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Carbon fluxes controlled by land management and disturbances at a cluster of long-term ecosystem monitoring sites in Central Europe

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ABSTRACT

Terrestrial ecosystems play a crucial role in carbon sequestration and provide vital ecosystem services such as food, energy, and raw materials. Climate change, through rising temperatures, altered precipitation patterns, and extreme events, threatens the carbon sink potential of these ecosystems, with forests and grasslands particularly at risk. Long-term data from flux tower networks offer valuable insights into how different ecosystems respond to climate change and management interventions, helping to develop strategies to mitigate greenhouse gas emissions and maintain ecosystem resilience. In this study, we present such data from a <10 km cluster of long-term FLUXNET/ICOS sites in Central Europe, comprising an old spruce forest (DE-Tha), a young oak plantation after a cleared windthrow (DE-Hzd), a permanent grassland site (DE-Gri), and an agricultural site with a crop rotation typical for this region (DE-Kli). By analysing decades of data from these eddy covariance measurement sites, the research highlights the influence of drought, management, and land cover changes on CO_2 and H_2O fluxes. The interannual variability of evapotranspiration depends less on land use than the CO_2 exchange. Our findings show that intact forests can act as larger carbon sinks than previously estimated. DE-Tha is a consistent carbon sink, with thinning helping to maintain the CO_2 sequestration at a stable level of 350 gC m^{-2} a^{-1}. In contrast, disturbances like clear cutting or windthrow can cause ecosystems to become carbon sources for several years, with recovery delayed due to soil carbon losses from increased respiration (DE-Hzd). While DE-Hzd was resilient to drought, the carbon uptake of DE-Tha was significantly reduced by around 50 % during dry years compared to wet years. Furthermore, sustainable management maintains carbon sequestration and land-use practices, such as crop selection, significantly impact net ecosystem productivity. These insights are valuable for optimizing land management strategies to enhance carbon sinks in similar regions.

1. Introduction

Terrestrial ecosystems like forests and intensively (crops) and extensively (grasslands) managed agricultural ecosystems are crucial for our society as they provide important ecosystem services, such as the provision of food, renewable energy and raw materials. Overall, vegetated ecosystems are an important sink for CO_2, removing on average 3.8 ± 0.8 Gt C per year from the atmosphere (Friedlingstein et al., 2023; IPCC 2022). Hence, they may serve as natural climate solutions in order to compensate for unavoidable greenhouse gas emissions in industry and agriculture (Griscom et al. 2017). While crops typically present a source of CO_2, grasslands and especially forests, with a net sink of 3.5 ± 0.4 Gt C a^{-1}, are important carbon sinks (Pugh et al. 2019; Harris et al. 2021; Xu et al. 2021; IPCC, 2022; Pan et al. 2024). As climate change affects the boundary conditions of carbon exchange, the future of this important sink is already at stake (e.g., Peñuelas and Nogué 2023). Preserving functioning ecosystems by minimising the CO_2 emissions from crops and maximising carbon sequestration by grasslands and forests therefore has the potential to mitigate climate change, whereas a failure to maintain functioning ecosystems, on the other hand, can lead to a positive feedback amplifying climate change (Dinerstein et al. 2020; Patacca et al. 2023).

The functioning of ecosystems is coupled to external (e.g., climate) and internal factors (e.g., the genetics of contributing species). The consequences of environmental changes are therefore hard to predict. The changes caused by climate change alone have different direct effects: The increase in air temperature can lead to an extension of the vegetation period and the increase in atmospheric CO_2 concentration

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triggers an improved water use efficiency (*WUE*) and a fertilisation effect in many species but not in all (Lee et al. 2003; Norby et al. 2005; Huang et al. 2007; Lee et al. 2011; Scheelbek et al. 2018; Singer et al. 2020). Both factors could contribute to more CO_2 being absorbed by the vegetation, while reducing the water needs in parallel. In contrast, changing precipitation patterns cause more frequent and more extreme drought events in many regions including Central Europe (Woollings et al. 2018; IPCC 2022). The extreme drought events in Central Europe in 2018–2020 damaged 500.000 ha of forested land in Germany (Thonfeld et al. 2022) and are expected to further affect tree growth and mortality on the longer term (Schuldt et al. 2020) possibly decreasing net ecosystem productivity (Grünzweig et al. 2022). Indirect effects from insect infestations and diseases are expected to be more common due to climate change (Anderegg et al. 2015; Kolb et al. 2016; Stephenson et al. 2019; Koontz et al. 2021; Trugman et al. 2021). This challenges traditional forest management and calls for re-thinking the shaping of future forests by today's decisions.

Active management may boost or diminish the CO_2 sequestration by ecosystems. For example, crops can be irrigated to bridge periods of drought (Yu et al. 2021). The selection of crops in agriculture (Ziska et al. 2012; Yu et al. 2021) or tree species in forestry (Schelhaas et al. 2015; Thom et al. 2023a) can contribute to maintain ecosystem functions by being more resilient to the changing climatic conditions including droughts. Also, a higher water use efficiency at higher atmospheric CO_2 levels can help to stabilise carbon uptake (Mooney et al. 1999). High biodiversity should help maintain carbon sequestration by ecosystems as plant diversity increases the chances for some plants to tolerate future climate conditions (Hisano et al. 2018; Yang et al. 2019; Mori et al. 2021). Another factor is the frequency and procedure style of harvesting (mowing of grasslands, selective cutting of forests). However, studies have shown different effects of such measures. For example, thinning of forest stands may increase resource availability for the remaining trees and thus reduce their vulnerability to drought (van der Maaten 2013; Sohn et al., 2016; Bose et al. 2022) but they may also hinder the tree regeneration success after a drought event by reducing the microclimatic buffering capacity against extreme events (Thom et al. 2023b). Other factors influencing carbon sequestration are tillage and fertilization practices as well as the use of cover crops and crop rotation (e.g., Berhane et al. 2020, Wang et al. 2018, Yang et al. 2024, Zhang et al. 2024).

A wide range of studies on ecosystem responses to trends, specific disturbances and management strategies have been published. They found both positive and negative effects on carbon sequestration. Zscheischler et al. (2014) showed that rather short and local extreme events can explain most of the interannual variation in gross primary production (*GPP*). However, it is generally not clear which contribution is associated with trends or disturbances, respectively and which factors dominate in the long term.

In recent decades, atmospheric flux measurements of energy, water and CO_2 have been widely used to study the behaviour of ecosystems (Baldocchi 2020). Long-term measurements, for example in monitoring networks such as ICOS (Integrated Carbon Observation System), are particularly suitable for investigating the reactions of ecosystems to changing climate conditions. Today, data records of several decades allow for investigating the response of ecosystems to trends such as the increase in temperature and CO_2 concentration in the atmosphere (Keenan et al. 2013; Keenan et al. 2014). In addition, long-term measurements are suitable for investigating the response of an ecosystem to rare extreme events (Frank et al. 2015), such as drought (Ciais et al. 2005; Schwalm et al. 2012; Wolf et al. 2016) or windthrow (Barr et al. 2012; Knohl et al. 2002). The influence of various management measures can be deduced, as long time series also provide information on the behaviour of the ecosystem before the intervention, which serves as a reference.

The cluster of flux towers operated by the Dresden University of Technology (TUD) is especially suited to tackle research questions related to carbon balances and land use. The main reasons are (i) the close similarity in climate and weather among of these neighbouring sites, (ii) the long-term records of CO_2 fluxes from EC dating back as early as 1996, (iii) the excellent coverage of drought (Pluntke et al. 2023) and storm related disturbances, (iv) and the large general database on climate, soil, vegetation and forest management. The old spruce site (DE-Tha; Grünwald and Bernhofer, 2007) features one of the longest records in the global FLUXNET database, the related data requests were ranking 3rd (or 4th) in the global survey of 2017 (Pastorello et al. 2020). The site is part of basically all early or long-term regional and global studies on carbon fluxes (e.g., Valentini et al. 1999; Bernhofer et al. 2003; Ciais et al. 2005). Paired with the grassland site (DE-Gri), it allowed to check for different ecosystem responses to the droughts of 2003 and 2006 (Teuling et al. 2010). The long-term water budget was compared to a small catchment in the vicinity (Teuling et al. 2013), with much lower values in annual evapotranspiration *ET* for DE-Tha and still somewhat lower numbers for DE-Hzd (Pluntke et al. 2023). However, they could show the interplay of climate change and land use/forest management in analysis (Pluntke et al. 2023) and modelling (Vorobevskii et al. 2022). A cluster wide comparison of carbon fluxes by Prescher et al. (2010) could quantify the potential climate change mitigation effect; with managed forests ranking first for amount of C sequestered and with cropping systems as the best option for fast improvement in reducing the annual C emissions. All these studies showed the strong coupling between carbon and water fluxes, while droughts are a relatively frequent risk to carbon sequestration in the area. The adaptation of the high ICOS standards (Rebmann et al. 2018; Sabbatini et al. 2018) and the consistent management of the cluster for almost 30 years should allow an across-sites comparison of ecosystem responses to environmental (including climate) changes.

The first objective is to investigate the reactions of different ecosystems in Central Europe to aspects of climate change such as higher atmospheric demand for water due to rising air temperatures and altered precipitation patterns. The second objective is to identify potential effects of disturbances on these ecosystems, both from climate extremes (e.g., extreme drought) and from management (e.g., harvest and harvest related fallow periods).

The related research questions are:

1) How do the carbon fluxes of different ecosystems react to climate changes, such as warmer and sometimes drier summers with longer drought periods?
2) How large is the effect of disturbances due to climate extremes and management on annual net ecosystem productivity (NEP)?
3) How can the effect of management strategies enhance the resilience of forests or cropping systems regarding a persistently large *NEP* over many years?

2. Methods

2.1. Monitoring at ICOS sites

The data presented in this study were gathered in a cluster of four ICOS ecosystem sites in geographical proximity (maximum mutual distance is 8.5 km, Fig. 1). These sites are located inSaxony (East Germany), and include an old spruce forest within the Tharandt forest (DE-Tha), a permanent pasture in Grillenburg (DE-Gri), a cropland in Klingenberg (DE-Kli), and a young mixed oak forest that was planted after a disturbance by windthrow in 2007 near Hetzdorf (DE-Hzd). The suboceanic/subcontinental climate is characterised by an annual precipitation of 827 mm (1959–2022), an increasing annual mean temperature from 7.6 °C (1959–1990) to 8.8 °C (1991–2022), respectively and a global radiation of 128 W m^{-2} (1997–2022). The CO_2 concentration increased from 376 ppm (annual mean of 1997) to 429 ppm (2022). Fig. 2 provides an overview of the meteorological conditions since 1960. Given the proximity of the sites to each other, this development can be assumed to be

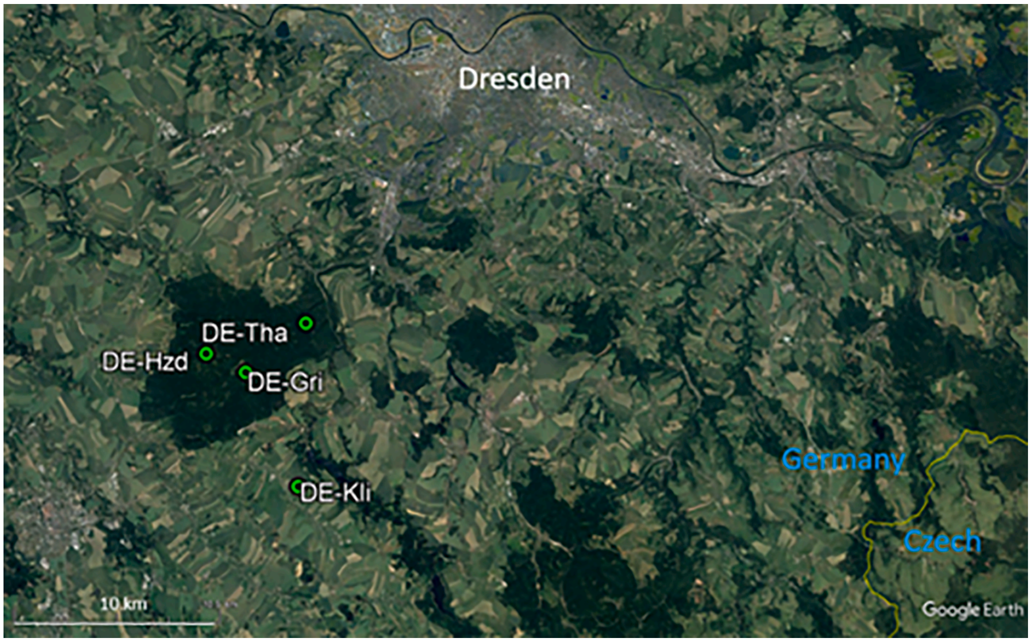

Fig. 1. Locations of the ICOS sites around 20 km southwest of the city of Dresden (Germany).

representative of all the sites analysed here.

The forest at DE-Tha (50°57′49″N, 13°34′01″E, 380 m a.s.l.) is characterised as homogeneous on the flux footprint scale (Mellmann et al. 2003; Rebmann et al., 2005). 90 % of the half-hourly fluxes exceed the threshold of an 80 % flux contribution from the target land-cover type (Göckede et al. 2008). The main canopy species are 81 % spruce (*Picea abies* (L.) H. Karst.), 9 % European larch (*Larix decidua* Mill.) and 3 % birch (*Betula pendula* Roth). The spruce stand was seeded in 1887 and the canopy height, diameter at breast height and green area index are 29.4(±6.9) m, 42.0(±12.9) cm and 3.2(±1.4), respectively. The above-ground carbon pool in spruce trees is 107 tC ha^{-1} (2019) and the soil carbon pool (without roots) is 135 tC ha^{-1} (2019). The above-ground biomass of the spruce forest has been calculated using diameter at breast height (DBH) measurements and site specific allometric relation between DBH and above-ground biomass of picea abies. Soil C pools have been determined at around 20 sampling points (measurements of bulk density, stone fraction and C content) up to 60 cm depth. The forest has been managed since 1811 (Wotte, 1976). In addition to thinning and afforestation, liming is one of the main management measures to increase the soil pH after the acidification due to 'acid rain' during the 1970s and 1980s, which resulted in large forest losses, e.g., in the Ore Mountains. During the reporting period of this study, the forest was subjected to three main thinning events (before the start of the growing season in 2002, 2011, and 2016, respectively). The exported biomass has been estimated to be between 3.2 tC ha^{-1} and 9.9 tC ha^{-1} in carbon equivalents.

The disturbed forest site DE-Hzd (50°57′50″N, 13°29′23″E, 395 m a.s.l.) near the village of Hetzdorf within the Tharandt Forest is located on a 40 ha windthrow area. Until the windthrow in January 2007, the site was characterised as an old spruce forest very similar to DE-Tha. After removal of the stems of spruce, a mixture of two oak species has been planted in 2008 and 2010 without any additional management (e.g., thinning) until now. The mixed young oak forest has reached a canopy height of 9.5 m (2021) and the LAI (leaf area index) increased from 1.3 (2014) to 5.5 (2023). The main canopy species are 51 % oak (*Quercus robur* L. (48 %), *Quercus rubra* L. (3 %)), 26 % birch (*Betula pendula* Roth), and 13 % spruce (*Picea abies* (L.) H. Karst.). The Hetzdorf tower and the measurement heights have been adjusted to the growing oak forest when necessary. A conservative fetch estimate for this site yields a distance of about 300 m to the next inhomogeneity while the 2023 footprint of 90 % of the fluxes is 180 m to 220 m (dependent on wind direction). Since the forest and the height of measurement did grow, a non-negligible contribution of the surrounding spruces is assumed to affect the tower data since 2022. For DE-Hzd, biomass and soil C pools are not yet available.

The permanent grassland at DE-Gri (50°57′04″N, 13°30′50″E; 385 m a.s.l.) is located in the middle of the Grillenburg clearing (around 40 ha) within the Tharandt Forest. Typical and observed plant species are couch grass (*Agropyron repens* L.), meadow foxtail (*Alopecurus pratensis* L.), yarrow (*Achillea millefolium* L.), common sorrel (*Rumex acetosa* L.) and white clover (*Trifolium repens* L.). Biomass inventories include canopy height, LAI and above-ground biomass. The soil carbon pool is 86 tC ha^{-1} (2019). The grassland is managed by regular cuttings one to three times a year resulting in estimated annual carbon exports from 0.7 tC ha^{-1} a^{-1} to 1.3 tC ha^{-1} a^{-1}. Mineral fertilisers are occasionally applied in spring. The 2023 footprint of 90 % of the fluxes is 90 m to 120 m (dependent on wind direction). For agricultural land use, only the soil C pool is a long-term C storage because above-ground biomass is either harvested or decomposed.

The cropland at DE-Kli (50°53′34″N, 13°31′21″E; 478 m a.s.l.) is situated 4 km south of the Tharandt Forest and has been managed solely as cropland since 1975 (partially grassland before 1975). Typical crop rotation includes winter barley (*Hordeum vulgare* L.), rapeseed (*Brassica napus* L.), winter wheat (*Triticum aestivum* L.), forage maize (*Zea mays* L.) and spring barley (*Hordeum vulgare* L.). Faba bean (*Vicia faba* L.) was grown once in 2019. Intermediate crops or catch crops are typically not planted before a spring crop. Biomass inventories include canopy height, LAI and above-ground biomass. The soil carbon pool is 104 tC ha^{-1} (2019). Besides harvests, including removal of residue except for rapeseed straw, sowings and tillage (scarifications) the cropland is fertilised using regular mineral and non-regular organic (solid and liquid manure) fertilisers and is treated with pesticides, herbicides, and fungicides. Carbon exports due to corn and straw yield range from 1.5 tC ha^{-1} a^{-1} to 5.6 tC ha^{-1} a^{-1}. The carbon import due to solid and liquid manure application is on average 3.7 tC ha^{-1} and 0.15 tC ha^{-1} per organic fertilisation event, respectively. All management data are provided by the agricultural cooperative. A comprehensive overview over all management measures is given in Table A1 in the appendix. The 2023 footprint of 90 % of the fluxes is 130 m to 160 m (dependent on wind direction). Similar to DE-Gri, only the below-ground biomass is a long-term C

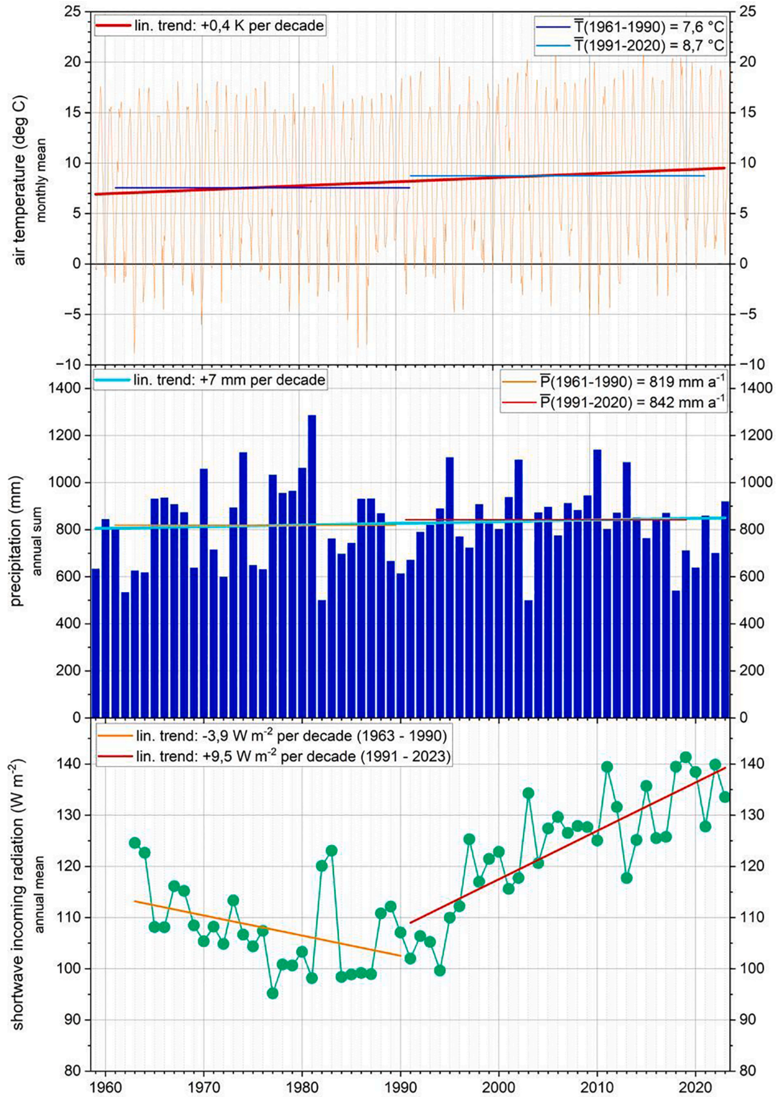

Fig. 2. Long-term meteorological conditions at the ICOS site DE-Tha (1959–2023), upper panel: mean monthly air temperature including 30-year averages and linear trend, middle panel: annual precipitation sum including 30-year averages and linear trend, lower panel: mean annual incoming shortwave radiation including linear trends.

storage.

Eddy covariance (EC) measurements of CO_2, heat and momentum fluxes started in 1996 (DE-Tha), 2003 (DE-Gri), 2004 (DE-Kli), and 2010 (DE-Hzd), respectively. The EC setups typically include Gill ultrasonic anemometers (Gill Instruments, Lymington, UK) and LI-COR gas analyzers (LI-COR Inc., Lincoln, NE, USA). All EC sites are equipped with accompanying meteorological monitoring including short-, longwave and diffuse radiation (CNR1/4, Kipp and Zonen, Delft, The Netherlands and BF2/5, Delta-T Devices Ltd., Cambridge, UK), photosynthetic photon flux density (LI-190SZ, LI-COR Inc., Lincoln, NE, USA), air temperature and humidity (HMP35/45D, Vaisala, Helsinki, FI), soil temperature and moisture (CS655 or SoilVUE10, Campbell Scientific Ltd., Logan, Utah, USA), precipitation (PLUVIO^2, OTT Messtechnik, Kempten, Germany or TRwS204, MPS system Ltd., Bratislava, SVK), and soil heat flux (HFP01, Hukseflux, Delft, The Netherlands). Site characteristics and instrumentation details are listed in Table 1 and 2, respectively, and characteristics of the EC setups and canopy heights are indicated in Table 3.

Table 1
ICOS sites of the TUD cluster and associated characteristics. The land use classes covered by the cluster are evergreen needleleaf forest (ENF), grassland (GRA), crops (CRO) and deciduous broadleaf forest (DBF).

ICOS site	Land use classification	Elevation (m a.s.l.)	Soil classification	Management	Site years
DE-Tha	ENF	380	Podsol	Thinnings (around 1 per decade), understory of beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.) (to replace the dominating spruce)	27
DE-Gri	GRA	385	Gleysol	1–3 cuts per year (infrequent cattle grazing)	19
DE-Kli	CRO	478	Gleysol	Typical crop rotation (rapeseed, winter wheat, winter barley, spring barley, maize), occasional intercropping	19
DE-Hzd	DBF	395	Stagnic Albeluvisol	Regrowth after wind throw 2007 as well as natural rejuvenation	14

Table 2
EC, meteorological and soil measurement devices at the ICOS sites (refer to text).

Site	Ultrasonic anemometer	Gas analyzer	Meteo and Soil
DE-Tha	GILL Solent R2 (1996–2006) GILL R3–50 (since 2006) GILL HS-50 (since 2016)	LI-COR LI-6262 (1996–2006) LI-COR LI-7000 (since 2006) LI-COR LI-7200 (since 2016)	CNR1/4, LI-190SZ, BF2/5, HMP35/45D, CS655, PLUVIO², HFP01
DE-Gri	METEK USA-1 (2003–2007) GILL R3–50 (since 2007)	LI-COR LI-7500 (2003–2005) LI-COR LI-7000 (since 2005)	CNR1, LI-190SZ, HMP45, CS655, SoilVUE, TRwS204, HFP01
DE-Kli	GILL R3–50 (2004–2016) Young 81,000 (2016–2018) GILL R3–50 (since 2018)	LI-COR LI-7000 (since 2004)	CNR1, LI-190SZ, HMP45, CS655, SoilVUE, PLUVIO², HFP01
DE-Hzd	Campbell CSAT3 (since 2010)	LI-COR LI-7500 (since 2010)	CNR1, LI-190SZ, HMP45, SoilVUE, HFP01

Table 3
Technical characteristics regarding EC measurements and canopy heights at the ICOS sites.

Site	EC level (m a.g.)	Separation of EC sensors (m)	EC raw data frequency (Hz)	Tube length (m)	Typical CO_2 time lag (*sec*)	Canopy height (m)
DE-Tha	42	0.31	20–25	63	4	31 (2019)
DE-Gri	3	0.13	20–25	4.6	0.6	0.02–0.87
DE-Kli	3.5	0.12	20–25	4.1	0.6	0–2.2
DE-Hzd	5 (2010)–17.2 (2022)	0.21	10	–	0	0.7 (2010)–9.5 (2021)

2.2. Data processing

The post-processing of EC raw data uses EddyPro® v7.0.x. and is based on block averaging of half-hourly intervals. It includes despiking (Mauder et al. 2013), raw data statistical screening (Vickers and Mahrt, 1997), axis rotation for tilt correction (planar fit acc. to Wilczak et al. 2001), compensation of density fluctuations (Ibrom et al. 2007; Burba et al. 2012), automatic time lag optimization and compensation of density fluctuations or converting concentrations into mixing ratios (Ibrom et al. 2007; Burba et al. 2012), respectively. Corrections of co-spectral low- and high-frequency damping are applied according to Moncrieff et al. (2004), Fratini et al. (2012) and Horst and Lenschow (2009). Storage fluxes of CO_2, latent and sensible heat in the canopy air layer have been calculated based on temporal changes of CO_2, water vapour concentration and temperature in the respective EC measurement level.

After discarding implausible CO_2 fluxes and accounting for instrument failures, the half-hourly data availabilities are on average 93 % (DE-Tha), 86 % (DE-Gri), 83 % (DE-Kli), and 55 % (DE-Hzd), respectively. Only DE-Hzd has a solar power supply system causing remarkable data gaps during winter in initial years (the current data availability at DE-Hzd is around 80 %). The net ecosystem exchange of CO_2 (*NEE*) is the sum of atmospheric CO_2 flux F_c and the storage flux of CO_2 S_c, whereas the net ecosystem productivity (*NEP*) is the negative *NEE*:

$$NEP = -NEE = -(F_c + S_c) \quad (1)$$

Due to the focus on ecosystem behaviour, *NEP* is used in this study. Positive *NEP* numbers indicate that the ecosystem is a C sink removing C from the atmosphere according to this definition. The change in the C pool of an ecosystem is a result of the atmospheric exchange (*NEP*) and the lateral C fluxes due to management (e.g., harvest, fertilisation). The resulting ecosystem C budget (Net Biome Productivity *NBP*), ignoring dissolved or total organic (*DOC/TOC*) fluxes is

$$NBP = NEP + C_{im} - C_{ex} \quad (2)$$

Note that positive *NBP* numbers indicate that the ecosystem is a C sink removing C from the atmosphere. Carbon import (C_{im}) includes organic fertilisation (solid/liquid manure), inorganic fertilisation (lime) and seeds, and carbon export (C_{ex}) components are grain and straw yield, hay, grass silage, as well as timber.

Missing half-hourly fluxes and meteorological data have been filled as well as *NEP* fluxes have been corrected for insufficient turbulence (variable u_* correction) using the 'Eddy covariance data post-processing tool' of the Department of Biogeochemical Integration at Max Planck Institute for Biogeochemistry Jena (Wutzler et al. 2018).

To correct the heat fluxes (and consequently evapotranspiration) for the imbalance in the measured energy budget (outgoing heat fluxes are typically lower than the available energy) a procedure according to Pastorello et al. (2020) has been applied. Latent (*LE*) and sensible (*H*) heat fluxes are corrected by multiplying the original, gap-filled *LE* and *H* data by an energy balance closure correction factor based on daily means. Note that changes in instrument setup and post-processing did influence the fluxes and led to deviations between this study and older publications of the same sites.

The flux partitioning of the net CO_2 flux *NEP* in the gross fluxes *GPP* and R_{eco} (total ecosystem respiration) is based on an algorithm provided by Reichstein et al. (2005). Data of all sites were partitioned with the nighttime method using nighttime data to parameterize a respiration-temperature model that is then applied to the whole dataset to estimate R_{eco} . *GPP* is then calculated as the sum of R_{eco} and *NEP* (Pastorello et al. 2020).

3. Results

3.1. Interannual variability of NEP and ET

The results presented in this section may serve as the basis to address our research questions. The most important climate extremes are the drought years of 2018, 2019, 2020, and 2022, as well as a wind throw of a spruce-dominated forest in 2007 at the DE-Hzd site that has been subsequently established there after planting oaks for the regeneration. Other relevant management measures are the thinning at the DE-Tha spruce-dominated forest site, the harvest at the grassland site DE-Gri, and the crop selection and manure application at the agricultural site DE-Kli.

By the end of 2023, the time series of DE-Tha covered slightly >27 years of flux measurements. The annual sums of *NEP* and *ET* during this period are shown in Table 4. Annual *NEP* was largest in 2017 (560 g C m^{-2}) and lowest in 2022 (251 g C m^{-2}) with all other years in between. Largest daily CO_2-sinks commonly occur in spring and early summer. In contrast to all other investigated sites, DE-Tha was always a net CO_2-sink regarding annual *NEP*. However, the forest was CO_2 neutral within the growing season for several weeks during dry and very warm periods (e.g., summer 2018, 2022), and the cumulative sum declined accordingly (cf. Fig. 3, year 2022, blue line). The years in which thinning took place (2002, 2011, and 2016) do not stand out as years with much lower or much larger cumulative *NEP* than the long-term average. In the case of DE-Tha, the year of maximum *ET* (2017) coincides with the year of the

Table 4
Annual sums of *NEP* (gC m^{-2} a^{-1}) and *ET* (mm a^{-1}) as well as uncertainties caused by gap-filling at the ICOS sites (Maxima are highlighted in green, Minima are highlighted in red).

year	*NEP*				*ET*			
	DE-Tha	DE-Gri	DE-Kli	DE-Hzd	DE-Tha	DE-Gri	DE-Kli	DE-Hzd
1997	430 (±62)				482 (±3)			
1998	446 (±22)				513 (±30)			
1999	506 (±9)				507 (±9)			
2000	458 (±14)				513 (±34)			
2001	445 (±15)				535 (±4)			
2002	440 (±34)				403 (±115)			
2003	315 (±21)				419 (±2)			
2004	325 (±1)				462 (±6)			
2005	388 (±25)	94 (±18)	62 (±15)		411 (±13)	646 (±14)	526 (±12)	
2006	340 (±20)	125 (±30)	26 (±28)		397 (±6)	582 (±3)	486 (±20)	
2007	402 (±63)	84 (±11)	28 (±19)		462 (±0)	584 (±8)	486 (±15)	
2008	465 (±6)	127 (±5)	-77 (±18)		494 (±1)	554 (±7)	475 (±100)	

(continued on next page)

Table 4 (*continued*)

2014	532 (±25)	56 (±40)	277 (±12)	**-551 (±28)**	505 (±4)	630 (±24)	601 (±14)	602 (±96)
2015	472 (±2)	41 (±26)	67 (±2)	-388 (±54)	505 (±0)	663 (±1)	**628 (±7)**	651 (±269)
2016	480 (±17)	54 (±62)	314 (±13)	-325 (±45)	536 (±7)	643 (±21)	481 (±71)	**711 (±326)**
2017	**560 (±9)**	46 (±32)	101 (±10)	-306 (±28)	**585 (±1)**	646 (±24)	**389 (±11)**	654 (±108)
2018	327 (±1)	16 (±24)	123 (±2)	173 (±82)	442 (±3)	551 (±7)	409 (±2)	649 (±129)
2019	439 (±19)	88 (±11)	-10 (±5)	26 (±41)	467 (±28)	626 (±3)	558 (±3)	645 (±137)
2020	320 (±61)	**3** (±28)	117 (±45)	26 (±25)	**393 (±16)**	**528 (±44)**	608 (±4)	581 (±113)
2021	367 (±12)	50 (±2)	343 (±2)	127 (±22)	574 (±1)	**725 (±3)**	582 (±13)	710 (±37)
2022	**251 (±16)**	115 (±96)	3 (±9)	124 (±136)	420 (±4)	583 (±5)	487 (±5)	599 (±112)
2023	481 (±11)	**276 (±76)**	313 (±35)	**206 (±51)**	466 (±4)	573 (±6)	530 (±16)	593 (±39)
2009	434 (±0)	87 (±28)	229 (±1)		495 (±0)	604 (±76)	455 (±21)	
2010	489 (±9)	114 (±8)	63 (±6)	-404 (±4)	484 (±1)	553 (±27)	441 (±36)	534 (±70)
2011	437 (±24)	157 (±30)	**315 (±38)**	-303 (±38)	484 (±2)	643 (±30)	523 (±22)	612 (±197)
2012	495 (±2)	121 (±40)	**-201 (±51)**	-395 (±13)	484 (±4)	652 (±12)	467 (±10)	593 (±237)
2013	416 (±10)	110 (±12)	-142 (±19)	-439 (±81)	498 (±7)	551 (±8)	415 (±95)	**446 (±102)**

largest cumulative *NEP*, whereas the years for lowest *NEP* and lowest *ET* differ. However, in 2022 (lowest *NEP*) the *ET* was in the lower range, but does not constitute the year with lowest *ET* in 2020.

Fig. 4 shows the corresponding plots for the grassland site DE-Gri and the annual sums of *NEP* and *ET* are presented in Table 4. The lowest *NEP* was recorded in 2020 resulting in a CO_2-neutrality of that year. 2020 was a dry year after two years of drought, which indicates that the grassland site can be affected by (long term) drought under such extreme conditions. In 2023, the largest *NEP* was recorded (two cuts). Periods with declining cumulative sums within the growing season are commonly related to decreased *NEP* in the three weeks after mowing events. Years of lowest and largest cumulative *NEP* do not agree with the corresponding years for DE-Tha. This can be generally ascribed to a better soil moisture supply for this site, but also to the fact that grass differs in its water use strategy and its reaction to drought compared to forest (cf. Teuling et al. 2010; Rotenberg and Yakir 2011). However, the year 2022 (lowest *NEP* at DE-Tha) showed the largest decrease in *NEP* after mowing and very likely reflects effects of drought also at DE-Gri in 2022. The lowest *NEP* and ET were recorded in 2020 at DE-Gri. Largest annual *ET* was recorded in 2021, which however does not coincide with the year for which the largest *NEP* at DE-Gri was recorded.

Fig. 5 presents the annual cumulative curves of *NEP* and *ET* for the agricultural site DE-Kli. The annual sums of *NEP* and *ET* are shown in Table 4. The lowest annual sum of *NEP* was recorded in 2012 (maize), indicating that the site already became a considerable CO_2-source in terms of *NEP*. This behaviour could be also observed in other years when maize or spring crops have been cultivated. Within those years, maize was grown and it was sown only in April, as a certain soil temperature is required for germination. The ground was bare up to that point, which in turn favoured soil respiration. Interestingly, the annual budget of the maize year indicated a CO_2-sink in 2018. Despite the drought year, the annual *NEP* profited from intercropping and from the general advantage

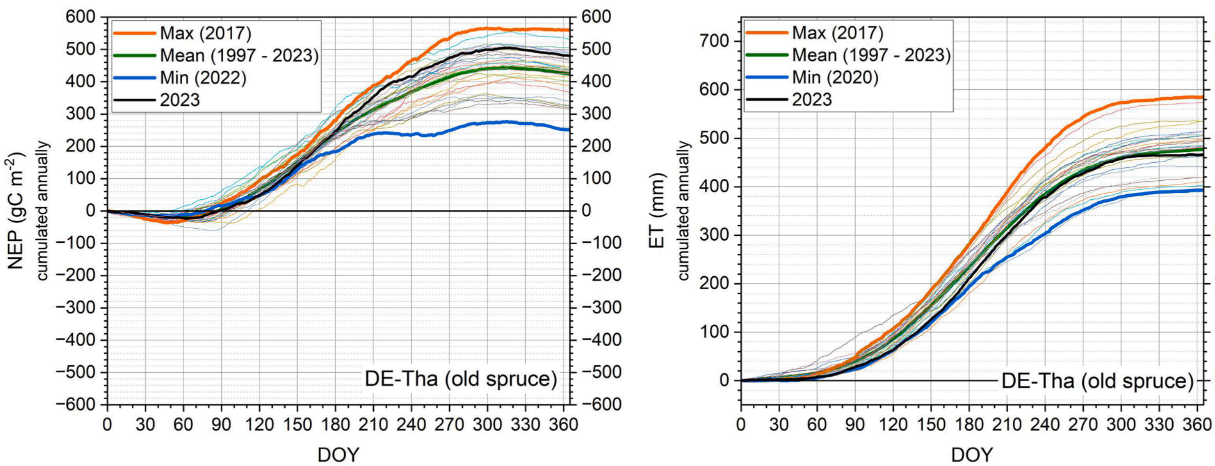

Fig. 3. Ensemble of annually cumulated Net Ecosystem Productivities (*NEP*, left) and annually cumulated evapotranspiration (*ET*, right) of an old spruce forest at DE-Tha for 27 years (1997–2023).

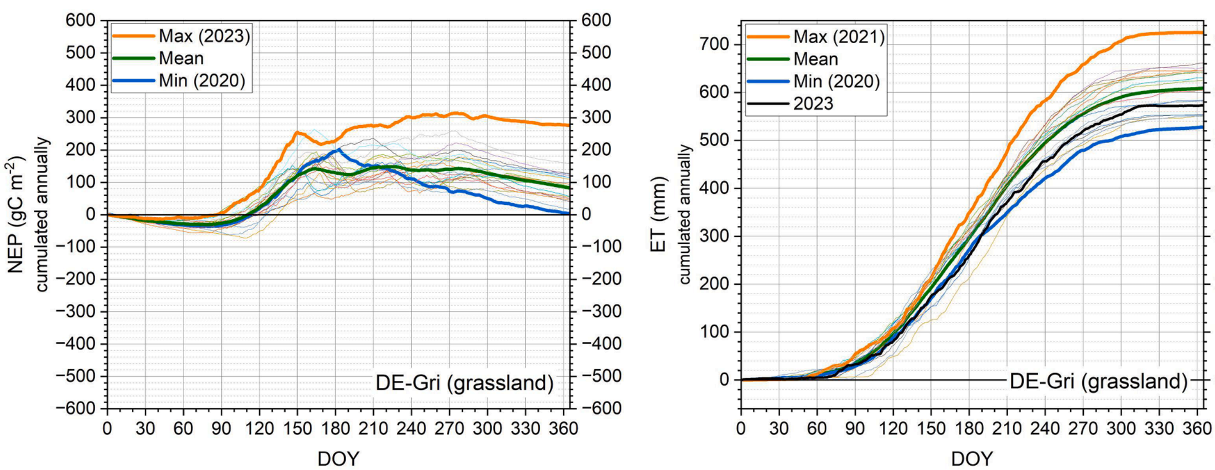

Fig. 4. Ensemble of annually cumulated Net Ecosystem Productivities (*NEP*, left) and annually cumulated evapotranspiration (*ET*, right) of a permanent grassland at DE-Gri (1 to 3 mowings per year) for 19 years (2005–2023).

of a C4 plant under drought conditions. Winter wheat (sown in the preceding year) reduced periods with bare soil and could (partly) compensate for soil respiration. In the year 2022, when the lowest *NEP* at DE-Tha was recorded, DE-Kli was CO_2-neutral in terms of *NEP* (Table 4). This can be attributed to the crop grown (spring barley, sown in spring, C3-plant) but also to the general dry conditions of that year. In contrast to the forest site DE-Tha, the agricultural site DE-Kli was not an annual net CO_2-sink in each year. Its CO_2 sink capacity highly depends on the cultivated crop and management (use of intercropping or not). At the annual level, it can be a CO_2-source, a CO_2-sink or CO_2-neutral.

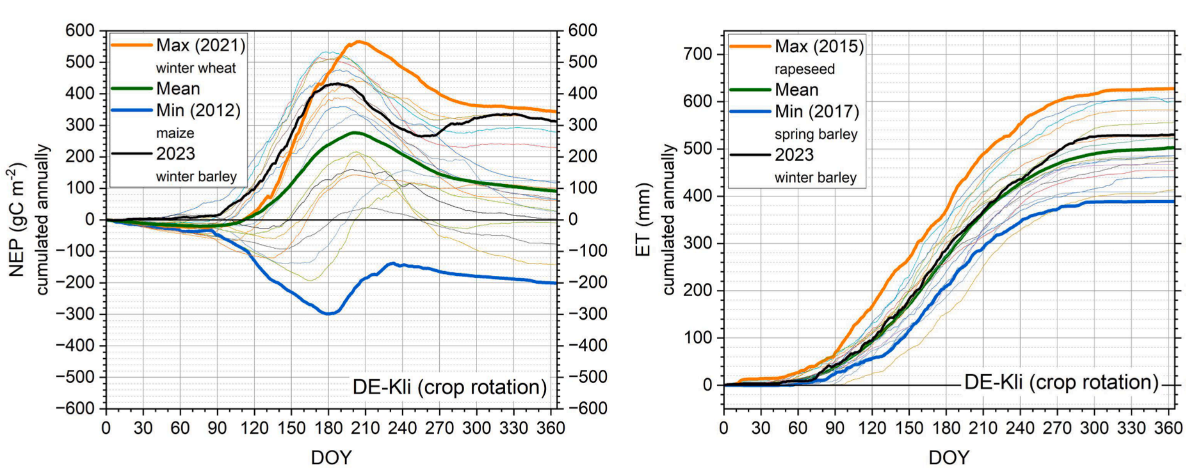

Fig. 5. Ensemble of annually cumulated Net Ecosystem Productivities (*NEP*, left) and annually cumulated evapotranspiration (*ET*, right) of a cropland at DE-Kli (crop rotation includes winter wheat, rapeseed, forage maize, winter barley, spring barley and field bean) for 19 years (2005–2023).

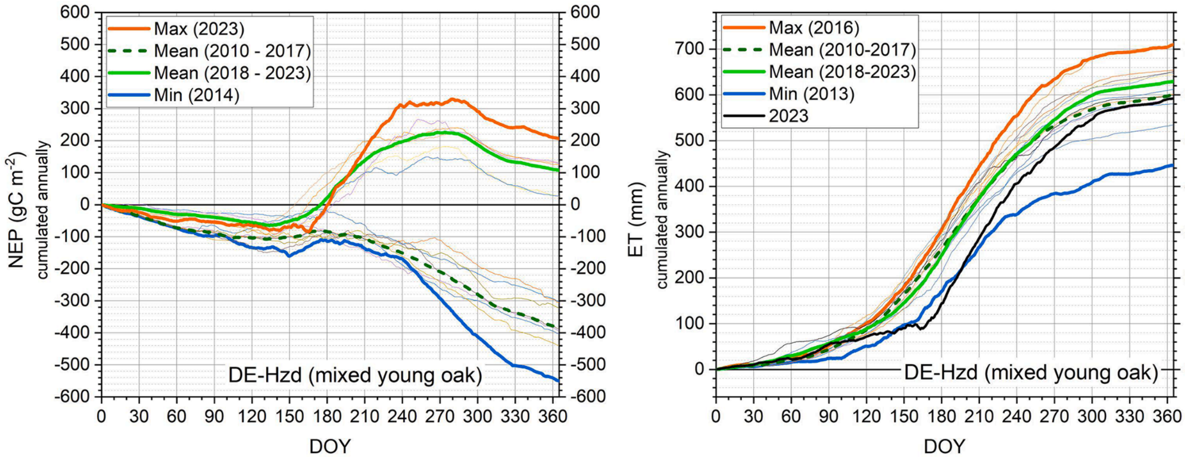

Fig. 6. Ensemble of annually cumulated Net Ecosystem Productivities (*NEP*, left) and annually cumulated evapotranspiration (*ET*, right) of a mixed young oak forest established after windthrow of an old spruce forest in 2007 at DE-Hzd for 14 years (2010–2023).

Lowest and largest annual sums of *ET* did not coincide with years of lowest and largest annual *NEP*. The largest annual *ET* sum was observed in 2015 (dry and warm year), when rapeseed was cultivated. As a winter crop sown in late summer of 2014 roots and leaves were already well developed in 2015, which favours higher transpiration rates earlier in the year and provides better access to soil water.

The youngest of the four investigated sites is DE-Hzd (Fig. 6), where the CO_2 exchange of a young oak plantation has been observed since 2010. Within the first eight years of measurement (11 years after windthrow), the oak site did act as a CO_2 source. This means that more CO_2 was released by the ecosystem than absorbed by the pioneering vegetation, resulting in negative annual *NEP* as shown in Table 4. This CO_2 source could be as large as the CO_2 sink of the old spruce forests of DE-Tha on an annual basis. Therefore, the CO_2 sink per area of the old spruce forest was almost totally offset by the CO_2 source per area of the young oak plantation. The transition of the oak plantation from a CO_2 source to a CO_2 sink took place very quickly without the source having steadily decreased in previous years. We hypothesise that very warm years, vegetation growth (canopy closure) in concert with comparatively sufficient soil moisture supply, despite a general drought, contributed to this shift. Since 2018, the oak plantation has acted as a CO_2 sink with the largest *NEP* in the year 2023 illustrating the ongoing rise in CO_2 sink. But the sink remained smaller than the sink of the old spruce forest (DE-Tha). The lowest *NEP* was observed in 2014. This can be attributed to the generally more open stand as a result of the small trees. More sunlight could reach the ground, which heated the soil and favoured soil respiration. Unlike for old spruce forest DE-Tha, the year with largest *NEP* did not coincide with the year of largest cumulative *ET* in this young oak forest.

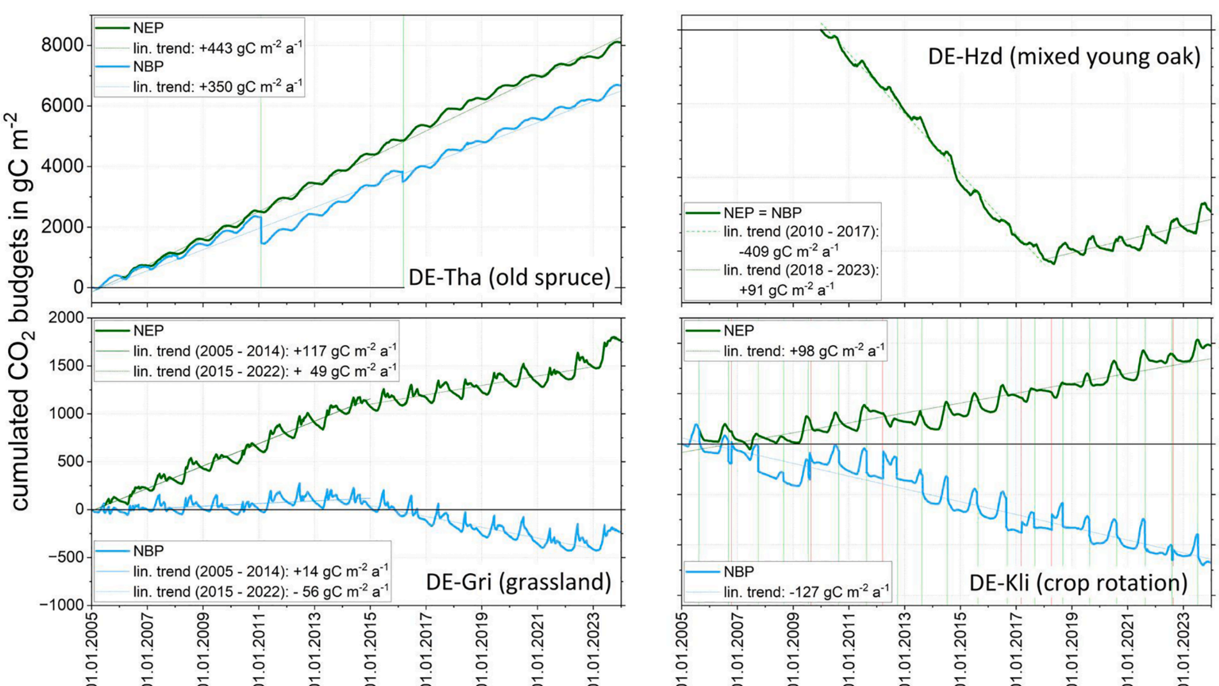

Fig. 7. Cumulated *NEP* (green lines) and *NBP* (blue lines) (including linear trends) at the forest sites DE-Tha (old spruce) and DE-Hzd (mixed young oak), the grassland site DE-Gri and the crop site DE-Kli for the period 2010–2023 (positive numbers indicate a C sink, Y axes differently scaled). At DE-Hzd, there has been no management since the beginning of the EC-measurements. Therefore, *NBP* equals *NEP* (no blue line). At DE-Kli and DE-Tha vertical green lines indicate the harvest, vertical red lines indicate the application of solid manure (DE-Kli).

3.2. Effects of agricultural management, thinnings and disturbances on NBP

Lateral fluxes like yield export, organic fertilisation of croplands or thinnings of forests are additional components in the ecosystem C budget besides atmospheric exchange (Eq. (2)). Those fluxes can result in distinct differences between *NEP* and *NBP* especially at agricultural sites. An example is the cropland site DE-Kli providing a long-term net CO_2 sink regarding EC measured atmospheric fluxes (*NEP*) of 98 gC m^{-2} a^{-1} but a decrease in ecosystem C pool (*NBP*) of 127 gC m^{-2} a^{-1} despite occasional solid manure applications (Fig. 7). Significant differences exist regarding the gross fluxes *GPP* and R_{eco} of winter and spring crops. Due to a longer greening phase the mean *GPP* and mean R_{eco} (including autotrophic respiration) of winter crops are 603 gC m^{-2} a^{-1} and 388 gC m^{-2} a^{-1} higher, respectively, than those of the spring crops (Fig. 8). This results in a mean *NEP* of 193 gC m^{-2} a^{-1} (winter crops) and −22 gC m^{-2} a^{-1} (spring crops). In addition, the resulting *NBP* of spring crops is more negative (−182 gC m^{-2} a^{-1}) than the *NBP* of winter crops (−69 gC m^{-2} a^{-1}) with small yield differences between winter and spring crops (Fig. 9). Based on emission factors (Umweltbundesamt 2024), the application of organic fertilisers (manure, slurry) result in additional N_2O emissions of 17 (±5) g CO_2eq m^{-2} per event, whereas the mineral fertilisations cause mean N_2O emissions of 37 (±17) g CO_2eq m^{-2} per year.

The NEP of the grassland site DE-Gri indicates a moderate CO_2 sink (*NEP* of 49 to 117 gC m^{-2} a^{-1}) but when considering lateral fluxes, DE-Gri is nearly C neutral or a small C source (*NBP* of 14 to −56 gC m^{-2} a^{-1}) (Fig. 7). For a complete greenhouse gas balance, methane fluxes would also have to be taken into account at this site as cattle grazing takes place occasionally. However, there are no measurements or estimates for this.

During the reporting period of this study, the forest was subjected to three main thinning events in 2002, 2011 and 2016. The exported biomass has been estimated to 57 m^3 ha^{-1} or 9.9 tC ha^{-1} in carbon equivalents (2002), 49 m^3 ha^{-1} or 8.5 tC ha^{-1} (2011) and 19 m^3 ha^{-1} or 3.2 tC ha^{-1} (2016), respectively. Thinnings at the old spruce site DE-Tha reduce the increase in ecosystem C pool from 443 gC m^{-2} a^{-1} (*NEP*) to 350 gC m^{-2} a^{-1} (*NBP*). A complete loss of an old spruce forest due to windthrow followed by a re-established young oak forest is an example for a drastic ecosystem disturbance (DE-Hzd). For 11 years after the windthrow (2007–2017) the affected ecosystem switches to a net CO_2 source of 409 gC m^{-2} a^{-1} (*NEP*, no management at the site except planting oaks) followed by a CO_2 sink of 113 gC m^{-2} a^{-1} since 2018 (increasing trend). Compared to the old spruce site, the sum of missing CO_2 uptake and additional CO_2 release amounts to 852 gC m^{-2} a^{-1} (443+409 gC m^{-2} a^{-1}) at the disturbed site for the period 2007 to 2017. Since 2018, the reduced CO_2 sinks are just 330 gC m^{-2} a^{-1} (443–113 gC m^{-2} a^{-1}) (Fig. 7, upper panel).

3.3. Effect of drought at the old spruce site

The dry years 2003, 2018, 2020, and 2022 were characterised by a mean precipitation deficit of at least 241 mm or 29 % (compared to the mean annual sum for the EC measurement period 1997–2023), which resulted in a mean *NEP* reduction of 121 gC m^{-2} a^{-1} or 29 % on average (Fig. 9). This reduced C sink is typically caused by a decrease in *GPP* of 165 gC m^{-2} a^{-1} or 11 % while R_{eco} is decreased by 44 gC m^{-2} a^{-1} or 4 % only. Interestingly, the lowest precipitation deficit of those four years resulted in the highest *NEP* deficit (2022) despite the higher soil moisture since mid of August in contrast to the other dry years. This may be caused by a legacy effect of several preceding dry years since 2018.

Typically, the spruce forest is still a net CO_2 sink during the vegetation period also in dry years ($GPP > R_{eco}$) as shown in Fig. 10. An exception was observed in August 2022 when R_{eco} increased but *GPP* continued to decrease for roughly two more weeks before slightly increasing again. This led to a partly higher R_{eco} than *GPP* (Fig. 10, blue circle) resulting in the rapid increase of the *NEP* deficit of that year (Fig. 9, lower right panel). Maybe soil respiration has been more boosted than *GPP* by the increasing soil moisture since the end of August 2022. During the other dry years soil moisture remained low until the end of the year in contrast to 2022.

4. Discussion

4.1. Energy balance closure

The lack of energy balance closure is one of the indications of methodological uncertainties and a systematic bias of eddy covariance estimates as these heat fluxes are typically underestimated when compared to the available energy at the surface (Wilson et al. 2002; Foken 2008; Mauder et al. 2020). At the sites of the TUD cluster the

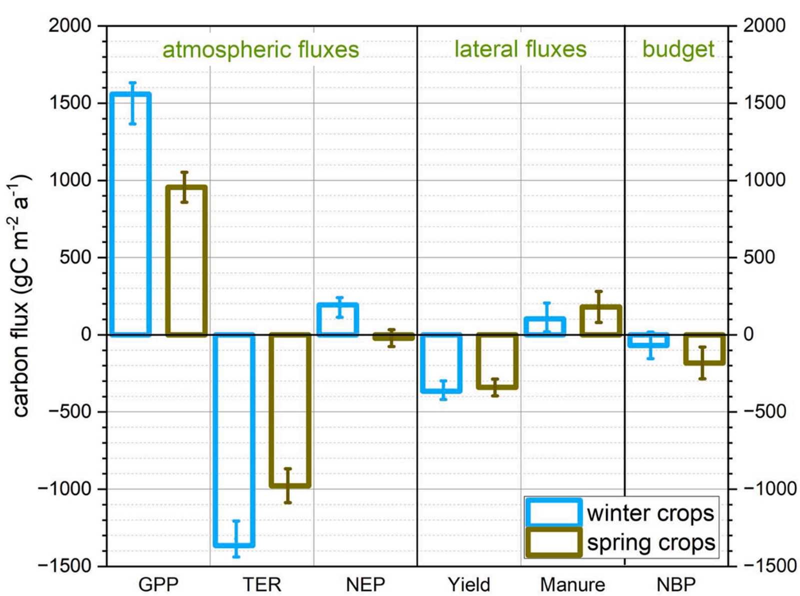

Fig. 8. Mean gross (*GPP*, R_{eco}) and net fluxes (*NEP*), mean lateral C fluxes (yield, manure) and mean crop site C budgets (*NBP*) for winter crops (winter wheat, rapeseed, winter barley) and spring crops (maize, spring barley, faba bean) at DE-Kli (2005–2023). Negative signs indicate a C loss regarding the ecosystem (soil) C pool and the error bars show the standard deviation between the individual years.

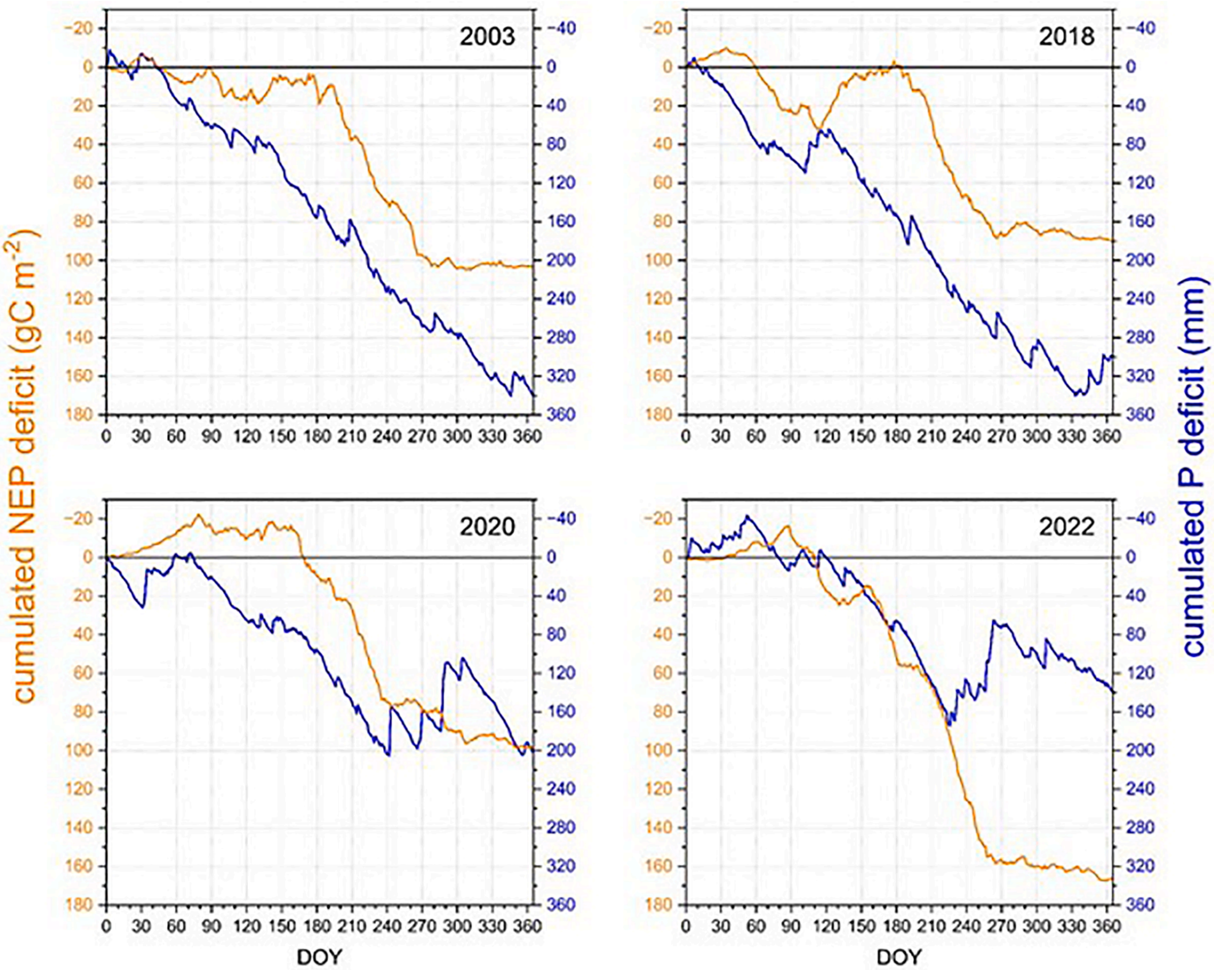

Fig. 9. Cumulated deficits of Net Ecosystem Productivity *NEP* and precipitation *P* (based on daily sums, positive numbers indicate a deficit) at DE-Tha during the dry years 2003, 2018, 2020 and 2022.

mean energy balance closure is 70 % (DE-Tha, 2006–2023), 64 % (DE-Gri), 72 % (DE-Kli) and 65 % (DE-Hzd), respectively. To compensate for this error, we applied the adjustment method of Pastorello et al. (2020) on the basis of daily data, which preserves the Bowen ratio in accordance with the FLUXNET2015 data set and the ONEflux processing pipeline. Recently, more sophisticated adjustment methods have been proposed with a special focus on specific sources of error, e.g., low-pass filtering effects on water vapour fluxes (Zhang et al. 2023; Smidt et al. 2025) or the otherwise neglected contribution of dispersive fluxes, which emerge from a spatial covariance between the temporal averages of the vertical velocity components and the scalar to be transported (Margairaz et al. 2020; Wanner et al. 2024). However, these correction methods only aim at correcting for specific effects related to the energy balance closure problem. Hence, we decided in favour of the relatively simple bulk correction of sensible and latent heat fluxes of Pastorello et al. (2020) for this investigation. It is still under debate whether CO_2 fluxes should be corrected in a similar way since the closure problem may hint at a general underestimation of all scalar fluxes (Huang et al. 2008; Mauder et al., 2021a; Mauder et al., 2021b). However, no correction algorithm has been proposed for CO_2 yet and hence, we did not apply any additional flux adjustment method.

4.2. Methodological uncertainties

The gap-filling procedure, which is necessary to obtain monthly or annual fluxes of *ET* or *NEP*, represents another source of methodological uncertainty. We used a marginal distribution sampling (MDS) approach according to Reichstein et al. (2005). Many other alternative methods have been proposed in the literature. A comprehensive comparison of 15 techniques (Moffat et al. 2007) found a modest effect of gap filling on the annual sums of *NEP*, and the MDS was one of the best performing methods. We applied this same approach to all four sites of the TUD cluster in this study to ensure comparability between sites. Nevertheless, other approaches would also be valid and this results in an uncertainty regarding the accuracy of these results. Similarly, a multitude of methods have been proposed that can be used to partition net CO_2 fluxes into R_{eco} and *GPP* based on different assumptions (Klosterhalfen et al. 2019; Wohlfahrt et al. 2017; Scanlon et al. 2010; Tramontana et al. 2020), which is particularly important for improving our process understanding and for improving ecosystem models.

In order to assess the CO_2 mitigation potential by an optimised management of different land use types, the net biome production (*NBP*) is of greater interest than *NEP*, since this term refers to the long-term storage of carbon in the ecosystem (Baldocchi et al. 1998). This means lateral carbon flux, i.e., imports and exports, have to be accounted for. For the spruce forest at DE-Tha, major thinnings were applied in March 2002, February 2011 and February 2016, removing 57, 49 and 19 m^3 ha^{-1} wood biomass, respectively. This is equivalent to 9.9, 8.5 and 3.2 tC ha^{-1}, respectively. The grassland DE-Gri is typically cut 1 to 3 times per year, thereby harvesting biomass with a dry matter of 0.3 to 2.1 t ha^{-1}, which is equivalent to 0.1 to 1.0 tC ha^{-1}. No manure is applied. The cropland at DE-Kli is harvested once per year, removing dry matter of 3.4 to 12.5 t ha^{-1} or 1.5 to 5.6 tC ha^{-1}, respectively. To partially compensate for these losses in organic matter, solid manure is applied in

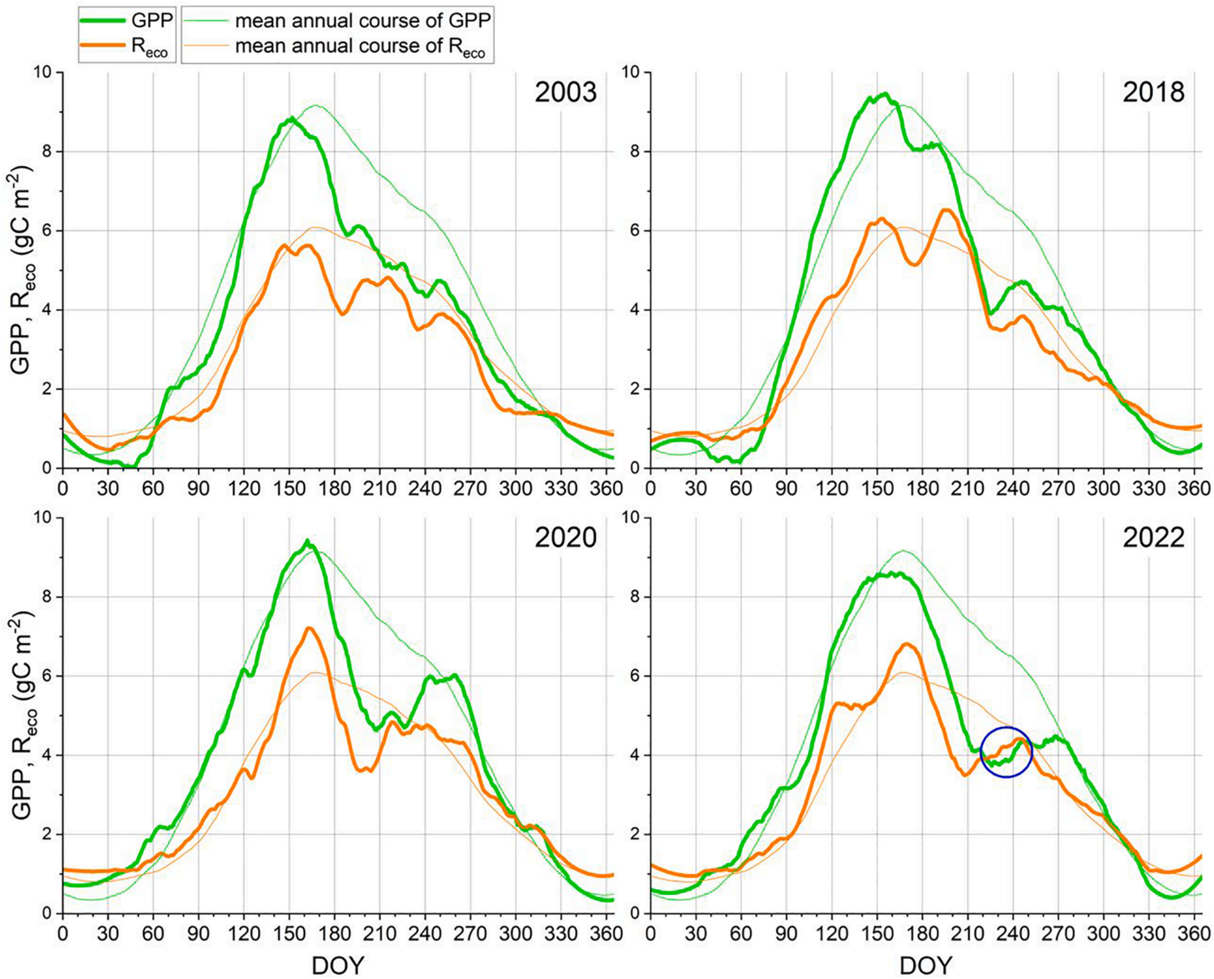

Fig. 10. Gross Primary Productivity *GPP* (bold green line) and Total Ecosystem Respiration R_{eco} (bold orange line) as well as mean annual course of *GPP* (fine green line) and R_{eco} (fine orange line) at DE-Tha during the dry years 2003, 2018, 2020 and 2022 (moving average values).

7 out of 20 years, importing between 2.1 and 5.3 tC ha^{-1} into this ecosystem. This means that the old-growth spruce forest represents a strong long-term carbon sink, the grassland system is close to carbon neutral in the long-term, and the agricultural crop rotation system represents a long-term carbon source.

The resulting *NBP* estimates for DE-Tha can be compared to the estimates of changes in carbon stocks from inventories (Fig. 11). The overall agreement between the cumulated *NBP* and the change in carbon pools between 2007 and 2019 is good, although estimates based on the atmospheric CO_2 flux measurements are slightly larger. This can be explained partially by the fact that the understory vegetation and other species than spruce are not included in the accounting of the above-ground biomass and partially by methodological uncertainty of both estimates.

4.3. Benefits and limitations of the cluster approach

There are only a limited number that report annual sum of *NEP* and *ET*, respectively, over a long period for paired sites. Stoy et al. (2008) investigate 5 years of three adjacent sites of different land use. Novick et al. (2015) investigate two adjacent forested sites over 9 years. Hemes et al. (2019) study *NEP* of 10 sites over a time period of 9 years (managed wetlands and agricultural sites with peat soils). However, their study suffered from the fact that none of the investigated sites covered the whole 9 years and 6 sites only covered 4 years and less. All authors called for longer studies in order to capture the variability between sites, which can have different sources. From this point of view, the presented data set gathered at the TUD cluster is a unique data set and forms an excellent basis for further development.

Despite the same general setup, geographic vicinity, and similar meteorological conditions between the four sites of the TUD cluster, systematic differences exist, limiting their comparability to a certain extent. These are differences in land use and management, soil characteristics, exposition, and the growth stage within a full life cycle. The latter is important, as the carbon balance of an ecosystem or any LU (land use) or LC (land cover) type needs this full cycle perspective in order to judge on the mitigation potential, regardless whether this mitigation is a reduced emission of CO_2 or a long/short-term carbon sequestration. The soil characteristics of DE-Tha and DE-Hzd are different (Table 1). We also know that there is a small gradient in climate, which is triggered by height a.s.l. and location relative to the Ore Mountains.

Our results show that most important for the carbon exchange are (i) management, (ii) the growth stage within the full life cycle, and (iii) possibly the already occurred climate change since the beginning of the measurement period in 1996. A reasonable approach for a site comparison despite the above limitations is to concentrate on the interannual variability relative to the long-term mean (Table 4). Nevertheless, it should be noted that annual sums already bear some uncertainty, e.g., due to different duration of data gaps, which inevitably translate into the differences between two sites.

To fully eliminate the effect of site differences, a modelling experiment would be necessary, where individual natural and management disturbances can be investigated systematically under identical

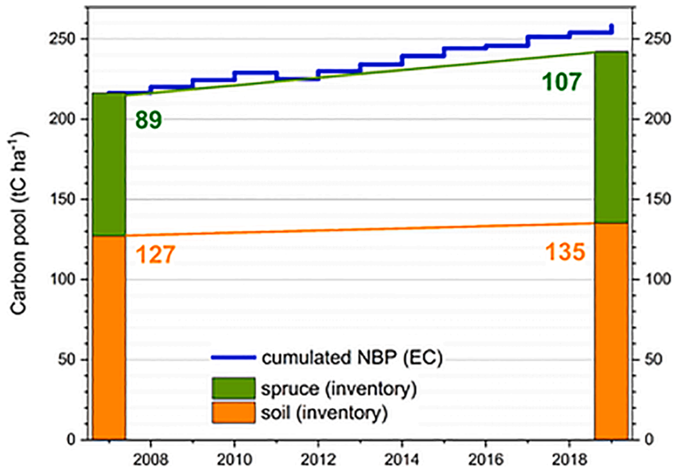

Fig. 11. Carbon pools in the soil (up to 60 cm) and in the above-ground spruce biomass at two inventories (2007, 2019) as well as cumulated *NBP* flux (starting on top of the 2007 pools) at DE-Tha.

environmental conditions. This would also enable the investigation of ecosystem behaviour under different climate scenarios considering various economic pathways to estimate mitigation potential by ecosystems. Furthermore, experiments specifically focusing on the effects of management measures, such as thinning, forest conversion or intercropping could complement monitoring of carbon and water fluxes to support decision making in forestry and agriculture.

4.4. Interannual variability and comparison of land covers

The interannual variabilities are small for the continuous LC (DE-Tha and DE-Gri), but larger in intensively managed sites with a more rapid change in stages, i.e., at the newly developing forest stand after a major disturbance and replanting (DE-Hzd) or between years of different crop types (DE-Kli). In general, this is supported by findings of Stoy et al. (2008), which report annual sums of NEP for three adjacent sites (hardwood forest, young pine plantation, old-field) for 5 years. They found that the differences between the annual means at the hardwood site and the young pine plantation site were more variable than the differences to the old-field (only moderately managed). The larger variability in the difference between the old hardwood forest and the young pine plantation was attributed to a larger drought sensitivity of the pine plantation and lagged recovery of the pine plantation from an ice storm.

At the disturbed forest site DE-Hzd, the young deciduous broadleaf forest turns into a carbon sink after canopy closure, but the carbon gain is still much lower than at the undisturbed evergreen needleleaf forest site DE-Tha. The observation period in DE-Hzd is shorter than at the other sites within the TUD cluster and covers the development of a very young forest. It is likely that the interannual variability will decrease over time as the forest matures. At DE-Tha, an increase of interannual variability is expected as major forest conversion measures are planned within the next years. The grassland at DE-Gri is nearly carbon neutral and the crop rotation at DE-Kli is generally a source of carbon to the atmosphere. Therefore, the soil needs organic fertilization (e.g., manure) for continuous use, but the large interannual variation indicates a large mitigation potential through improved management practices. For all LU/LC types under investigation, it remains an open question which management should be applied when ecosystem services, such as food or wood from harvest, are considered as benefit. Nevertheless, we can deduce that continuous LU/LC is more favourable than longer periods of uncovered soil. Mitigation or prevention of disturbances leading to a total collapse of a forest stand would be beneficial for optimising the carbon sequestration. This is particularly challenging due to a changing climate. For croplands, winter cereals and rapeseed show a larger carbon sink than summer cereals and corn on an annual scale. Direct planting without turning soil preparation could be an alternative to the current practice. In lieu of the growing risk to fail on the Paris agreement target and the associated need for negative emissions, a contribution of the LULUCF (Land Use, Land Use-Change and Forestry) sector as a nature-based solution is vital to climate change mitigation.

The *NEP*-variability behaves similar to the variability in annual sums

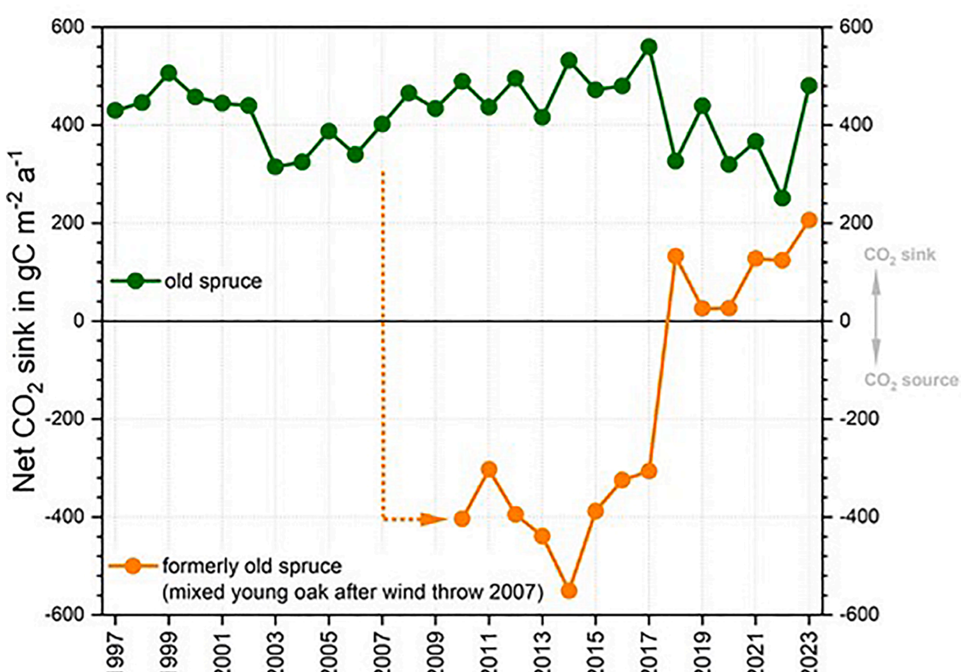

Fig. 12. Comparison of *NEP* for DE-Tha (old spruce, green) and DE-Hzd (formerly old spruce, mixed young oak after windthrow in 2007, orange) for the period 1997–2023.

of *ET* (Table 4), which show the largest ranges in DE-Kli and DE-Hzd and smaller ranges in DE-Tha and DE-Gri. However, the interannual variability in *ET* is smaller than in *NEP* at DE-Tha and DE-Hzd. This was also found by Novick et al. (2015), who investigated two adjacent forested sites over 9 years. They relate to Oishi et al. (2010), who explain that, at an annual scale, effects of drought and interception on transpiration might compensate. Different reasons might have contributed to the most variable annual *ET* in DE-Kli. The ET of DE-Kli is influenced by the different crops including maize, which is a C4-plant and better adapted to drought. Additionally, the duration of periods with bare soil differed from year to year. The variability at DE-Hzd, dominated by the sudden shift in 2018, can be explained by the canopy closure. Before canopy closure at DE-Hzd, the soil respiration due to decay of organic material from the former spruce canopy and the contribution of microbial activity were very likely substantial. Simultaneously, *ET* of herbaceous plants contributed more to total *ET* than after canopy closure. ET was generally larger at DE-Hzd compared to DE-Tha, which agrees with the findings by Novick et al. (2015). They compared annual values of ET for a young pine plantation and an old hardwood forest and also recorded larger annual ET sums for the younger site. However, in contrast to DE-Tha and DE-Hzd, their investigated sites had very similar soil conditions, i.e., a difference in soil moisture supply cannot explain the consistent difference between both.

The drought years between 2018 and 2022 resulted in a decrease in net CO_2 uptake in the spruce-dominated stands at DE-Tha. Particularly in 2022, which was one of the driest years on record, NEP was roughly 50 % less than in 2017, which can be considered as a historically typical year in terms of weather conditions. The reduction in CO_2 uptake was accompanied by an increase in forest disturbance: All over Saxony, tree mortality has dramatically increased, both as a result of lethal drought as well as of secondary agents, such as bark beetles, that typically require stressed trees to be lethal. In 2022, the vitality of >40 % of spruce trees in Saxony was significantly reduced and unprecedented forest fires occurred in the region. In sub-montane and montane regions, even >45 % of crown clearing was reported (Sachsenforst 2022). The forest at DE-Tha was not directly affected by fire and bark beetle, but the wind throw at DE-Hzd shows how potentially devastating such climate-related disturbance can be (Fig. 12). This ecosystem was a strong carbon source to the atmosphere for about ten years, and only afterwards turned into a carbon sink, which is, however, smaller than the spruce forest of DE-Tha. After a forest clear cutting, similar CO_2 sources of around 350 gC m^{-2} a^{-1} have been reported by Ney et al. (2019) for four years after the disturbance at the ICOS site DE-Wue.

The *NEP* estimates for this old-growth spruce forest are unexpectedly large. This may have several reasons. Firstly, the forests in this region were severely damaged by air pollution (heavy metals and acid rain) mostly due to burning of high-sulfuric coal by industry and power plants in the second half of the twentieth century. In the 1990s most of this industry collapsed and filters were implemented in coal-fired power plants. The Tharandt forest was able to recover since then, leading to an increased growth rate, until drought stress became more severe in recent years. Also, the seeding approach ("Plätzesaat") provided a random positioning of the young trees. Together with the small-scale variability in orography and stone content in the soil and the competition of a multitude of seedlings, the favorably placed seedlings developed better root systems and may therefore be more resilient to drought. Moreover, the thinning in 2011 may have aided to the vitality of the overall forest stand, at least this was the goal of this silvicultural measure. However, it is also interesting to note that thinning may have a stronger but temporary negative effect on the carbon sink strength for forests in other regions, as was shown, e.g., by Aslan et al. (2024) for boreal forests. The increasing ambient CO_2 concentrations may have resulted in a fertilisation effect, which, however, could not be proven for DE-Tha in the study of Zhan et al. (2023), since the thinning measure and droughts affected the carbon cycle more strongly. In this sense, the *NEP* and *NBP* estimates for DE-Tha are probably in the upper range of spatial variability in this region. When looking at the differences between the four study sites, it becomes obvious that the large variations in site-specific *NEP* propagate into differences among the sites from one year to another. This means applying a mean difference to deduce the *NEP* for another neighbouring site with different land use will very likely result in erroneous estimates. This limitation applies less for *ET* of forests due to their conservative water utilisation. However, variability in annual sums of *ET* and hence differences between sites are more marked, if one site is heavily managed.

There are only few studies that report annual sum of NEP and ET, respectively, over a long-term period for paired sites. Stoy et al. (2008) investigate 5 years of three adjacent sites of different land use. Novick et al. (2015) investigate two adjacent forest sites for 9 years. Hemes et al. (2019) study NEP of 10 sites over a time period of 9 years (managed wetlands and agricultural sites on peat soils). However, their study suffered from the fact that none of the investigated sites covered the whole 9 years and 6 sites only covered 4 years or less. All authors called for longer studies in order to capture the variability between sites, which can have different sources. From this point of view, the presented data set is unique and forms an excellent basis for further development. Stoy et al. (2023) found that 692 flux stations from various global monitoring networks could be considered paired sites, which holds great potential for further studies similar to this one.

5. Conclusions

This study highlights the importance of long-term observations of ecosystem processes, which are a statistical prerequisite to derive trends related to climate change and to determine extremes relative to the "normal" state. Moreover, we follow a research approach that is based on a cluster of sites in the same area to extract the effect of different land use and land cover. We have conducted long-term observations of four EC measurement sites, which are also part of the ICOS network, within a radius of <10 km. The longest time series is DE-Tha starting in 1997, DE-Gri and DE-Kli joining in 2002 and 2005, respectively, and DE-Hzd with measurements starting in 2010. Besides the trends of increasing air temperatures and atmospheric CO_2-concentrations, we focus on the effect of drought on the carbon balance. However, different management practices also influence CO_2- and H_2O-fluxes of different land uses/land covers differently. Important aspects for the management of forest sites are the planting of oak trees after the wind throw disturbance at DE–Hzd and the conversion of the predominantly spruce site DE-Tha into a mixed forest with thinning of old spruce trees and parallel planting of beech and silver fir. In addition to the direct biosphere-atmosphere exchange (*NEP*), we have also included lateral fluxes, e.g., harvest and manure, in our analysis to obtain estimates of NBP.

In summary, we found that old forest stands, such as DE-Tha, provide a consistently high CO_2 sink, which can be maintained by sustainable management practice, in this case forest conversion with planting and thinning, on a reduced but stable level. For DE-Tha, the long-term *NBP* was estimated as 350 gC m^{-2} a^{-1}. In contrast, a complete loss of a forest stand by disturbance, e.g. a clear cutting or windthrow, results in a substantial CO_2 source over several years of similar magnitude. DE-Hzd remained a carbon source for 11 years before it turned into a carbon sink again. The newly planted oak trees were growing well and accumulated biomass over the entire period, but the soil lost even more carbon through respiration due to the sparse crown cover, less shading, less stable stratification inside the forest stand, and the decay of organic material from the previous spruce stand in the soil. Until now, its carbon sink is still smaller than for the neighbouring old spruce forest. This oak dominated stand did, however, not show a reduced *NEP* during drought years. We attribute this to a better water retention in the soil and to the reduced interception loss of precipitation by the deciduous oaks (see also Pluntke et al. 2023). In contrast, *NEP* of the old spruce forest ecosystem of DE-Tha was reduced by about 50 % between dry and wet years.

In our study, the interannual variability served as an indicator for the effect of disturbances and management at the different sites. The "undisturbed" spruce site had the highest sink on average with a limited interannual variability, the oak site and the crop rotation showed a larger interannual variability. This indicates that reducing disturbances by site- and climate-adapted management of forests and a targeted management of crops to minimize the associated CO_2 emissions can benefit climate change mitigation. Together with other management options, e.g., for water storage, these nature-based solutions may help to sustain the positive effects of the LULUCF sector on the carbon balance and eventually generate an extra income based on carbon certificates (but only if the effect becomes part of the national or international carbon inventory).

If lateral fluxes, such as harvest and manure application, are included in estimates of NBP, the grassland site DE-Gri was more or less CO_2 neutral and the crop rotation site DE-Kli was a small but persistent CO_2 source to the atmosphere. Generally, the cultivation of winter crops resulted in a smaller CO_2 source than for summer crops. This management decision which type of crop is planted appears to be the dominating factor for the annual carbon budget of an agricultural site. For winter crops, the soil is covered with green plants for a longer period, which leads to a higher *GPP* and also to a higher R_{eco}, where the increase in *GPP* dominates the overall effect on *NEP*. For grassland and the cropland, climate extremes, such as drought, have a minor effect. In contrast, management decisions, such as the timing of harvest and the selection of the crop type dominate variability in the annual carbon budget. Catch crops may reduce the negative effect of summer crops, and a sufficient re-supply of organic fertilizer may help to maintain the proportion of organic matter in the soil.

Interestingly, the results of the direct EC measurements indicate a larger sink of atmospheric CO_2 at the old spruce forest stand than the inventory estimate from the increase in carbon stocks in soils and aboveground biomass. This can partially be explained by the fact that understory vegetation and minor tree species are usually neglected in inventory-based estimates. For DE-Tha, the increase in sequestered carbon is about 7 % larger from the direct EC measurements after 12 years. Among the potential reasons to be investigated for this discrepancy, are the expansion factors for the quantification of the below ground biomass from above ground biomass and the contribution of fine roots to the carbon content of the soil.

To our knowledge, this data set is unique with respect to its length and comprehensiveness of land cover types. The findings from these long-term measurements of biosphere-atmosphere exchanges at a cluster of sites, offers a wealth of data. It supports decision makers in harnessing the potential for optimised land management to increase the terrestrial carbon sink in comparable regions in Central Europe. The length of the time series allows a statistically sound consideration of climatic trends, weather extremes and disturbances. This underlines once more the importance of these long time series and the value of such data sets, which will likely increase with their length in the future.

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DFG	BE 1721/13–1	External factors of eco-technological water management – influences of land use and climate change
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Freistaat Sachsen	1–0452/147/158	C-Speicherung und -Freisetzung aus Böden unter landwirtschaftlicher und forstlicher Nutzung
Freistaat Sachsen	65–0456/49/10	Sicherstellung des Treibhausgasmonitorings an sächsischen ICOS-Standorten
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Freistaat Sachsen	65–0456/56/23	Sicherstellung des Treibhausgasmonitorings an sächsischen ICOS-Standorten
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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Thomas Grünwald: Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luise Wanner:** Writing – original draft, Conceptualization. **Uwe Eichelmann:** Data curation. **Markus Hehn:** Data curation. **Uta Moderow:** Writing – original draft. **Heiko Prasse:** Data curation. **Ronald Queck:** Writing – review & editing. **Christian Bernhofer:** Writing – original draft, Funding acquisition. **Matthias Mauder:** Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors 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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Measurements under real-life conditions are generally not easy, both to make and to analyse. However, a complicated micrometeorological setup (namely, EC systems) and the need for long-term data to answer climate related questions makes it merely impossible to avoid errors or misinterpretations. About 1998, John Moncrieff (University of Edinburgh) compared the different "final" versions of carefully

postprocessed, gap-filled data from EUROFLUX, the very first network of EC sites including the old spruce site, to a roller coaster ride. Only over time, confidence in the data grew. This was achieved through a better signal to noise ratio of larger data sets and due to the hope that some random effects cancel to produce a Gaussian distribution. To collect these particularly valuable long-term records in decent quality, you need good people – from the financial support to the technical support and a mutual understanding in the science community. The authors do not know of any group of people being as open and as interested in a common goal, as the ecosystem group in ICOS and the preceding networks. For TU Dresden, the help and persistent work of many have to be mentioned, but we want to reduce this to Uwe Eichelmann, the person behind most of the technical setups in the TU Dresden cluster. His life ended in 2021, but his data still speak to us.

Appendix

Table A1
Management measures at the crop site DE-Kli for the entire observation period.

Date of site disturbance	Crop management	Mineral fertilization	Organic fertilization	Use of pesticide, insecticide, or fungicide	Planting of live plants or seeds	Tillage, scarification and plowing	Site disturbance comments
2004/08/07			Solid manure				18 t ha^{-1}
2004/08/16						Scarification	12 cm depth
2004/08/18					Sowing crop seeds		rapeseed
2005/03/18				Herbicide			1.979 l ha^{-1} Butisan Top
2005/03/22		N					102.87 kg N ha^{-1}
2005/03/22		Lime					91.44 kg ha^{-1}
2005/03/31				Insecticide			0.099 l ha^{-1} Fastac
2005/04/04		P					43.6 kg P ha^{-1}
2005/04/14		N					88.76 kg N ha^{-1}
2005/04/19		Other					1.979 l ha^{-1} Bor
2005/04/19				Fungicide			0.693 l ha^{-1} Folicur
2005/04/19				Insecticide			0.099 l ha^{-1} Karate Zeon
2005/05/12				Fungicide			0.396 l ha^{-1} Cantus
2005/05/12				Insecticide			0.139 l ha^{-1} Trafo
2005/08/20	Harvest						0.45 kg DM m^{-2} (grain)
2005/09/08				Herbicide			2.5 l ha^{-1} Durano
2005/09/23						Scarification	12 cm depth
2005/09/25					Sowing crop seeds		winter wheat
2005/10/11				Herbicide			0.95 l ha^{-1} Bacara
2005/10/11				Herbicide			0.008 kg ha^{-1} Pointer
2006/04/08		N					74.25 kg N ha^{-1}
2006/04/08		Lime					66 kg ha^{-1}
2006/04/22		P					60 kg P ha^{-1}
2006/05/04		N					53.76 kg N ha^{-1}
2006/05/04				Other			1 l ha^{-1} CCC720 (growth regulator)
2006/05/14				Other			0.5 l ha^{-1} CCC720 (growth regulator)
2006/05/22				Fungicide			0.4 l ha^{-1} Amistar
2006/05/22				Fungicide			0.45 l ha^{-1} Gladio
2006/05/22				Other			0.25 l ha^{-1} Moddus
2006/06/04		N					35.84 kg N ha^{-1}
2006/06/08				Herbicide			0.125 kg ha^{-1} Hoestar Super
2006/06/08				Herbicide			1 l ha^{-1} MCPA
2006/06/22		N					43.12 kg N ha^{-1}
2006/09/06	Harvest						1.1458 kg DM m^{-2} (grain and straw)
2006/10/17			Solid manure				20 t ha^{-1}
2006/10/18						Conventional	30 cm depth
2007/04/11				Herbicide			2 l ha^{-1} Durano
2007/04/21						Scarification	12 cm depth
2007/04/22		N					17.28 kg N ha^{-1}
2007/04/22		P					62.21 kg P ha^{-1}
2007/04/23					Sowing crop seeds		maize (cultivar KWS Salgado)
2007/05/23				Herbicide			0.75 l ha^{-1} Buctril
2007/05/23				Herbicide			2 l ha^{-1} Gardogold
2007/06/13		N					67.2 kg N ha^{-1}
2007/10/02	Harvest						1.14 kg DM m^{-2} (whole plant)
2008/04/23						Scarification	12 cm depth
2008/04/25					Sowing crop seeds		winter barley
2008/04/29		N					48 kg N ha^{-1}
2008/04/29		P					48 kg P ha^{-1}
2008/05/19				Herbicide			0.15 l ha^{-1} Husar
2008/06/07				Insecticide			0.27 l ha^{-1} Bulldock
2008/08/27	Harvest						0.493 kg DM m^{-2} (grain and straw)

(continued on next page)

Table A1 (*continued*)

Date of site disturbance	Crop management	Mineral fertilization	Organic fertilization	Use of pesticide, insecticide, or fungicide	Planting of live plants or seeds	Tillage, scarification and plowing	Site disturbance comments
2008/09/10						Scarification	12 cm depth
2008/09/12					Sowing crop seeds		winter barley
2008/10/09				Herbicide			0.85 l ha^{-1} Bacara
2008/10/09				Herbicide			0.25 l ha^{-1} Cadou
2009/04/02		N					44.64 kg N ha^{-1}
2009/04/02		Lime					39.06 kg ha^{-1}
2009/04/29		N					53.76 kg N ha^{-1}
2009/05/01				Other			0.5 l ha^{-1} Camposan extra (growth regulator)
2009/05/01				Fungicide			0.7 l ha^{-1} Fandango
2009/07/08				Herbicide			2.2 l ha^{-1} Durano
2009/07/22	Harvest						0.969 kg DM m^{-2} (grain and straw)
2009/08/08			Solid manure				25 t ha^{-1}
2009/08/13						Scarification	12 cm depth
2009/08/25					Sowing crop seeds		rapeseed
2009/08/26				Herbicide			2.3 l ha^{-1} Nimbus
2009/09/08				Herbicide			0.5 l ha^{-1} Agil
2009/09/21		Other					2.1 l ha^{-1} Bor
2009/09/21				Fungicide			0.7 l ha^{-1} Tebuzol
2010/03/28		N					108 kg N ha^{-1}
2010/03/28		Lime					96 kg ha^{-1}
2010/04/19		N					0.138 kg N ha^{-1}
2010/04/19				Insecticide			0.2 l ha^{-1} Decis
2010/04/19				Fungicide			0.5 l ha^{-1} Folicur
2010/04/22		N					58.8 kg N ha^{-1}
2010/05/17				Fungicide			0.8 l ha^{-1} Harvesan
2010/05/18				Insecticide			0.1 l ha^{-1} Fastac
2010/08/24	Harvest						0.43 kg DM m^{-2} (grain)
2010/09/30						Scarification	12 cm depth
2010/10/02					Sowing crop seeds		winter wheat
2010/10/28				Herbicide			1.0 l ha^{-1} Bacara forte
2011/03/16		N					78.96 kg N ha^{-1}
2011/04/19		N					43.11 kg N ha^{-1}
2011/05/02				Herbicide			1.0 l ha^{-1} Bacara forte
2011/05/02				Fungicide			0.344 l ha^{-1} Fandango
2011/05/02				Other			0.5 l ha^{-1} CCC720
2011/05/02				Other			0.15 l ha^{-1} proagro Netzmittel
2011/06/04		N					72.8 kg N ha^{-1}
2011/06/04		N		Herbicide			0.493 l ha^{-1} Starane Ranger
2011/06/04				Fungicide			0.395 l ha^{-1} Input Xpro
2011/06/04				Insecticide			0.049 l ha^{-1} Karate Zeon
2011/06/04				Other			0.099 l ha^{-1} proagro Netzmittel
2011/06/09		N					53.76 kg N ha^{-1}
2011/08/22	Harvest						1.224 kg DM m^{-2} (grain and straw)
2011/09/02						Scarification	12 cm depth
2012/03/25			Solid manure				25 t ha^{-1}
2012/04/11				Herbicide			2.25 l ha^{-1} Albaugh Rosate 36
2012/04/25					Sowing crop seeds		maize (cultivar KWS Salgado)
2012/04/25		N					107.18 kg N ha^{-1}
2012/04/26		P					41.4 kg P ha^{-1}
2012/04/26		N					16.2 kg N ha^{-1}
2012/05/20				Herbicide			1.0 l ha^{-1} Gardobuc
2012/05/20				Herbicide			1.0 l ha^{-1} MaisTer Flüssig
2012/09/18	Harvest						0.924 kg DM m^{-2} (whole plant)
2013/04/16						Scarification	12 cm depth
2013/04/17					Sowing crop seeds		spring barley
2013/04/17		N					54 kg N ha^{-1}
2013/04/17		P					54 kg P ha^{-1}
2013/05/07				Herbicide			0.075 l ha^{-1} Husar
2013/06/17				Fungicide			0.8 l ha^{-1} Adexar
2013/06/17				Herbicide			1.0 l ha^{-1} U46M fluid
2013/08/24	Harvest						0.9588 kg DM m^{-2} (grain and straw)
2013/09/14						Scarification	12 cm depth
2013/09/29						Scarification	10 cm depth
2013/10/01					Sowing crop seeds		winter barley
2013/10/05				Herbicide			1.0 l ha^{-1} Bacara forte
2014/02/25		N					54.5 kg N ha^{-1}
2014/03/31		N					70 kg N ha^{-1}
2014/04/07				Fungicide			0.5 l ha^{-1} Capalo

(*continued on next page*)

Table A1 (*continued*)

Date of site disturbance	Crop management	Mineral fertilization	Organic fertilization	Use of pesticide, insecticide, or fungicide	Planting of live plants or seeds	Tillage, scarification and plowing	Site disturbance comments
2014/04/07				Other			0.2 l ha^{-1} Moddus
2014/04/07		Other					2 l ha^{-1} AKRA Blatt
2014/04/07		Other					0.5 l ha^{-1} AKRA Plus 9
2014/04/28				Other			0.25 l ha^{-1} Moddus
2014/04/28				Fungicide			0.3 l ha^{-1} XPro
2014/04/28		Other					1 l ha^{-1} AKRA Blatt
2014/04/28		Other					0.25 l ha^{-1} AKRA Plus 9
2014/04/29		N					27 kg N ha^{-1}
2014/07/20	Harvest						1.2155 kg DM m^{-2} (grain and straw)
2014/07/23			Liquid manure				30 m^{3} ha^{-1}
2014/07/23						Scarification	8 cm depth
2014/08/21						Scarification	15 cm depth
2014/08/21					Sowing crop seeds		rapeseed
2014/08/23				Herbicide			3.0 l ha^{-1} Colzor Trio
2014/09/10				Herbicide			1.0 l ha^{-1} Fusilade Max
2014/09/10				Insecticide			0.05 l ha^{-1} Karate Zeon
2014/09/29				Fungicide			0.5 l ha^{-1} Toprex
2014/09/29				Insecticide			0.05 l ha^{-1} Karate Zeon
2014/09/29		Other					0.6 l ha^{-1} Bor
2015/03/10		N					80.16 kg N ha^{-1}
2015/03/10		Other					20.04 kg S ha^{-1}
2015/04/09		N					86.4 kg N ha^{-1}
2015/04/09		Other					21.6 kg S ha^{-1}
2015/04/15				Fungicide			0.4 l ha^{-1} Carax
2015/04/15		Other					2 l ha^{-1} AKRA Blatt
2015/04/15		Other					0.5 l ha^{-1} AKRA Plus 9
2015/05/11				Fungicide			0.2 l ha^{-1} Cantus Gold
2015/05/11				Fungicide			0.5 l ha^{-1} Ortiva
2015/08/08	Harvest						0.4213 kg DM m^{-2} (grain)
2015/08/13						Scarification	5 cm depth
2015/09/03				Herbicide			3.0 l ha^{-1} Albaugh Rosate
2015/09/14						Scarification	15 cm depth
2015/09/18					Sowing crop seeds		winter wheat
2015/11/04				Herbicide			1.0 l ha^{-1} Bacara forte
2015/11/04				Herbicide			0.012 kg ha^{-1} Pointer
2016/03/23		N					62.88 kg N ha^{-1}
2016/03/23		Other					15.72 kg S ha^{-1}
2016/04/19		Other					1 l ha^{-1} AKRA Blatt
2016/04/19		Other					0.25 l ha^{-1} AKRA Plus 9
2016/04/19				Other			0.3 l ha^{-1} Moddus
2016/04/19				Other			0.3 l ha^{-1} CCC720
2016/04/21		N					70.47 kg N ha^{-1}
2016/04/30				Herbicide			1.0 l ha^{-1} Lodin
2016/05/13		N					51.33 kg N ha^{-1}
2016/05/30				Fungicide			0.4 l ha^{-1} Adexar
2016/05/30				Fungicide			0.5 l ha^{-1} Input XPro
2016/05/30				Other			0.2 l ha^{-1} Moddus (growth regulator)
2016/08/24	Harvest						1.584 kg DM m^{-2} (grain and straw)
2016/09/01					Sowing crop seeds		catch crop (oil radish, mustard)
2017/03/13				Herbicide			3.0 l ha^{-1} Durano TF
2017/03/15						Scarification	10 cm depth
2017/03/15			Solid manure				10 t ha^{-1}
2017/04/01						Scarification	15 cm depth
2017/04/02					Sowing crop seeds		spring barley
2017/04/02		N					37 kg N ha^{-1}
2017/04/02		P					37 kg P ha^{-1}
2017/04/28		N					21.6 kg N ha^{-1}
2017/04/28		Lime					19.2 kg ha^{-1}
2017/05/11				Herbicide			0.15 l ha^{-1} Husar PLUS
2017/06/03				Fungicide			1 l ha^{-1} Capalo
2017/06/03				Fungicide			0.2 l ha^{-1} Vegas
2017/06/03		Other					1 l ha^{-1} AKRA Blatt
2017/06/03		Other					0.25 l ha^{-1} AKRA Plus 9
2017/08/25	Harvest						0.8456 kg DM m^{-2} (grain and straw)
2017/09/13						Scarification	8 cm depth
2017/09/13					Sowing crop seeds		catch crop (oil radish, mustard)
2017/09/13			Liquid manure				20 m^{3} ha^{-1}

(*continued on next page*)

Table A1 (*continued*)

Date of site disturbance	Crop management	Mineral fertilization	Organic fertilization	Use of pesticide, insecticide, or fungicide	Planting of live plants or seeds	Tillage, scarification and plowing	Site disturbance comments
2018/04/13			Solid manure				15 t ha^{-1}
2018/04/13						Scarification	10 cm depth
2018/04/24			Liquid manure				35.431 m^3 ha^{-1}
2018/04/30						Scarification	20 cm depth
2018/05/02					Sowing crop seeds		maize (cultivar DKC 3142)
2018/05/28				Herbicide			0.075 kg ha^{-1} PRINCIPAL A
2018/05/28				Herbicide			0.25 l ha^{-1} PRINCIPAL B
2018/05/28				Herbicide			2.5 l ha^{-1} Successor T
2018/05/28				Herbicide			0.2 l ha^{-1} Buctril
2018/09/04	Harvest						1.0122 kg DM m^{-2} (whole plant)
2018/09/26						Scarification	8 cm depth
2019/03/21						Conventional	25 cm depth plowing
2019/03/23					Sowing crop seeds		field bean (Tiffany), 60 seeds per m2
2019/08/18	Harvest						0.2814 kg DM m^{-2} (beans)
2019/08/20						Scarification	10 cm depth
2019/08/29						Scarification	20 cm depth
2019/08/31					Sowing crop seeds		rapeseed (LG Architekt), 50 seeds per m2
2019/09/03				Herbicide			2 l ha^{-1} FUEGO
2019/10/22				Insecticide			0.075 l ha^{-1} Karate Zeon
2019/10/22				Fungicide			0.5 l ha^{-1} Orius
2019/10/22				Other			0.3 l ha^{-1} Carax (growth regulator)
2019/10/22				Herbicide			0.2 l ha^{-1} Runway
2020/03/10		N					74.1 kg N ha^{-1} (Ammonsulfatsalpeter)
2020/04/07		N					116.36 kg N ha^{-1} (Ammoniumnitrat + *S* (LAS))
2020/04/08		Other					1 l ha^{-1} AKRA Blatt
2020/04/08		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2020/04/08				Other			0.5 l ha^{-1} Carax (growth regulator)
2020/04/08				Fungicide			0.5 l ha^{-1} Orius
2020/04/08				Insecticide			0.2 l ha^{-1} Trebon 30 EC
2020/04/08		Other					1.0 l ha^{-1} AKRA Milchsäure
2020/05/09		Other					1 l ha^{-1} AKRA Blatt
2020/05/09		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2020/05/09				Fungicide			0.3 l ha^{-1} Cantus Gold
2020/05/09		Other					1.0 l ha^{-1} AKRA Milchsäure
2020/08/09	Harvest						0.3523 kg DM m^{-2} (grain)
2020/08/11						Scarification	8 cm depth
2020/09/08				Herbicide			3.0 l ha^{-1} Durano TF
2020/10/10						Scarification	12 cm depth
2020/10/12					Sowing crop seeds		winter wheat (cultivar Reform), 230 seeds per m2
2020/11/10				Herbicide			0.4 l ha^{-1} Battle Delta
2020/11/10				Herbicide			0.3 l ha^{-1} Beflex
2021/03/30		N					63.7 kg N ha^{-1} (Ammonsulfatsalpeter)
2021/05/06		N					66.96 kg N ha^{-1} (Kalkammonsalpeter)
2021/05/06		Lime					59.52 kg CaCO3 ha^{-1} (Kalkammonsalpeter)
2021/05/08				Other			0.3 kg ha^{-1} Prodax (growth regulator)
2021/05/08				Other			0.3 l ha^{-1} CCC720 (growth regulator)
2021/05/08				Fungicide			0.8 l ha^{-1} Balaya
2021/05/08		Other					1.0 l ha^{-1} AKRA Milchsäure
2021/05/08		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2021/06/19		N					40.23 kg N ha^{-1} (Kalkammonsalpeter)
2021/06/19		Lime					35.76 kg CaCO3 ha^{-1} (Kalkammonsalpeter)
2021/06/26				Fungicide			1.2 l ha^{-1} Revytrex
2021/06/26				Fungicide			0.4 l ha^{-1} Comet
2021/06/26		Other					1.0 l ha^{-1} AKRA Milchsäure
2021/06/26		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2021/06/26		Other					0.65 l ha^{-1} AKRA Sulpur +
2021/08/15	Harvest						0.7295 kg DM m^{-2} (grain) + 0.4204 kg DM m^{-2} (straw)
2021/09/13		Lime					700 kg ha^{-1} AKRA DGC
2021/09/13						Scarification	8 cm depth
2021/09/13			Liquid manure				20 m^3 ha^{-1}
2021/09/14					Sowing crop seeds		catch crop (Phacelia tanacetifolia Benth., Linum usitatissimum L., Trifolium squarrosum L., Guizotia abyssinica (L.f.) Cass.)
2022/03/17				Herbicide			2.2 l ha^{-1} Glyphosat
2022/03/23						Scarification	15 cm depth
2022/03/25					Sowing crop seeds		spring barley

(*continued on next page*)

Table A1 (*continued*)

Date of site disturbance	Crop management	Mineral fertilization	Organic fertilization	Use of pesticide, insecticide, or fungicide	Planting of live plants or seeds	Tillage, scarification and plowing	Site disturbance comments
2022/04/29		N					54 kg N ha^{-1} (200 kg KAS ha^{-1})
2022/05/14				Herbicide			0.15 l ha^{-1} Husar Plus
2022/06/01				Insecticide			0.2 l ha^{-1} Sumicidin Alpha
2022/06/01		Other					1.0 l ha^{-1} Milchsäure
2022/06/01				Fungicide			1.0 l ha^{-1} Revytrex + Comet
2022/06/01				Other			0.2 l ha^{-1} Cerone 660 (growth regulator)
2022/06/01		Other					1 l ha^{-1} AKRA Blatt
2022/06/01		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2022/06/01				Fungicide			1 l ha^{-1} Sulfur
2022/08/04	Harvest						0.395 kg DM m^{-2} (grain) + 0.229 kg DM m^{-2} (straw)
2022/08/12						Scarification	5 cm depth
2022/08/17			Solid manure				10 t ha^{-1}
2022/08/17						Scarification	8 cm depth
2022/09/12						Scarification	12 cm depth
2022/09/13					Sowing crop seeds		winter barley (320 m^{-2}), brand name: KWS Kosmos
2022/09/30				Herbicide			0.4 l ha^{-1} Battle Delta
2022/09/30				Herbicide			0.3 l ha^{-1} Beflex
2023/03/24		N					63.2 kg N ha^{-1} (234 kg ha^{-1} YARABela Nitromag/Extr)
2023/04/30		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2023/04/30		Other					1 l ha^{-1} AKRA Blatt
2023/04/30				Herbicide			0.098 l ha^{-1} Saracen
2023/04/30				Fungicide			1.071 l ha^{-1} Orius
2023/04/30				Other			0.699 kg ha^{-1} Prodax
2023/05/02		N					62.73 kg N ha^{-1} (232 kg ha^{-1} YARABela Nitromag/Extr)
2023/05/21		Other					1 l ha^{-1} AKRA Blatt
2023/05/21		Other					0.25 l ha^{-1} AKRA Plus 9 Frucht
2023/05/21		Other					1 l ha^{-1} AKRA Sulpur+
2023/05/21				Fungicide			1 l ha^{-1} Balaya
2023/07/13	Harvest						0.668 kg DM m^{-2} (grain) + 0.330 kg DM m^{-2} (straw)
2023/07/21						Scarification	5 cm depth
2023/07/26			Liquid manure				20 m^3 ha^{-1}
2023/08/22					Sowing crop seeds		rapeseed
2023/09/02				Herbicide			2 l ha^{-1} FUEGO TOP
2023/09/07				Herbicide			0.8 l ha^{-1} GramFix
2023/09/07				Insecticide			0.2 l ha^{-1} Sumicidin Alpha
2023/09/20				Herbicide			0.2 l ha^{-1} Runway
2023/09/20				Fungicide			0.4 l ha^{-1} Orius
2023/09/20		Other					1 l ha^{-1} Bor
2024/02/29		N					85.28 kg N ha^{-1} (328 kg ha^{-1} LOVODASA)
2024/03/11		N					60 kg N ha^{-1} (250 kg ha^{-1} LOVOFERT)
2024/03/27				Insecticide			75 ml ha^{-1} Karate Zeon
2024/03/27				Fungicide			0.5 l ha^{-1} Carax
2024/03/27		Other					1.0 l ha^{-1} Milchsäure
2024/03/27				Fungicide			0.5 l ha^{-1} Tilmor
2024/04/26				Fungicide			0.5 l ha^{-1} Cantus Gold
2024/04/26		Other					1.0 l ha^{-1} Milchsäure
2024/07/15	Harvest						0.229 kg DM m^{-2} (grain)
2024/07/23						Scarification	5 cm depth
2024/08/20						Scarification	5 cm depth
2024/09/18				Herbicide			3 l ha^{-1} Profi 360 (360 g/l Glyphosat)
2023/10/15						Scarification	15 cm depth
2024/10/17					Sowing crop seeds		winter wheat (330 seeds m^{-2})
2024/10/22				Herbicide			0.5 l ha^{-1} Battle Delta
				Herbicide			0.4 l ha^{-1} Beflex

Data availability

Data will be made available on request.

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