that were deemed to be inappropriate spikes or periods with problems in the measurement tools or measurement errors were excluded. The MPT u* threshold detection and configurable gap filling was applied following Reichstein et al. (2005). However, it should be noted that the data did not have any significant gaps. For the analysis of NEE, GPP and $R_{eco}$ no gap-filling was applied as only three months of data have been analysed to investigate the effect of sudden flooding.

## 3. Results

### 3.1. Hydrological conditions

To elucidate the flooding in the clear-cut of the floodplain forest in Marchegg, which followed the severe flooding events in southern Germany and along the Danube catchment in Austria the precipitation values are investigated. The report of Mohr et al. (2024) presents the record rainfall in the whole region of southern and western Bavaria and in eastern Baden-Württemberg, causing widespread flooding, particularly along the right tributaries of the Danube from the Iller to the Isar, with precipitation totalled over 100 mm within 48 h across the region. The daily and cumulative rainfall in southern Germany (Donauwörth-Osterweiler), which was hardly affected by floods are presented representative for the whole region. The precipitation is provided publicly by Deutscher Wetterdienst (DWD) in a daily resolution over the three-month study period. On 1st June, south Germany experienced heavy rainfall, with precipitation levels reaching nearly 100 mm in less than 48 h (see Fig. 4). This was followed by a severe flooding event, which caused significant damage across the region. The intense precipitation in the Danube catchment area, particularly in southern Germany, resulted in elevated water levels in the Danube in Austria, creating a backwater effect in the Morava River and subsequently causing flooding at the study site.

The data regarding the water level are provided and publicly available at a 30-min resolution at the NÖ Landesregierung, with viadonau acting as the operator. During the study period, the water level of the Danube at Thebnerstraßl reached an extreme high-water level above the highest navigable water level (HNWL) of 2020 (638 cm) on 4th June until 8th June 2024, with a maximum of 719 cm on 5th June. The water level of the Morava river exceeded the mean value of 251 cm in the study period several times. The data set was divided into different periods based on the water level data of the Danube and the Morava river (Fig. 5). The interval between the 1st of May 2024 and the 31st of May represents the pre-flood period. The water reached the study site at approximately 4:00 am on 4th June, coinciding with a Morava river water level above 350 cm, which is the threshold for flooding of the study site. On 5th June 2024, the maximum recorded water level was 468 cm with a water level in the open lab reaching approximately 1.5 m, which corresponds to a 30-year event. This period where the whole study site is completely flooded from the first flood wave in the three-month study period persisted until 8th of June. As the water slowly retreats the period between 9th and 18th June is indicated in the following analysis as directly after the flood with still a lot of water bodies in the study site. Everything after is defined as period after the flood. However, from 2nd July at 12:00 until 5th July, a minor flood with Morava water levels reaching approximately 380 cm occurred, resulting in the partial inundation of the lower area of the study site. This smaller second flood wave was excluded from the diurnal NEE

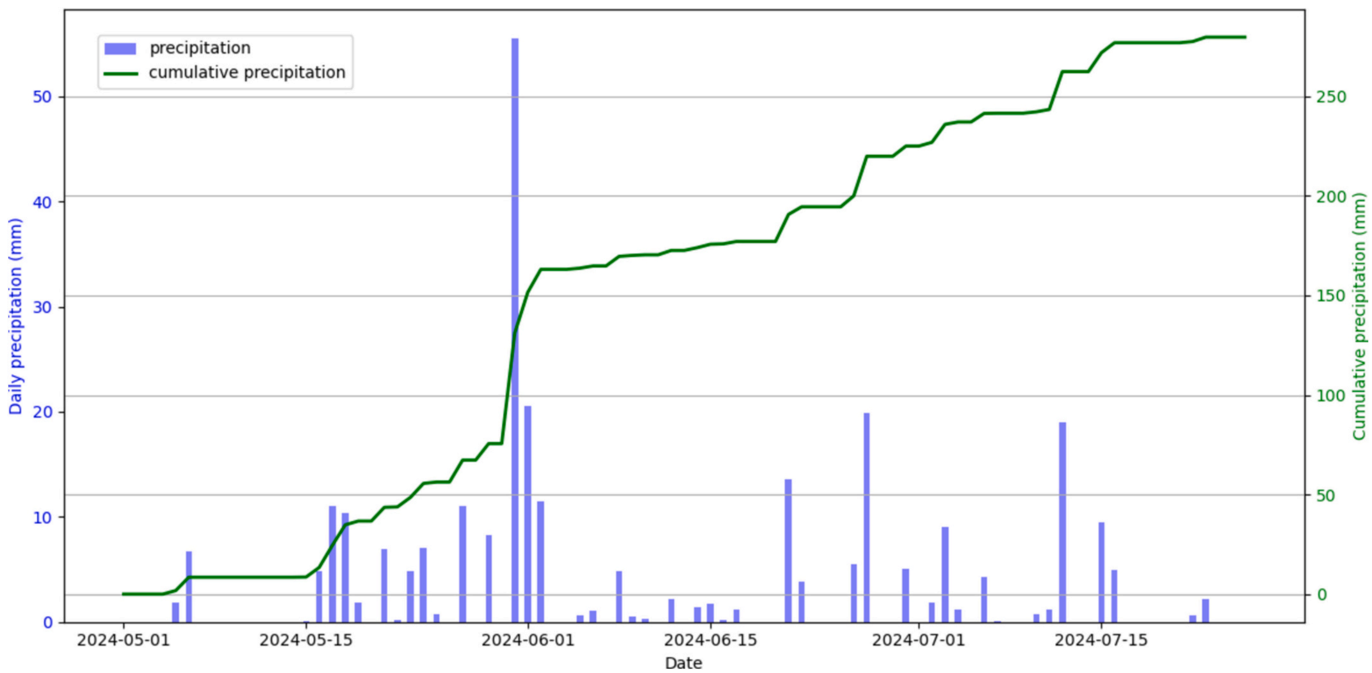


**Fig. 4.** Daily and cumulative precipitation in south Germany at the weather station Donauwörth-Osterweiler from May until end of July 2024.

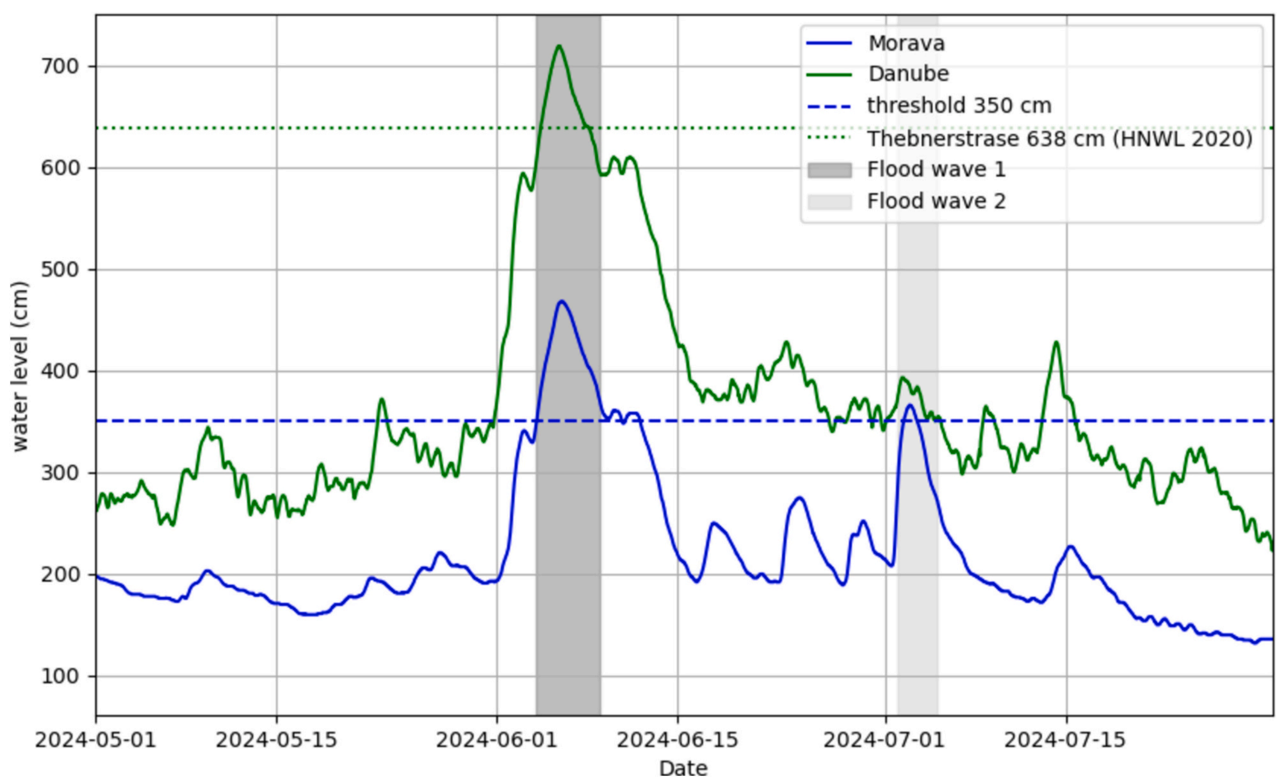


**Fig. 5.** Water level of the Danube and the Morava River from May until end of July 2024. The dotted green line gives the highest navigable water level (HNWL) of 2020, which is the value from when the Danube is no longer navigable. The dashed lines give the mean values of the two rivers, both values refer to the period 1991–2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis.

### 3.2. NEE, GPP, $R_{eco}$

We analysed the fluxes of $CO_2$ between the floodplain area and the atmosphere to show the effect of the different hydrological regimes in the above-mentioned periods. Fig. 6 clearly shows the influence of the two flood waves, setting the flux around zero with no significant changes between day and night. Also, the different extend of the flood waves can be seen, where the effect of no difference between day and night is more visible in the flood wave one in the beginning of June than for the minor flood wave two beginning of July. NEE, GPP, and Reco are analysed

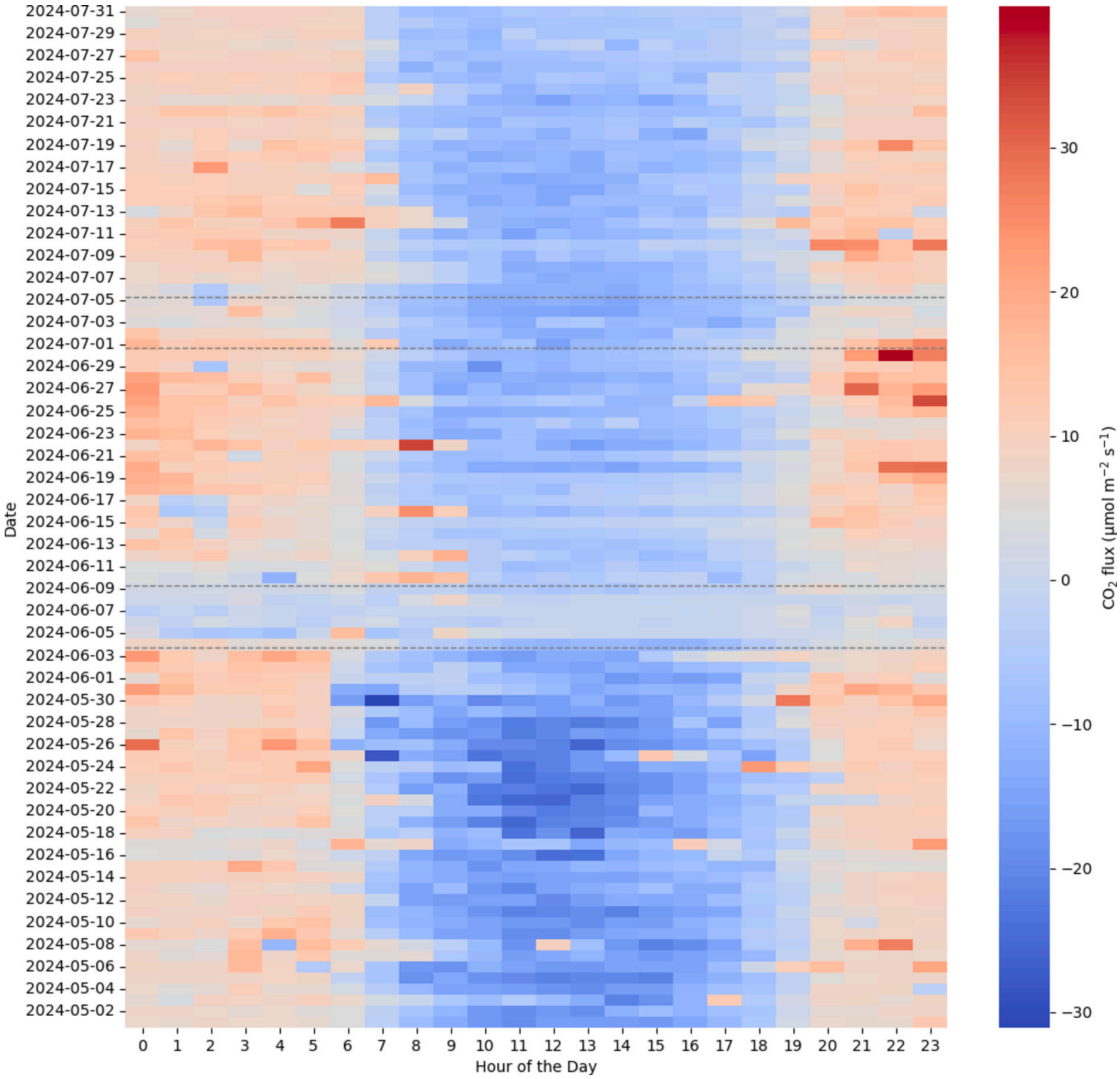


**Fig. 6.** $CO_2$ flux from May until July 2024. The two flood waves are maked with a grey dashed line.

separately. Fig. 6 shows the daily mean values of NEE, GPP and Reco and their cumulative sums over the whole three-month study period. This allows us to investigate the dynamics of $CO_2$ fluxes influenced by the water level in the clear-cut of the floodplain forest. From the beginning of May until the end of July, the ecosystem absorbs 38.8 g carbon per m2, while the cumulative GPP reaches 143.1 g carbon per m2 over the study period. Thus, the floodplain area is undoubtedly acting as a sink for $CO_2$ over the three-month period. However, it is evident that the cumulative sum of NEE does not rise in a linear or continuous manner. This is due to the fact that the ecosystem and $CO_2$ uptake are influenced to varying degrees by the water levels and flooding events. As the water arrives in the study site, the daily mean value of NEE drops. When the area is totally flooded, NEE reaches zero or even negative values, indicating that the ecosystem is a source of $CO_2$. Therefore, the cumulative NEE over the three-month period plateaus during the flood and remains low afterwards. It takes time for the ecosystem to recover, and the cumulative NEE curve rises after the flood when the ecosystem begins absorbing $CO_2$ again (Fig. 7a). The GPP over time (Fig. 7b) follows a similar pattern to NEE, implying that carbon storage due to photosynthetic processes is the main driver of the variations. With the water pushing into the study site, Reco drops continuously down to 2.5 g C m-2 (Fig. 7c). As soon as the area is no longer flooded, Reco rises again, reaching values higher than before the flood, indicating the temperature differences as main driver. Also, when the small flood occurs on 2nd July the values of Reco drops significantly. GPP only has one drop and then continues with similar values than before flood wave two. Thus, the second flood has almost no effect to the GPP, while the first flood halted GPP for some period of time (see Fig. 7b).

The diurnal variations in the different water level periods have a significant impact on the flood's effect on NEE. Fig. 8 shows the diurnal variations of NEE for the periods influenced differently by the water level. Following sunrise, an increase in NEE was noted, occurring between 5:30 am (1st of May) and 4:55 am (1st of June) local time. The maximum rate of $CO_2$ uptake is observed around noon. Prior to the flood, the NEE was observed to be significantly higher than during the flood with a maximum of 18.59 μmol $m^{-2}$ $s^{-1}$ reaching the maximum at 11 am and a mean value of −8 μmol $m^{-2}$ $s^{-1}$ during the nocturnal period. The flooding of the area resulted in a significant alteration of the diurnal variations, with a notable absence of a discernible difference between night and day. The observed values in the flooding period exhibited a smaller range, spanning only from −6.7 to 3.8 μmol $m^{-2}$ $s^{-1}$. The period directly following the flood, with still large water bodies in the study

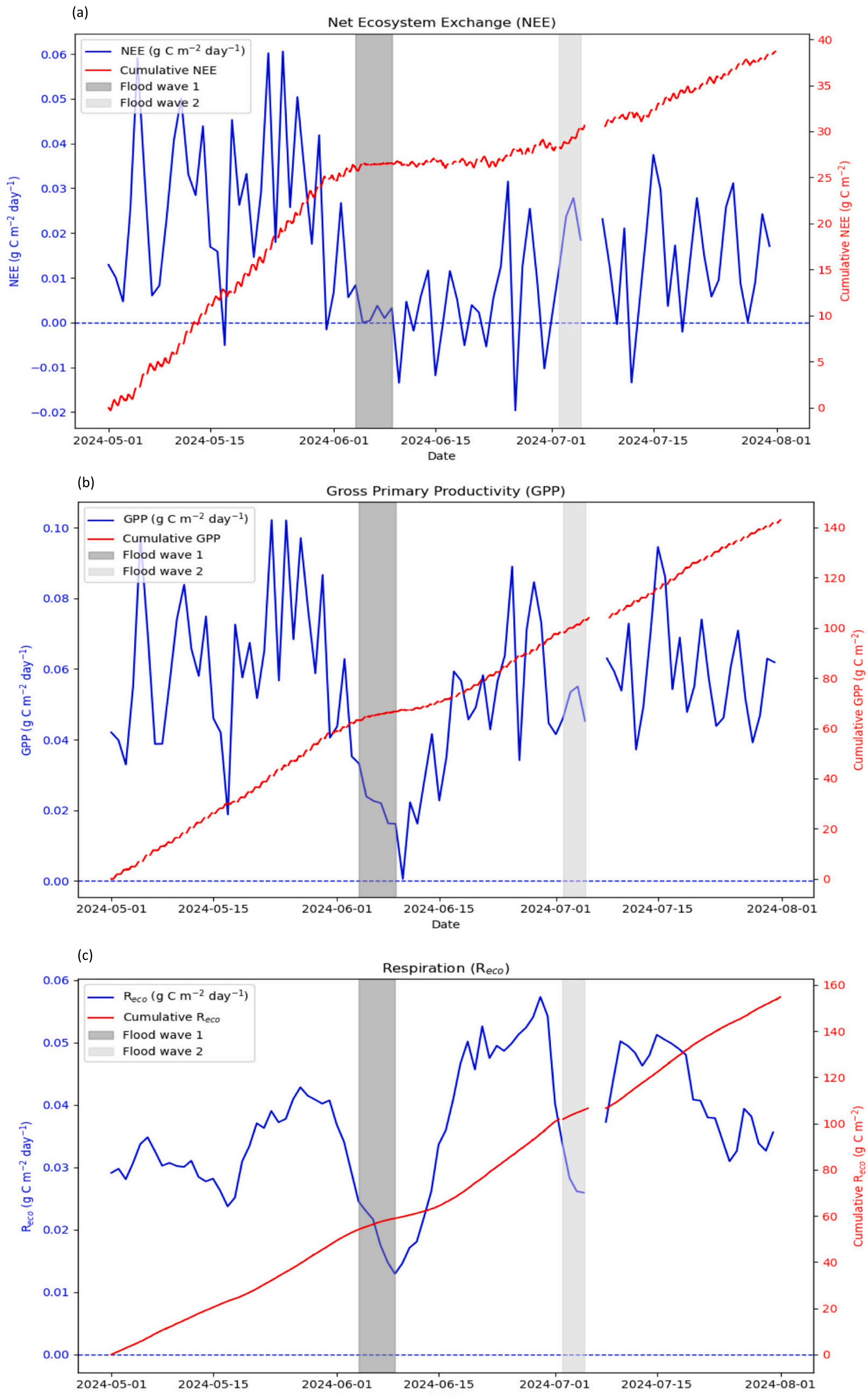


**Fig. 7.** Daily mean values and cumulative sums of NEE (a), GPP (b) and $R_{eco}$ (c) over the three-month study period (daily mean values in blue, cumulative sum of the half hourly values in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

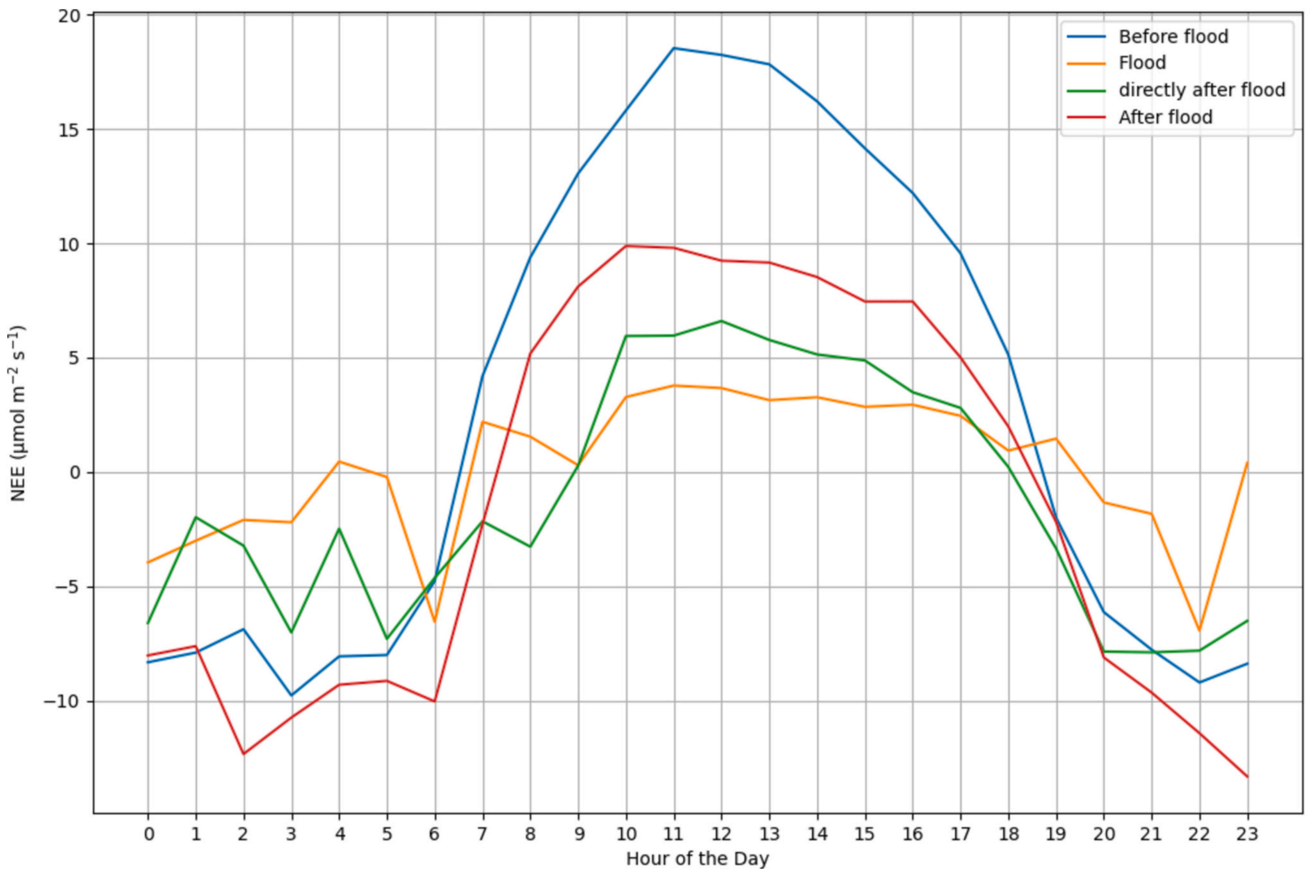


**Fig. 8.** Diurnal variations of NEE for the different periods, before the flood (blue), during the first flood wave (orange), directly after the flood (green), and longer after the flood (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

site, indicates that the ecosystem requires time to recuperate, as the peak reaches less than half of the pre-flood NEE values with 6.65 μmol $m^{-2}$ $s^{-1}$. A longer interval following the flood (9.7. - 31.07, data from the small flood event has been excluded) reaching a maximum of 9.89 μmol $m^{-2}$ $s^{-1}$. Average daily GPP ranges from 1.048 g C $m^{-2}$ $day^{-1}$ before the flood, down to 0.470 g C $m^{-2}$ $day^{-1}$ during the flood and recovers to 0.930 g C $m^{-2}$ $day^{-1}$ after the flood. As the $R_{eco}$ after the flood is higher (1.013 g C $m^{-2}$ $day^{-1}$) than before the flood (0.797 g C $m^{-2}$ $day^{-1}$, also the daily average net uptake is slightly in the negative after the flood (−0.123 g C $m^{-2}$ $day^{-1}$) and a net sink with 0.255 g C $m^{-2}$ $day^{-1}$ before the flood and during flood (0.0172 g C $m^{-2}$ $day^{-1}$).

## 4. Discussion

The ecosystem scale $CO_2$ monitoring in the restored floodplain grassland, provides invaluable data regarding the sequestration of carbon in wetlands. The carbon flux measurements provide insight and a more comprehensive understanding of the impact of renaturation processes on the carbon balance of the ecosystem and their contribution to climate change mitigation and the restoration of ecosystem services. Various studies exist quantifying the net ecosystem exchange of peatlands (Helbig et al., 2022; Mander et al., 2024; McDonald et al., 2023), forests (Chi et al., 2021; Foken et al., 2022; Knohl et al., 2003) or agricultural use (Anapalli et al., 2023; Cardenas et al., 2022), while studies about floodplain grassland are significantly underrepresented.

### 4.1. *Impact of flooding events on the $CO_2$ uptake*

The study site was subject to flooding at varying degrees and over different periods. As a result, the daily net uptake and GPP in the different periods exhibit considerable variation. The average daily GPP of the floodplain grassland in Marchegg ranges from 1.048 g C $m^{-2}$ $day^{-1}$ before the flood, down to 0.470 g C $m^{-2}$ $day^{-1}$ during the flood are smaller compared to the Dongting Lake floodplain in China with average daily GPP of 2.52 g C $m^{-2}$ $day^{-1}$ before the flood and dropping down to 1.98 g C $m^{-2}$ $day^{-1}$ during the flood season. The lower GPP values observed in the floodplain grassland of Marchegg compared to those in the Dongting Lake wetland can be largely attributed to differences in climatic conditions. Marchegg is located in a temperate climate, while Dongting Lake lies within the subtropical monsoon region. The warmer temperatures and longer daylight hours in the subtropical monsoon climate support higher photosynthetic activity, leading to increased GPP in Dongting Lake. Additionally, differences in vegetation between the two regions, influenced by climate, likely contribute to this variation, as subtropical plant species may be more photosynthetically active under these favourable conditions. However, the Dongting Lake study also highlights the significant role of flooding in reducing GPP during inundation events, suggesting that while subtropical climates promote higher overall GPP, flood events can still impose substantial limitations on photosynthetic output in floodplain grasslands (Wang et al., 2024).

The daily net uptake before the flood is 0.255 g C $m^{-2}$ $day^{-1}$ for $CO_2$ comparable with the findings of a wet meadow in the Czech Republic in Dušek et al. (2009), with daily average $CO_2$ net uptake of 0.53 and 2.74 g $CO_2$ $m^{-2}$ $day^{-1}$ in 2006 and 2007 years, respectively. Our daily net uptake is to some degree smaller as it represents just one month before the flood compared to the annual average values of the wet meadow.

The net uptake of the floodplain in Marchegg one month after the flood is lower than before the flood, as the ecosystem copes with the stress of the flood event. In addition, conditions in May 2024 were ideal for plant growth, with warm temperatures and abundant rainfall. In July, however, the plant's growth phase is coming to an end, less biomass is being produced and the plants have to cope not only with the flood damage but also with extreme temperatures. The pattern of the daily and cumulative NEE and GPP is consistent throughout the entire period, suggesting that the primary driver of the observed differences was the photosynthetic carbon assimilation (Dušek et al., 2009). However, Valach et al. (2021) indicates in his study, that the correlation between plant cover and NEE only accounts for approximately 50 % of the interannual variability. The NEE will also vary depending on the time of the flood event, with a flood in May having a greater impact than a flood in August or even in the winter months, as there will be different amounts of sunlight available depending on the time of year due to different sunrise and sunset times and the plants are more vulnerable during growing season. This is also confirmed by the study of van Eck et al. (2006) which states that summer floods have a more dramatic impact on plant survival than winter floods. In addition, a flood during the growing season will have a greater impact, and environmental conditions such as the availability of water in the soil prior to the flood can influence the impact of the flood. The ecosystem respiration $R_{eco}$ is higher after flood than before flood, which is consistent with the results in Dušek et al. (2009), where this phenomenon was found in years with flood and without flood. Thus, the differences in ecosystem respiration can be more explained by differences in temperature than by the effect of the flood (Dušek et al., 2009).

During the flood, the ecosystem $CO_2$ exchange is limited, resulting in a significant reduction of NEE with no significant changes for 24 h. This is due to the complete coverage of the area by water, which prevents vegetation from conducting photosynthesis. Additionally, the flood caused damage to plants, and a brown layer of dirt was visible on the plants. It was observed that the lower part of the plant was covered by sediment deposits for a longer period of time, whereas the newly growing plant parts were green again. This brown layer of dirt which affected their photosynthesis activity, lead to a notable decline of NEE during the period directly after the flood compared to the period preceding the flood. The sediment deposition on the plants likely accounts for the observed differences in GPP behaviour during the first and second flood waves. The first flood, driven by backwater from the Danube, involved significant sediment transport due to the large amounts of sediment carried by the river, especially after heavy precipitation. In contrast, the second, smaller flood wave was triggered by the opening of a sluice upstream of the Morava River, resulting in less sediment transport. This difference in sediment load may explain why the first flood halted GPP for a period, while the second flood caused only a temporary drop before GPP continued unaffected. The impact of sediment transport and plant vitality during different growth phases on $CO_2$ exchange of the ecosystem is an intriguing subject for further research.

Furthermore, the study site had immense water bodies in the period directly after the flood, as the water only withdraws slowly and evaporates. It is therefore evident that restoration processes require the presence of a diverse ecosystem. The floodplain forest around the grassland would continue to function as a sink, as the vegetation would not be entirely covered or damaged. This is supported by the findings of Shupe et al. (2022) who state that floodplains are well suited areas for reforestation acting as natural climate solutions because the trees in these areas have a high carbon sequestration rate even under severe conditions. Additionally, Kochendorfer et al. (2011) reports a floodplain cottonwood forest acting as a strong sink of $CO_2$, absorbing 310 g C $m^{-2}$ $yr^{-1}$ from the atmosphere during the first year of the study. Consequently, a floodplain forest comprising grassland and forest provides superior ecosystem services compared to the classic flood control reservoir. This is not only due to its status as a biodiversity hotspot and the creation of a recreational area for the local population, but also because of carbon storage and thus mitigating climate change.

In light of the presented results, it can be posited that the capacity of an ecosystem to sequester carbon is susceptible to alterations in water levels. Also, other studies state that the fluxes of $CO_2$, $CH_4$ and $N_2O$ in wetlands are dependent upon the water level in relation to the surface (Helbig et al., 2022; Zou et al., 2022). This study of the floodplain grassland in Marchegg shows that the ecosystem ability to sequester carbon gets interrupted by the flooding event, but continues to be a strong carbon sink over the whole study period. It can therefore be surmised that the rehabilitation of a wetland's water table has the potential to restore the natural process of wetland soil carbon sequestration and storage (Limpert et al., 2020). Moreover, additional research underscores the susceptibility of GHG fluxes to changes in soil water content, water table, salinity, soil nitrogen content, soil pH, and bulk density, due to changes in land use land cover changes of global restored and natural wetlands (Tan et al., 2020).

### 4.2. *Restored floodplain area acts as net carbon sinks*

The floodplain grassland area in Marchegg functions as a significant sink for $CO_2$ with a net cumulative NEE of 38.8 $CO_2$ g $m^{-2}$ during the vegetation growing season (May until the end of July). The net cumulative NEE is a widely metric for comparing the carbon sequestration capacity of ecosystems, as it represents the effect of multiple processes and their interaction at the ecosystem level (Valach et al., 2021). The net uptake of $CO_2$ values observed in this study for the floodplain grassland are comparable to those reported in other studies of floodplains (Dušek et al., 2009; Valach et al., 2021; Wang et al., 2024), and wetlands (Aurela et al., 2022; Valach et al., 2021) considering various climatic conditions. Nonetheless, the literature indicates that the majority of sites became net carbon sinks two years after restoration, with the carbon sequestration efficiency increasing as the wetlands aged (Valach et al., 2021). However, comparisons of the carbon sequestration capacity of wetlands in different regions are challenging, as climatic conditions exert a significant influence on this process (Valach et al., 2021). For instance, peatlands in polar regions demonstrate lower rates of carbon sequestration compared to those in boreal and temperate zones (Dušek et al., 2009). Moreover, the floodplain grassland ecosystem is distinctive and comparisons with other studies on peatlands, while studies of floodplain areas are underrepresented, are challenging. Therefore, this study offers new insights into the dynamics of carbon fluxes in response to changes in water levels in restored floodplain ecosystems. Carbon sequestration is a slow process and depending on the age and disturbance regime of the restored wetland, they become net sinks from the atmosphere after a century (Hemes et al., 2019). Given the nature of this distinctive wetland as a grassland floodplain, the carbon fluxes are predominantly shaped by photosynthesis and thus the floodplain acts as a strong sink of $CO_2$ much faster. However, floodplains can be $CH_4$ sources, so to become a GHG sink it can take decades and further studies are needed.

Considering the prevailing climate crisis and the anticipated rise in the frequency and intensity of extreme events such as flooding, it is imperative to evaluate the long-term consequences of flooding on ecosystem processes. The study's finding of decreased GPP due to flooding is of particular significance, given that higher temperatures and more frequent flooding, as predicted with climate change, could exacerbate the negative impact on wetlands' carbon sequestration capacity (Sánchez-Rodríguez et al., 2019). Although the study's dataset encompasses a three-month period and concentrates on a singular flooding event, thereby limiting insights into long-term or seasonal effects, the implications of more frequent and intense flooding underscore the necessity for further research. To gain a full understanding of how repeated flooding events, coupled with rising temperatures, may disrupt elemental cycling and biomass production, and thereby reduce wetlands' ability to mitigate climate change, it will be essential to have data from multi-year studies. As this study focuses on the flood effect and evaluates only a short period, no valuable statements can be made about the interaction with climate or climate change. However, it is hoped that in the future, with data from several years, this issue can be addressed.

This study focuses on $CO_2$ fluxes and variability during flood events, so it is not possible to make significant statements about the ecosystem's contribution to climate change mitigation, which is often quantified in terms of global warming potential (GWP) (Aurela et al., 2022; Friborg et al., 2003). As $CH_4$ and $N_2O$ absorb more energy, their GWP and thus their contribution to global warming is higher than that of $CO_2$ (IPCC, 2021). In order to quantify the climate change mitigation potential of not only $CO_2$, but also $CH_4$ and $N_2O$ fluxes need to be investigated (Tan et al., 2020). The open-path $CH_4$ gas analyser (LI-7700, LI-COR Biosciences, Lincoln, NE, USA) was added to the station in March 2024. Additionally, it is anticipated that changes in the $CH_4$ fluxes will only become evident over a longer period than that covered by a single 5-day flooding event. Consequently, the CH4 fluxes are not considered in this study, which is designed to investigate the effect of flooding and water table variability in the case of severe flooding events in June 2024. Therefore, the GWP of the whole area, including $CH_4$ and $N_2O$ fluxes, is the subject of another study. However, the rewetting of wetlands could result in the emissions of $CH_4$ and $N_2O$ and their radiative forcing being outweighed by the uptake of $CO_2$ and the ecosystem becoming a carbon sink due to SWBE. Consequently, the greenhouse gas balances of wetlands and their reaction to changes, and therefore the impact of wetlands on climate, will be contingent upon the balance between future degradation and restoration (Zou et al., 2022).

In light of the challenges posed by climate change, it is imperative to gain insight into the ways in which ecosystems respond and their capacity for carbon sequestration, particularly in view of the influence of management and environmental factors such as flooding events. This understanding is vital for gauging the long-term impact of wetland restoration on climate change mitigation (Baldocchi, 2020; Hemes et al., 2019). In order to assist in the mitigation of climate change, it is of importance to gain a deeper understanding of ecosystem-scale C fluxes from complex heterogeneous wetlands over longer timeframes. This is because studies have demonstrated that wetlands can vary significantly in their role as a carbon sink or source (Valach et al., 2021). Furthermore, the restoration of wetlands can play a crucial role in maintaining and transforming them into large net carbon sinks. Additionally, to the described findings, the capacity of carbon sequestration is fundamental for the development of the SWBE approach (Rauch et al., 2022; UN, 2015).

## 5. Conclusion

The floodplain grassland in Marchegg as a restored ecosystem provides ecosystem services beyond flood protection to prevent severe damage, as seen in the severe flood in southern Germany in June 2024. They also have a large potential for carbon sequestration, thus the $CO_2$ exchange of a restored floodplain grassland was investigated. To quantify the impact of flooding event on the carbon sequestration, EC measurements of $CO_2$ were analysed in the different time periods before, during and after the flood event. Our results show that ecosystem services in terms of carbon balance is heavily influenced by water level in the study site, with the average daily GPP of the floodplain grassland in Marchegg dropping from 1.048 g C $m^{-2}$ $day^{-1}$ before the flood, down to 0.470 g C $m^{-2}$ $day^{-1}$ during the flood. However, the study demonstrates that the restored floodplain functions as a robust carbon sink with a cumulative NEE of 38.8 g carbon per $m^2$ over the three-months study period, despite temporary disruptions caused by flooding events.

This study's limitations, such as the exclusion of $CH_4$ and $N_2O$ measurements and the reliance on a short three-month dataset focused on a single flood event, restrict a full assessment of the wetland's overall global warming potential (GWP) and long-term impacts. Despite these constraints, the findings provide valuable insight into the effects of flooding on GPP in restored wetlands. Given the expected rise in flood frequency and intensity due to climate change, this research underscores the significant role of floodplain grasslands in carbon storage and climate mitigation. Furthermore, it emphasises the necessity for long-term studies to gain a comprehensive understanding of these dynamics. The data obtained from the EC station in this study provide valuable insights that can inform the enhancement of future restoration projects.

Finally, this supports the adoption of the EU Nature Restoration Law and the need for restoring wetlands, floodplains and rivers to secure water availability and biodiversity in these unique ecosystems. NBS and more specifically SWBE are methods with ecological advantages and a huge potential for sustainable recreation of near-natural ecosystems. It is a future goal of SWBE to pay more attention to its ecological effects at different spatial and temporal scales. It is of crucial importance to prove these beneficial effects, and to quantify them transparently in terms of quality assurance and use of resources in a sustainable and eco-friendly way. The general future idea of SWBE is to apply it as an environmentally friendly technique in terms of climate change and the Sustainable Development Goals.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DEEPL in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

## CRediT authorship contribution statement

**A. Lindenberger:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **H.P. Rauch:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **K. Kasak:** Writing – review & editing, Supervision. **M. Stelzhammer:** Writing – review & editing. **M. von der Thannen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Anna Lindenberger, Hans Peter Rauch, Kuno Kasak, Magdalena v. d. Thannen reports financial support was provided by European Union. Kuno Kasak reports financial support was provided by Estonian Research Council. Kuno Kasak reports financial support was provided by The Estonian Ministry of Education and Research, the Centre of Excellence for Sustainable Land Use. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

## References


Anapalli, S.S., Pinnamaneni, S.R., Chastain, D.R., Reddy, K.N., Simmons, C.D., 2023. Eddy covariance quantification of carbon and water dynamics in twin-row vs. single-row planted corn. Agric. Water Manag. 281, 108235. https://doi.org/10.1016/j.agwat.2023.108235.

Aubinet, M., Vesala, T., Papale, D., 2012. Eddy Covariance [Recurso electrónico]: A Practical Guide to Measurement and Data Analysis. Springer Atmospheric Sciences, Springer Netherlands.

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J.-P., Vesala, T., Tuittila, E.-S., Rinne, J., Haapanala, S., Laine, J., 2022. $CO_2$ exchange of a sedge fen in southern Finland—the impact of a drought period. Tellus Ser. B Chem. Phys. Meteorol. 59 (5), 826. https://doi.org/10.1111/j.1600-0889.2007.00309.x.

Baldocchi, D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob. Chang. Biol. 9 (4), 479–492. https://doi.org/10.1046/j.1365-2486.2003.00629.x.

Baldocchi, D., 2020. How eddy covariance flux measurements have contributed to our understanding of Global Change Biology. Glob. Chang. Biol. 26 (1), 242–260. https://doi.org/10.1111/gcb.14807.

Begemann, W., Schiechtl, H.M., 1994. Ingenieurbiologie: Handbuch zum ökologischen Wasser- und Erdbau, 2., neubearb. Aufl. Bauverl.

Bischetti, G.B., Di Fi Dio, M., Florineth, F., 2014. On the origin of soil bioengineering. Landsc. Res. 39 (5), 583–595. https://doi.org/10.1080/01426397.2012.730139.

Bohn, T.J., Lettenmaier, D.P., Sathulur, K., Bowling, L.C., Podest, E., McDonald, K.C., Friborg, T., 2007. Methane emissions from western Siberian wetlands: heterogeneity and sensitivity to climate change. Environ. Res. Lett. 2 (4), 45015. https://doi.org/10.1088/1748-9326/2/4/045015.

Burba, G., 2013. Eddy Covariance Method for Scientific, Industrial, Agricultural, and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates. LI-COR Biosciences.

Cardenas, L.M., Olde, L., Loick, N., Griffith, B., Hill, T., Evans, J., Cowan, N., Segura, C., Sint, H., Harris, P., McCalmont, J., Zhu, S., Dobermann, A., Lee, M.R.F., 2022. Co2 fluxes from three different temperate grazed pastures using Eddy covariance measurements. Sci. Total Environ. 831, 154819. https://doi.org/10.1016/j.scitotenv.2022.154819.

Chi, J., Zhao, P., Klosterhalfen, A., Jocher, G., Kljun, N., Nilsson, M.B., Peichl, M. [Matthias], 2021. Forest floor fluxes drive differences in the carbon balance of contrasting boreal forest stands. Agric. For. Meteorol. 306, 108454. https://doi.org/10.1016/j.agrformet.2021.108454.

Christensen, T.R., Ekberg, A., Ström, L., Mastepanov, M., Panikov, N., Öquist, M., Svensson, B.H., Nykänen, H., Martikainen, P.J., Oskarsson, H., 2003. Factors controlling large scale variations in methane emissions from wetlands. Geophys. Res. Lett. 30 (7). https://doi.org/10.1029/2002GL016848. Article 2002GL016848.

Dalmagro, H.J., Lathuillière, M.J., Hawthorne, I., Morais, D.D., Pinto Jr., O.B., Couto, E. G., Johnson, M.S., 2018. Carbon biogeochemistry of a flooded Pantanal forest over three annual flood cycles. Biogeochemistry 139 (1), 1–18. https://doi.org/10.1007/s10533-018-0450-1.

Dušek, J., Čížková, H., Czerný, R., Taufarová, K., Šmídová, M., Janous, D., 2009. Influence of summer flood on the net ecosystem exchange of CO2 in a temperate sedge-grass marsh. Agric. For. Meteorol. 149 (9), 1524–1530. https://doi.org/10.1016/j.agrformet.2009.04.007.

Egger, G., Hohensinner, S., Haidvogl, G., 2022. Die Marchauen: Eine Flusslandschaft im Wandel der Zeit. WWF Österreich. https://permalink.obvsg.at/AC16585006.

EPA, 2024. Why are Wetlands Important? United States Environmental Protection Agency (EPA). https://www.epa.gov/wetlands/why-are-wetlands-important.

Evette, A., Labonne, S., Rey, F., Liebault, F., Jancke, O., Girel, J., 2009. History of bioengineering techniques for erosion control in rivers in Western Europe. Environ. Manag. 43 (6), 972–984. https://doi.org/10.1007/s00267-009-9275-y.

Florineth, F., 2012. Pflanzen statt Beton: Sichern und Gestalten mit Pflanzen [2. völlig überarbeitete Auflage]. Patzer.

Foken, T., 2008. Micrometeorology (C. J. Nappo, Trans.).. Springer-Verlag, Berlin Heidelberg http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1610656.

Foken, T., Babel, W., Munger, J.W., Grönholm, T., Vesala, T., Knohl, A., 2022. Selected breakpoints of net forest carbon uptake at four eddy-covariance sites. Tellus Ser. B Chem. Phys. Meteorol. 73 (1), 1915648. https://doi.org/10.1080/16000889.2021.1915648.

Fratini, G., Mauder, M., 2014. Towards a consistent eddy-covariance processing: an intercomparison of EddyPro and TK3. Atmos. Meas. Tech. 7 (7), 2273–2281. https://doi.org/10.5194/amt-7-2273-2014.

Friborg, T., Soegaard, H., Christensen, T.R., Lloyd, C.R., Panikov, N.S., 2003. Siberian wetlands: Where a sink is a source. Geophys. Res. Lett. 30 (21), 2003GL017797. https://doi.org/10.1029/2003GL017797.

Gibbens, S., 2024. What are wetlands, and why are they so critical for life on Earth? [these unique ecosystems have a small footprint but play a big role in providing habitat for wildlife, and protecting us against floods and pollution]. https://www.nationalgeographic.com/environment/article/what-are-wetland-ecosystems.

Gray, D.H., Sotir, R.B., 1996. Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for erosion Control. A Wiley-Interscience publication. Wiley. http://www.loc.gov/catdir/bios/wiley041/96010211.html.

Helbig, M., Živković, T., Alekseychik, P., Aurela, M., El-Madany, T.S., Euskirchen, E.S., Flanagan, L.B., Griffis, T.J., Hanson, P.J., Hattakka, J., Helfter, C., Hirano, T., Humphreys, E.R., Kiely, G., Kolka, R.K., Laurila, T., Leahy, P.G., Lohila, A., Mammarella, I., Zaehle, S., 2022. Warming response of peatland CO2 sink is sensitive to seasonality in warming trends. Nat. Clim. Chang. 12 (8), 743–749. https://doi.org/10.1038/s41558-022-01428-z.

Hemes, K.S., Chamberlain, S.D., Eichelmann, E., Anthony, T., Valach, A., Kasak, K., Szutu, D., Verfaillie, J., Silver, W.L., Baldocchi, D., 2019. Assessing the carbon and climate benefit of restoring degraded agricultural peat soils to managed wetlands. Agric. For. Meteorol. 268, 202–214. https://doi.org/10.1016/j.agrformet.2019.01.017.

IPCC, 2021. Climate change 2021: The physical science basis. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896. In press.

Isaac, P., Cleverly, J., McHugh, I., van Gorsel, E., Ewenz, C., Beringer, J., 2017. OzFlux data: network integration from collection to curation. Biogeosciences 14 (12), 2903–2928. https://doi.org/10.5194/bg-14-2903-2017.

IUCN, 2020. Guidance for Using the IUCN Global Standard for Nature-Based Solutions: First Editions. IUCN, International Union for Conservation of Nature. https://portals.iucn.org/library/sites/library/files/documents/2020-021-En.pdf. https://doi.org/10.2305/IUCN.CH.2020.09.en.

Kettenhuber, P.L.W., dos Santos Sousa, R., Dewes, J.J., Rauch, H.P., Sutili, F.J., Hörbinger, S., 2023. Performance assessment of a soil and water bioengineering work on the basis of the flora development and its associated ecosystem processes. Ecol. Eng. 186, 106840. https://doi.org/10.1016/j.ecoleng.2022.106840.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P., 2015. A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP). Geosci. Model Dev. 8 (11), 3695–3713. https://doi.org/10.5194/gmd-8-3695-2015.

Knohl, A., Schulze, E.-D., Kolle, O., Buchmann, N., 2003. Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agric. For. Meteorol. 118 (3–4), 151–167. https://doi.org/10.1016/S0168-1923(03)00115-1.

Kochendorfer, J., Castillo, E.G., Haas, E., Oechel, W.C., Paw, U., K. T, 2011. Net ecosystem exchange, evapotranspiration and canopy conductance in a riparian forest. Agric. For. Meteorol. 151 (5), 544–553. https://doi.org/10.1016/j.agrformet.2010.12.012.

Kowalska, N., Chojnicki, B.H., Rinne, J., Haapanala, S., Siedlecki, P., Urbaniak, M., Juszczak, R., Olejnik, J., 2013. Measurements of methane emission from a temperate wetland by the eddy covariance method. Int. Agrophys. 27 (3), 283–290. https://doi.org/10.2478/v10247-012-0096-5.

Limpert, K.E., Carnell, P.E., Trevathan-Tackett, S.M., Macreadie, P.I., 2020. Reducing emissions from degraded floodplain wetlands. Front. Environ. Sci. 8. https://doi.org/10.3389/fenvs.2020.00008. Article 8.

Mander, Ü., Espenberg, M., Melling, L., Kull, A., 2024. Peatland restoration pathways to mitigate greenhouse gas emissions and retain peat carbon. Biogeochemistry 167 (4), 523–543. https://doi.org/10.1007/s10533-023-01103-1.

Mauder, M., Foken, T., 2006. Impact of post-field data processing on eddy covariance flux estimates and energy balance closure. Meteorol. Z. 15 (6), 597–609. https://doi.org/10.1127/0941-2948/2006/0167.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H.P., Schmidt, M., Steinbrecher, R., 2013. A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements. Agric. For. Meteorol. 169, 122–135. https://doi.org/10.1016/j.agrformet.2012.09.006.

McDonald, R.M., Moore, P.A., Helbig, M., Waddington, J.M., 2023. Reduced net CO 2 uptake during dry summers in a boreal shield peatland. J. Geophys. Res. Biogeosci. 128 (2). https://doi.org/10.1029/2022JG006923. Article e2022JG006923.

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., Jørgensen, S.E., Brix, H., 2013. Wetlands, carbon, and climate change. Landsc. Ecol. 28 (4), 583–597. https://doi.org/10.1007/s10980-012-9758-8.

Mohr, S., Daniell, J.E., Ehret, U., Küpfer, K., Ludwig, P., Mühr, B., Rosenberg, S., Schäfer, A.M., Wilhelm, J., Kunz, M., 2024. CEDIM Forensic Disaster Analysis Group (FDA): Außergewöhnliche Niederschläge und Hochwasser in Süddeutschland im Juni 2024. https://doi.org/10.5445/IR/1000171441.

Preti, F., Capobianco, V., Sangalli, P., 2022. Soil and Water Bioengineering (SWB) is and has always been a nature-based solution (NBS): a reasoned comparison of terms and definitions. Ecol. Eng. 181, 106687. https://doi.org/10.1016/j.ecoleng.2022.106687.

Pugh, C.A., Reed, D.E., Desai, A.R., Sulman, B.N., 2018. Wetland flux controls: how does interacting water table levels and temperature influence carbon dioxide and methane fluxes in northern Wisconsin? Biogeochemistry 137 (1–2), 15–25. https://doi.org/10.1007/s10533-017-0414-x.

Rauch, H.P., Sutili, F., Hörbinger, S., 2014. Installation of a riparian forest by means of soil bio engineering techniques—monitoring results from a river restoration work in Southern Brazil. Open J. Forest. 04 (02), 161–169. https://doi.org/10.4236/ojf.2014.42022.

Rauch, H.P., von der Thannen, M., Raymond, P., Mira, E., Evette, A., 2022. Ecological challenges* for the use of soil and water bioengineering techniques in river and coastal engineering projects. Ecol. Eng. 176, 106539. https://doi.org/10.1016/j.ecoleng.2021.106539.

Rebmann, C., Aubinet, M., Schmid, H., Arriga, N., Aurela, M., Burba, G., Clement, R., de Ligne, A., Fratini, G., Gielen, B., Grace, J., Graf, A., Gross, P., Haapanala, S., Herbst, M., Hörtnagl, L., Ibrom, A., Joly, L., Kljun, N., Franz, D., 2018. ICOS eddy covariance flux-station site setup: a review. Int. Agrophys. 32 (4), 471–494. https://doi.org/10.1515/intag-2017-0044.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob. Chang. Biol. 11 (9), 1424–1439. https://doi.org/10.1111/j.1365-2486.2005.001002.x.

Rey, F., Bifulco, C., Bischetti, G.B., Bourrier, F., de Cesare, G., Florineth, F., Graf, F., Marden, M., Mickovski, S.B., Phillips, C., Peklo, K., Poesen, J., Polster, D., Preti, F., Rauch, H.P., Raymond, P., Sangalli, P., Tardio, G., Stokes, A., 2019. Soil and water bioengineering: Practice and research needs for reconciling natural hazard control and ecological restoration. Sci. Total Environ. 648, 1210–1218. https://doi.org/10.1016/j.scitotenv.2018.08.217.

Sánchez-Rodríguez, A.R., Nie, C., Hill, P.W., Chadwick, D.R., Jones, D.L., 2019. Extreme flood events at higher temperatures exacerbate the loss of soil functionality and trace gas emissions in grassland. Soil Biol. Biochem. 130, 227–236. https://doi.org/10.1016/j.soilbio.2018.12.021.

Scheingross, J.S., Repasch, M.N., Hovius, N., Sachse, D., Lupker, M., Fuchs, M., Halevy, I., Gröcke, D.R., Golombek, N.Y., Haghipour, N., Eglinton, T.I., Orfeo, O., Schleicher, A.M., 2021. The fate of fluvially-deposited organic carbon during transient floodplain storage. Earth Planet. Sci. Lett. 561, 116822. https://doi.org/10.1016/j.epsl.2021.116822.

Schiechtl, H., 1980. Bioengineering for Land Reclamation and Conservation. University of Alberta Press. https://www.sidalc.net/search/record/unfao:611736/description.

Schiechtl, H., Stern, R., 1994. Handbuch für naturnahen Wasserbau: Eine Anleitung für ingenieurbiologische Bauweisen; 13 Tabellen. Österreichischer Agrarverl.

Shupe, H.A., Jensen, K., Oldeland, J., Ludewig, K., 2022. Droughts decrease and floods increase carbon sequestration rates of Quercus robur in hardwood floodplain forests. Trees, Forests People 9, 100294. https://doi.org/10.1016/j.tfp.2022.100294.

Tan, L., Ge, Z., Zhou, X., Li, S., Li, X., Tang, J., 2020. Conversion of coastal wetlands, riparian wetlands, and peatlands increases greenhouse gas emissions: A global meta-analysis. Glob. Chang. Biol. 26 (3), 1638–1653. https://doi.org/10.1111/gcb.14933.

Temmink, R.J.M., Lamers, L.P.M., Angelini, C., Bouma, T.J., Fritz, C., van de Koppel, J., Lexmond, R., Rietkerk, M., Silliman, B.R., Joosten, H., van der Heide, T., 2022. Recovering wetland biogeomorphic feedbacks to restore the world's biotic carbon hotspots. Science (New York, N.Y.) 376 (6593), eabn1479. https://doi.org/10.1126/science.abn1479.

UN, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. Department of Economic and Social Affairs. https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

Valach, A.C., Kasak, K., Hemes, K.S., Anthony, T., Dronova, I., Taddeo, S., Silver, W.L., Szutu, D., Verfaillie, J.G., Baldocchi, D., 2021. Productive wetlands restored for carbon sequestration quickly become net CO2 sinks with site-level factors driving uptake variability. PLoS One 16 (3), e0248398. https://doi.org/10.1371/journal.pone.0248398.

van Eck, W.H.J.M., Lenssen, J.P.M., van de Steeg, H.M., Blom, C.W.P.M., de Kroon, H., 2006. Seasonal dependent effects of flooding on plant species survival and zonation: a comparative study of 10 terrestrial grassland species. Hydrobiologia 565 (1), 59–69. https://doi.org/10.1007/s10750-005-1905-7.

von der Thannen, M., Hoerbinger, S., Paratscha, R., Smutny, R., Lampalzer, T., Strauss, A., Rauch, H.P., 2020. Development of an environmental life cycle assessment model for soil bioengineering constructions. Eur. J. Environ. Civ. Eng. 24 (2), 141–155. https://doi.org/10.1080/19648189.2017.1369460.

von der Thannen, M., Hoerbinger, S., Muellebner, C., Biber, H., Rauch, H.P., 2021. Case study of a water bioengineering construction site in Austria. Ecological aspects and application of an environmental life cycle assessment model. Int. J. Energy Environ. Eng. 12 (4), 599–609. https://doi.org/10.1007/s40095-021-00419-8.

Wang, T., Deng, Z., Zhang, C., Zou, Y., Xie, Y., Li, F., Xiao, F., Peng, C., 2024. Vegetation types and flood water level are dominant factors controlling the carbon sequestration potential in Dongting Lake floodplain, China. Sci. Total Environ. 921, 171146. https://doi.org/10.1016/j.scitotenv.2024.171146.

Wei, J., Li, X., Liu, L., Christensen, T.R., Jiang, Z., Ma, Y., Wu, X., Yao, H., López-Blanco, E., 2022. Radiation, soil water content, and temperature effects on carbon cycling in an alpine swamp meadow of the northeastern Qinghai–Tibetan Plateau. Biogeosciences 19 (3), 861–875. https://doi.org/10.5194/bg-19-861-2022.

Zeh, H., 2007. Ingenieurbiologie: Handbuch Bautypen = Génie biologique. vdf Hochschulverl.

Zou, J., Ziegler, A.D., Chen, D., McNicol, G., Ciais, P., Jiang, X., Zheng, C., Wu, J., Wu, J., Lin, Z., He, X., Brown, L.E., Holden, J., Zhang, Z., Ramchunder, S.J., Chen, A., Zeng, Z., 2022. Rewetting global wetlands effectively reduces major greenhouse gas emissions. Nat. Geosci. 15 (8), 627–632. https://doi.org/10.1038/s41561-022-00989-0.