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Selected breakpoints of net forest carbon uptake at four eddy-covariance sites

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ABSTRACT

Extensive studies are available that analyse time series of carbon dioxide and water flux measurements of FLUXNET sites over many years and link these results to climate change such as changes in atmospheric carbon dioxide concentration, air temperature and growing season length and other factors. Many of the sites show trends to a larger carbon uptake. Here we analyse time series of net ecosystem exchange, gross primary production, respiration, and evapotranspiration of four forest sites with particularly long measurement periods of about 20 years. The regular trends shown are interrupted by periods with higher or lower increases of carbon uptake. These breakpoints can be of very different origin and include forest decline, increased vegetation period, drought effects, heat waves, and changes in site heterogeneity. The influence of such breakpoints should be included in long-term studies of land-atmosphere exchange processes.

Keywords: carbon uptake, breakpoints, eddy-covariance, forest, climate change

1. Introduction

Nowadays, data sets of carbon uptake from FLUXNET sites are available and many papers have been published that analyse and compare these data and link them to ecosystems, phenology, regions, and climate (e.g. Baldocchi, 2008; Williams et al., 2012; Keenan et al., 2013, 2014; Kutsch and Kolari, 2015; Baldocchi et al., 2016; Fernandez-Martınez et al., 2017). The main factors investigated were the increases of the carbon dioxide concentration, the mean annual temperature, droughts, nutrients, and the length of the growing season. Thereby the inter-annual variability is high and not all sites or data are representative. With a statistical analysis and comparison of experimental and modelled data it is possible to give a comprehensive description of trends and influencing factors on a global scale (e.g. Frank et al., 2015; Shao et al., 2015; Tramontana et al., 2016; Chu et al., 2017; Jung et al., 2017; Baldocchi et al., 2018). These studies give important information about drivers of trends and changes of the carbon cycle; however, they do not focus on individual events or breakpoints in the time series of individual sites.

The recently published analyses of twenty years of carbon dioxide flux measurements at the FLUXNET site Waldstein-Weidenbrunnen (DE-Bay) showed that the fluxes were affected by a high inter-annual variability and several breakpoints making a simple presentation of sums and trends incomplete (Foken, 2017). By breakpoint we understand an *abrupt or step change in a time series, which may be associated with a regime transition of a driver variable* (Chu et al., 2017). For identifying breakpoints, it is necessary to have sufficiently long time series. We thus selected, in addition to DE-Bay, forest FLUXNET sites having about 20-year data coverage:

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Table 1. Site-specific information, climate period 1981–2010, Köppen-Geiger climate class according to Kottek et al. (2006).

Site, FLUXNET Code	Forest, trees	Coordinates, height	Climate zone, mean annual temperature and precipitation	Reference
Harvard forest, US-Ha1	Deciduous Broadleaf Forests, Red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), some hemlock (*Tsuga canadensis* (L.) Carrière), and pine (*Pinus strobus* L., *Pinus resinosa* Aiton)	42.5378° N −72.1715° W 340 m a.s.l.	Dfb 6.6 °C 1071 mm	Urbanski et al. (2007)
Hainich, DE-Hai	Deciduous Broadleaf Forests, Beech (*Fagus sylvatica* L., 64%) ash (*Fraxinus excelsior* L., 28%), sycamore (*Acer pseudoplatanus* L., 7%)	51.0792° N, 10.4530° E, 430 m a.s.l.	Cfb 8.3 °C 720 mm	Herbst et al. (2015)
Waldstein-Weidenbrunnen, DE-Bay	Evergreen Needleleaf Forests, Norway spruce (*Picea abies* (L.) H.Karst)	50.1342° N, 11.8669° E, 775 m a.s.l.	Cfb (before 1990 Dfb) 6.0 °C 1005 mm	Foken (2017)
Hyytiälä, Fi-Hyy	Evergreen Needleleaf Forests, Scots pine (*Pinus sylvestris* L.)	61.8474° N, 24.2948° E, 181 m a.s.l.	Dfc, 3.8 °C 709 mm	Rannik et al. (2006)

Harvard Forest (US-Ha1), Hyytiälä, (FI-Hyy), and Hainich (DE-Hai). These sites are affected by different breakpoints and thus serve as examples how forest decline, increased vegetation period, drought, heat waves, increased forest heterogeneity, and instrumentation changes may affect time series of net ecosystem exchange, gross primary production, respiration, and evapotranspiration. The aim of our study is to illustrate at some selected and well-studied sites how individual changes in the conditions of sites or breakpoints influence surface fluxes and possible long-term trends. The paper is intended to serve as an invitation to researchers to engage in further discussions on processes and breakpoints at individual sites and on their implications for global and long-term studies.

2. Material and methods

The four measurement sites were selected because of the availability of long time series of carbon dioxide fluxes and analyses of climate elements, as well as special breakpoints in the time series. The stations are forest sites in North America and Europe (Table 1) and cover different Köppen-Geiger climate classes (Kottek et al., 2006). The stations US-Ha1 and DE-Bay have nearly the same annual mean temperature and precipitation, but DE-Bay has four months with a mean temperature above 10 °C and is therefore classified as temperate climate (C-type), the same as DE-Hai. The boreal station FI-Hyy is of the cold continental climate type without a dry season (Df), together with US-Ha1, but summer in FI-Hyy is colder than in US-Ha1. The Hyytiälä forest stand (FI-Hyy) was thinned in 2002 with no clear effect on surface fluxes (except aerosol particle deposition) found when the following summer was compared with the previous years (Vesala et al., 2005).

Important information about instrumentation and data handling are given in Table 2. A significant difference is the use of either open path (LI-7500, LiCor Biosciences, USA) or closed path (LI-6262, LiCor Biosciences, USA) gas analysers, although this should not have an influence on the time series or for comparison of the stations (Ocheltree and Loescher, 2007; Haslwanter et al., 2009; Järvi et al., 2009). The change of the digitalisation of the electrical signals for carbon dioxide and water vapour concentrations, which was 12-bit for the LI-6262 and 16-

Table 2. Most relevant instrumentation during the period of observation.

Site, FLUXNET code	Sonic anemometer	Gas analyser	Eddy-covariance software	Threshold for gap filling
Harvard forest, US-Ha1	ATI K-style (Applied Technologies, Inc., Longmont CO, USA)	LI-6262 (LI-COR Inc., Lincoln, NE, USA)	Custom	u threshold, Goulden et al. (1996), Urbanski et al. (2007)
Hainich, DE-Hai	Solent R3 (Gill Instruments Ltd. Lymington, UK)	LI-6262 (LI-COR Inc., Lincoln, NE, USA)	EddyPro (LI-COR Inc., Lincoln, NE, USA)	u threshold, Goulden et al. (1996)
Waldstein-Weidenbrunnen, DE-Bay	up to 2006 Solent R2/R3 (Gill Instruments Ltd. Lymington, UK) since 2007 METEK USA-1 (METEK GmbH, Elmshorn, Germany)	up to 2001 LI-6262, since 2002 LI-7500 (LI-COR Inc., Lincoln, NE, USA)	TK3, Mauder and Foken (2015)	QA/QC based, Ruppert et al. (2006)
Hyytiälä, Fi-Hyy	Solent R2 (Gill Instruments Ltd. Lymington, UK)	LI-6262 (LI-COR Inc., Lincoln, NE, USA)	EddyUH, Mammarella et al. (2016)	u threshold, Goulden et al. (1996)

bit for the next generation of analysers, has only a negligible effect on annual sums, and only very low respiration fluxes in winter time differ slightly (Foken et al., 2019). The different software tools should also not have an influence on the results, because software comparison experiments have not shown relevant differences (Mauder et al., 2008; Fratini and Mauder, 2014; Mammarella et al., 2016). The different thresholds used for gap filling tools also show no differences for annual sums (Ruppert et al., 2006). Coordinate rotation was carried out using double rotation (Kaimal and Finnigan, 1994) for US-Ha1, DE-Hai, and FI-Hyy. For DE-Bay the planar-fit method (Wilczak et al., 2001) was used for each separate month, which was found as the sufficient length for the determination of the rotation angles based on an analysis by Siebicke et al. (2012). The software packages apply all necessary corrections and quality checks according to the micrometeorological standards (Foken et al., 2012) that are also applied in the recommendations for international networks like ICOS (Rebmann et al., 2018).

The net ecosystem exchange (NEE) was calculated as the sum of the eddy-covariance carbon dioxide flux and the change of the carbon dioxide storage in the air column below the sensor. The gap filling of the NEE data (Falge et al., 2001) was performed for respiration with the Lloyd-Taylor function (Lloyd and Taylor, 1994) and for assimilation with the Michaelis-Menten type function (Michaelis and Menten, 1913). These methods were also applied to calculate Gross Primary Production (GPP) and respiration (Res). Gaps in evapotranspiration (ET) measurements have been filled with a regression to the Priestley-Taylor potential evaporation (Priestley and Taylor, 1972). For the following analysis, the annual mean data or sums used are based on the FLUXNET database or the given publications (Table 1).

3. Results and discussions

3.1. Forcing due to climate change

The increase of the atmospheric carbon dioxide concentration from 360 to 400 ppm (1997–2015) could potentially have contributed to rising carbon dioxide fluxes, and is shown in Fig. 1a together with the annual growth rate of the carbon dioxide concentration for Mauna Loa (National Oceanic and Atmospheric Administration, NOAA). The trends of the mean annual temperature are shown in Fig. 1b. Significant trends in the mean annual temperatures of 0.3–0.4 K per decade exists for US-Ha1 and DE-Bay (Urbanski et al., 2007; Lüers et al., 2017). The European stations show similar inter-annual changes and the American station is often phase shifted due to the mean phase shift of the Rossby waves.

For the determination of the length of the carbon uptake season, the daily mean net ecosystem exchange (NEE) values were first smoothed in order to minimise the influence of possible short excursions from a single anomalous warm or cold/cloudy day. Finally, the vegetation season was defined as commencing on the first day after day 60 of the year with a daily mean NEE < -1 µmol m^{-2} s^{-1} and ending on the last day with a daily mean NEE ≥ 0.1 µmol m^{-2} s^{-1}. Similar trends are visible for US-Ha1 und DE-Bay. The shape looks similar if the length of the growing season is replaced by the first day

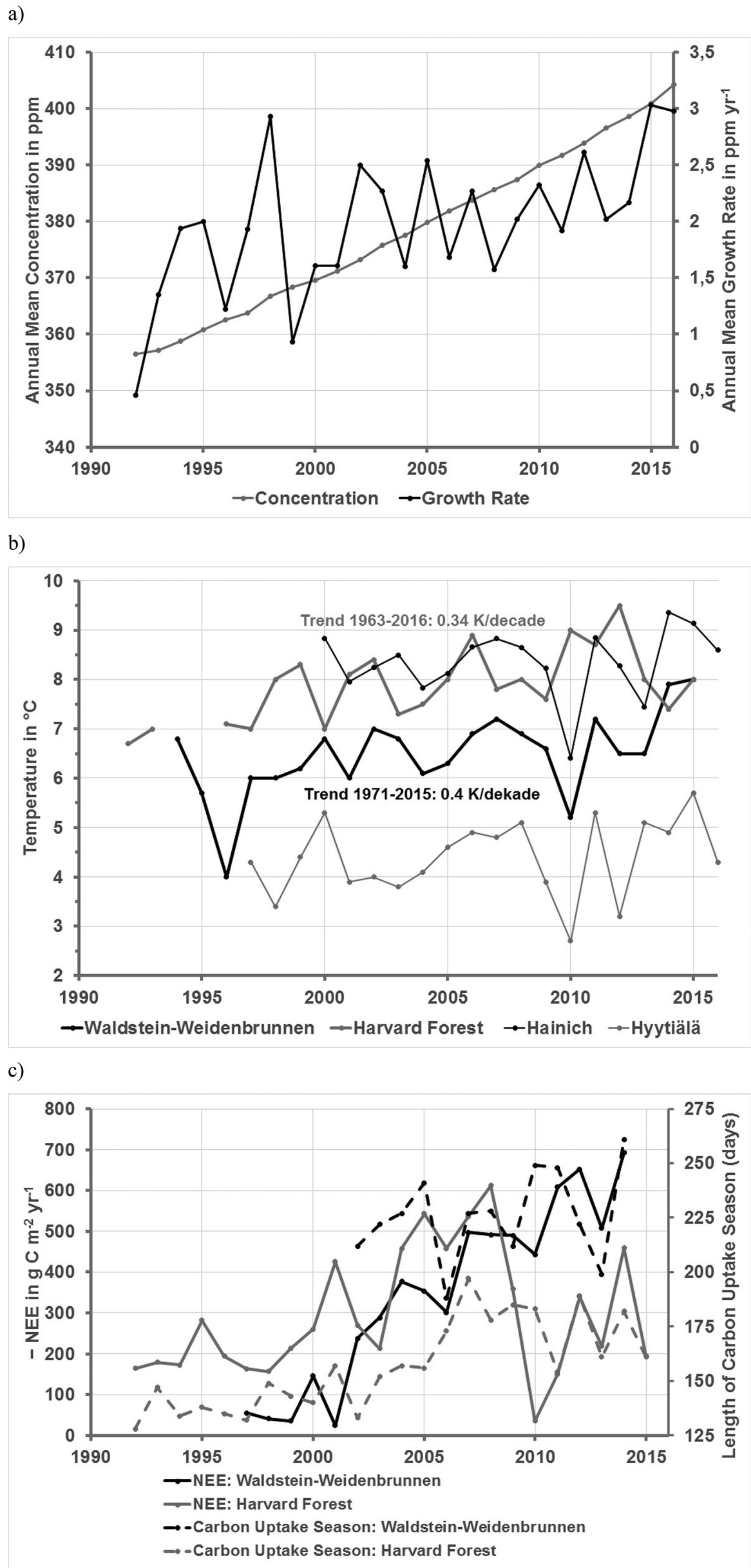


Fig. 1. (a) Time series of the carbon dioxide concentration and the growth rate for Mauna Loa station (data source: NOAA); (b) time series of the mean annual temperature of the four selected stations; (c) time series of the length of the carbon uptake season for US-Ha1 and DE-Bay together with annual sums of the Net Ecosystem exchange (for a better illustration at the ordinate (–1)-NEE is shown).

of the growing season. The results are shown together with NEE in Fig. 1c, which is analogous to the start and end of net carbon uptake used in Hadley et al. (2009), but uses filtered time series and a fixed threshold to reduce the influence of noisy data. Fixed absolute thresholds of positive NEE give similar results as phenology based on crossing 30% of mean maximum daily NEP (Net Ecosystem Productivity, Richardson et al., 2010; Keenan et al., 2014).

A statistical independence from the carbon dioxide concentration and the annual temperature cannot be assumed. Also the time series may contain breakpoints as discussed in the next section and possible self-correlations (Bartels, 1935; Vickers et al., 2009; Lasslop et al., 2010; Vickers et al., 2010; Desai, 2014). Therefore, statistical trend analysis with statistical significance tests was not done in this and the further sections.

3.2. *Breakpoints in carbon flux data*

The time series of annual sums and trends of carbon dioxide and water vapour fluxes are shown in Fig. 2. Where possible, the trends were calculated together with the coefficient of determination. The sites DE-Bay and US-Ha1 showed high inter-annual changes in carbon dioxide and water vapour fluxes. In contrast, the 250 year old beech forest stand DE-Hai and the boreal forest site FI-Hyy showed much less inter-annual variability. The DE-Hai site does not show any trend at all and the old forest is much more stable for extreme weather conditions than other sites (Herbst et al., 2015; Tamrakar et al., 2018). Similar characteristics are found for the boreal site FI-Hyy. Due to the much smaller fluxes at this site, significant changes cannot be as easily detected, although the trend of increasing carbon uptake and evaporation is clearly visible.

3.2.1. Forest decline. The Waldstein-Weidenbrunnen site DE-Bay, in the eastern part of central Europe, was affected by forest decline due to the acid rain that occurred up to the early 1990s, which was responsible for small-scale heterogeneities. During the influence of the decline the needles were yellow and only 2–3 year old cohorts of needles were on the trees. From 1997 to 2001, low NEE values of 40 ± 12 g C m^{-2} a^{-1} were measured mainly due to the forest decline, except in 2000 when there was an uptake of 146 g C m^{-2} a^{-1}. Following liming and thinning carried out in 2001, the density of trees was much lower and the forest recovered. After 2007, a growth of the understory was observed as fallen trees were removed to prevent bark-beetle infestations, and this reduced the respiration. Therefore, the Leaf Area Index of about 5 m^2 m^{-2} has not changed over the last 20 years. In the years 2002–2006 the net carbon sink ranged from 238 to 377 g C m^{-2} a^{-1} and increased up to 692 g C m^{-2} a^{-1} in 2014 (Babel et al., 2017).

3.2.2. Summer heat wave. The summer heat wave over Europe in 2003 was most significant in central and western Europe and occurred twice, in June and August. A significant decrease of GPP was reported for the European FLUXNET sites (Ciais et al., 2005) compared with the year 2002. The effect is only visible for DE-Hai and – not only in 2003 but also 2004 – mainly for GPP and NEE. The heat wave did not occur in Finland (FI-Hyy). For DE-Bay no effect could be detected. This may be due to the recovery after the forest decline, the higher ground water level, or the altitude with the resulting general lower temperatures. Only a comparison of the measured data with modelled data indicated that the measurements were not affected in June but probably in August (Falge et al., 2017), with no influence on the annual sum. However, it was found that even in the following years the soil water content was lower than in the years before 2003.

3.2.3. Extreme summer drought. The US-Ha1 site was affected in 2010 by an extended precipitation deficit in summer resulting in soil moisture below 5%. The NEE was significantly reduced in late summer (Fig. 3) followed by enhanced respiration and a net release of CO_2 from September, when typical precipitation resumed, continuing through May 2011.

Such intense drought events were not found at the other sites. It is only reported for DE-Bay that in the years 2003 and 2009 the potential evaporation was of the same order as the precipitation, which is normally 100–400 mm higher (Babel et al., 2017). This result was supported by Lischeid et al. (2017), who showed that in the warm years 2003 and 2009 the sum of evapotranspiration and runoff and of the precipitation was nearly identical, with no groundwater outflow – present in all other years – recognised.

3.2.4. Forest heterogeneity. In the years 2002–2006 and 2008–2014 the net carbon sink of the DE-Bay site ranged from 238 to 377 g C m^{-2} a^{-1} and 491 to 692 g C m^{-2} a^{-1}, respectively. Especially the values of the last years were larger than the average for evergreen humid temperate forest on a European basis (Luyssaert et al., 2010), and the year 2014 was extremely warm in the region. According to a Mann-Kendell trend test for NEE, the trends are significant as discussed by Babel et al. (2017).

The forest structure experienced severe disturbances because of two storm events: Kyrill on January 18, 2007 and Emma on February 29, 2008. Kyrill mainly destroyed large parts of the forest approximately 150 m southward (wind throw of about 1.5 km length) and 200 m westward of the flux tower (Fig. 4; Foken et al., 2017). However, no significant change in the footprint climatology was found. Two factors that could be responsible for larger fluxes were discussed.

Investigations of coherent structures around the site and at the edge of the new clearing south of the site

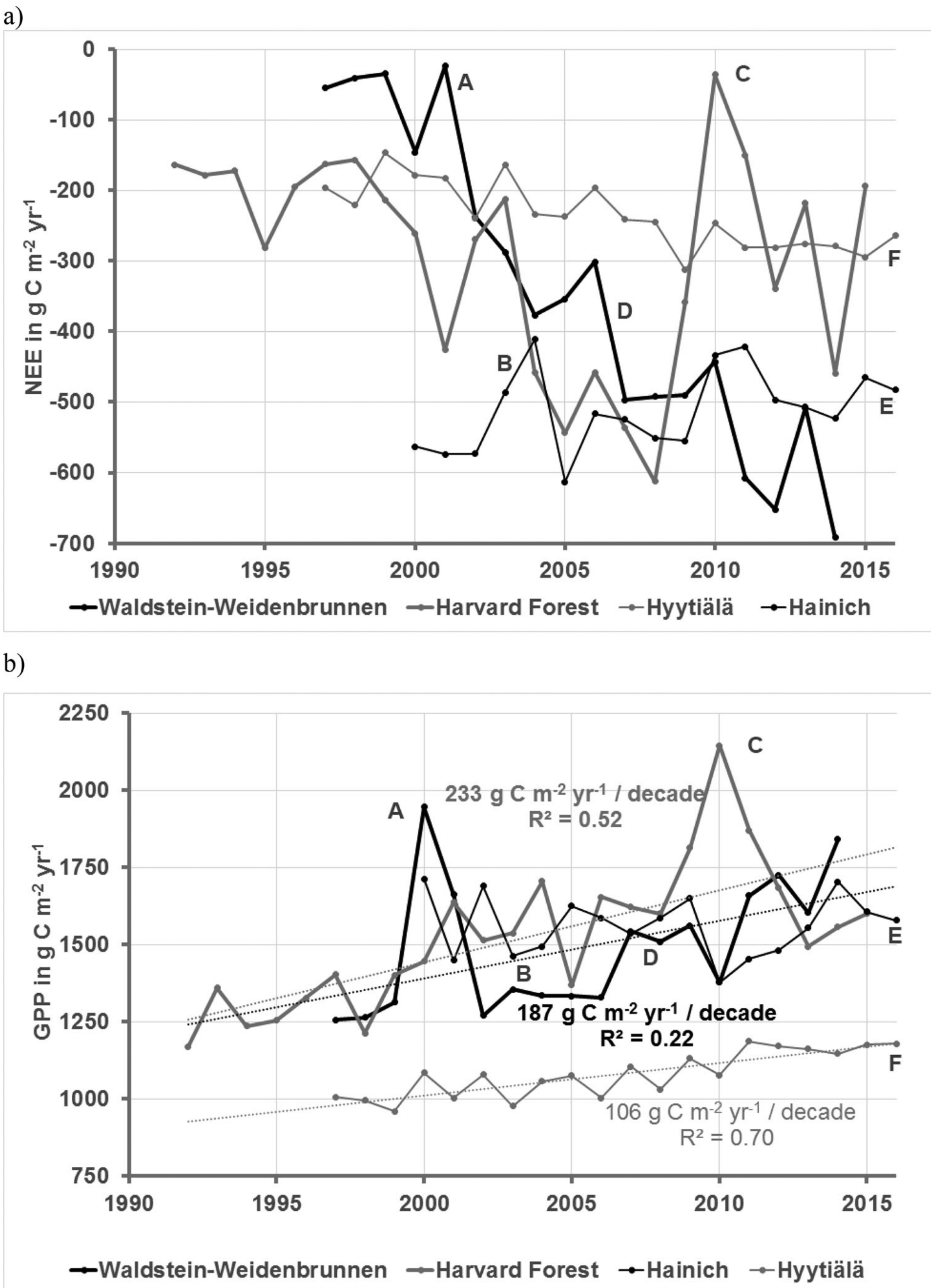
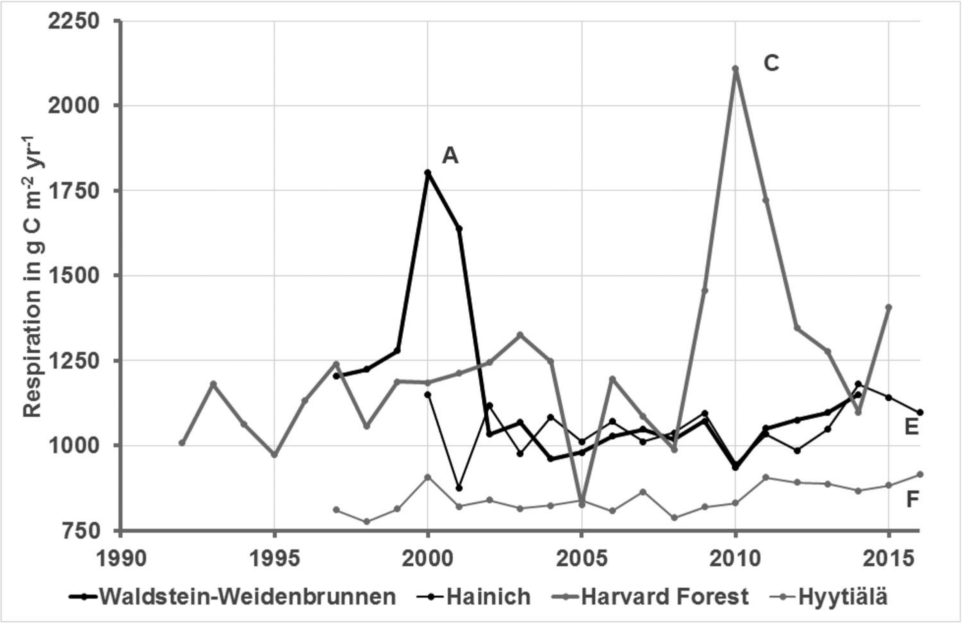


Fig. 2. Trends of carbon dioxide and water fluxes at the four stations. Trends and the coefficient of determination (R^2) were partly calculated (see text). (a) Net Ecosystem exchange; (b) Gross Primary Production; (c) Respiration; (d) Evapotranspiration; the following breakpoints are included in the graphs: A: Forest decline; B: Summer heat wave; C: Intense summer drought; Furthermore E: Old natural forest; F: Boreal forest. The trends reported by Ferna ndez-Mart ınez et al. (2017) differ slightly because of the shorter time period.

c)



d)

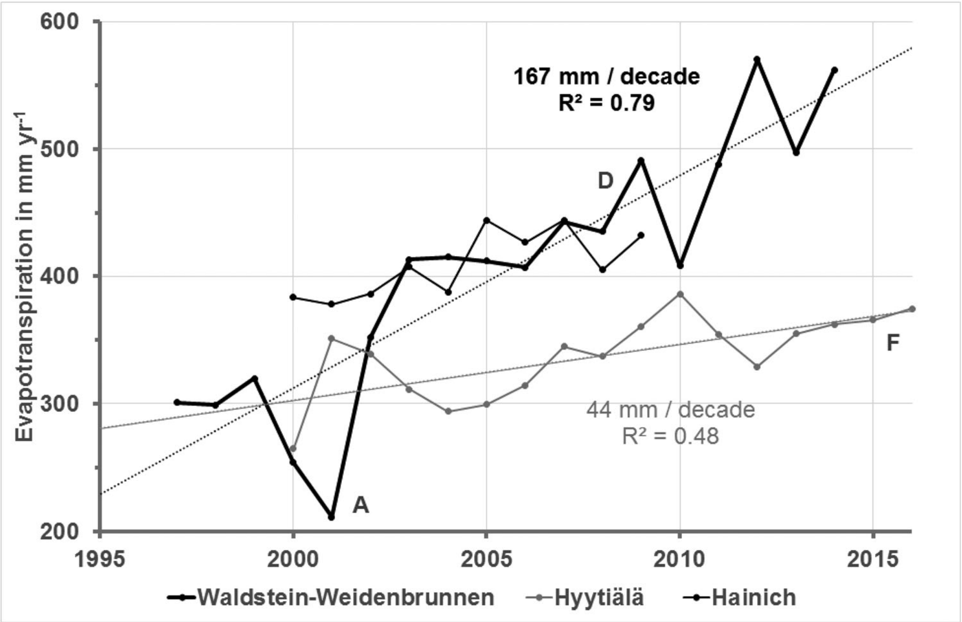


Fig. 2. (Continued).

showed that the strongest coherent structures were observed at the interface between the closed forest and a clearing or at gaps in the canopy (Eder et al., 2013; Thomas et al., 2017). This may generate higher fluxes and – as the sum of many heterogeneities – a larger measured carbon uptake (larger absolute value of NEE). Similar effects are known from the literature, e.g. Klaassen et al. (2002). By the way, coherent structures can be well detected with the eddy-covariance method according to Thomas and Foken (2007), suggesting that measurement methodical aspects can be excluded.

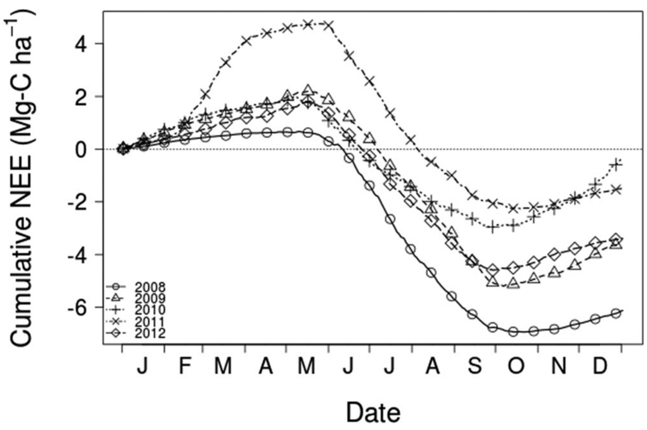


Fig. 3. Cumulative Net Ecosystem Exchange of the Harvard Forest site US-Ha1 from 2008 to 2012.

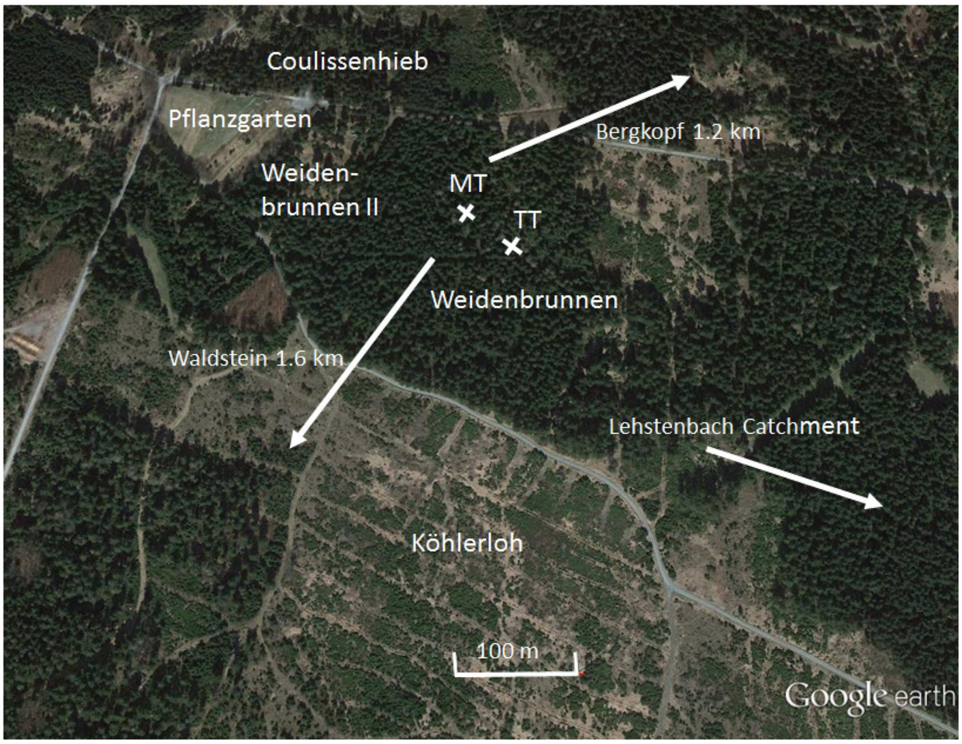


Fig. 4. Areal view of the DE_Bay site (photograph from April 19, 2015, showing nearly no changes since 2007) with the different measuring sites and the Main Tower (MT, used up to 2007) and the turbulence tower (TT, used since 2007) and the distances to relevant hills Waldstein and Bergkopf in the surrounding landscape. The main wind direction is SW. (Foken et al., 2017, published with kind permission of # Google earth and Springer).

In Large Eddy Simulation studies at a forest edge it has been found that a maximum flux occurs in the forest at a distance from the edge of about 10 times the canopy height (Dupont and Brunet, 2009; Finnigan et al., 2009; Kanani-Sühring and Raasch, 2015). This was also found in a model study for the DE-Bay site (Kanani-Sühring et al., 2017), and the related video can be seen at http://extras.springer.com/2017/978-3-319-49389-3. Indeed, because of the clearing and for the dominant south-westerly wind, and due to the use of a new tower located about 80 east of the former tower from 2007, the measurements are being made closer to the possible hot spot of fluxes at a distance from the forest edge of 10 times the canopy height. Carbon dioxide and water vapour fluxes have increased since 2007, probably beyond

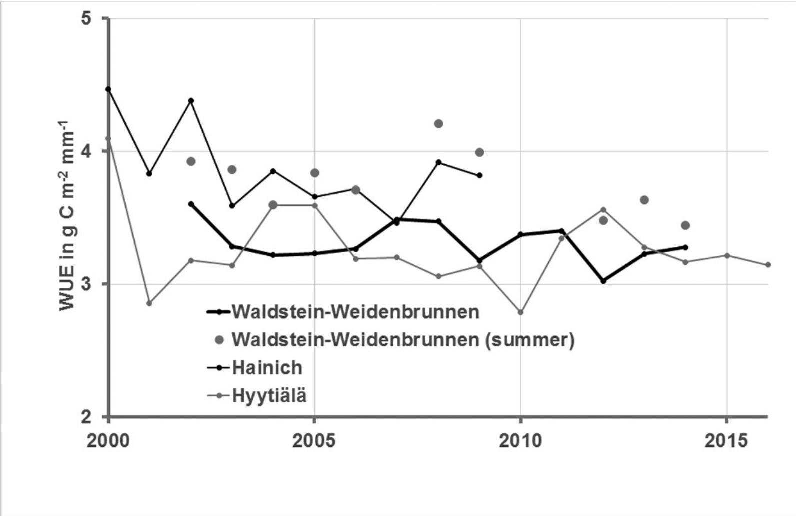


Fig. 5. Water use efficiency of three sites calculated as the ratio of annual sums of GPP and ET. Because of this simplification, for Waldstein-Weidenbrunnen site measurements in summer were calculated from the available single measured data (not gap-filled).

the level typical of spruce forests, while the water use efficiency has been nearly constant.

4. Conclusions

The increases of carbon uptake and evapotranspiration should be realistic for many FLUXNET sites. However, these are not only caused by climate change factors like higher temperatures, higher carbon dioxide concentrations or longer vegetation periods, with a multitude of other effects being investigated in the literature (e.g. Baldocchi et al., 2018) . Moreover, this study also has shown that certain breakpoints have an influence on sums and trends of carbon uptake. In long term data analyses over all biomes and latitudes these breakpoints could be excluded as less representative measurements (Chu et al., 2017). Therefore the study has addressed such breakpoints with the hope that detailed site-specific process studies will be added to long-term trend studies.

For the Central and East European area, the recovery from the forest decline of the 1980s may increase the general trend. Unfortunately, only DE-Bay operated at this time in the region and forest decline occurred mostly at higher altitudes.

This study also showed that the increases in heterogeneity or disturbance of the forest by wind throw or bark beetle infestation and the resulting changes of aerodynamic factors and an increase of the leaf area index of the understory are reasons for such trends. Several factors of the surface heterogeneity may explain increasing fluxes. Therefore it is recommended that the work by Stoy et al. (2013) to find criteria for the heterogeneity of a site should be continued. They investigated variations of MODIS Plant Functional Type and Enhanced Vegetation Index in the surroundings of measurement sites. Unfortunately the scale of the relevant heterogeneities is significantly smaller than the heterogeneities that can be detected with MODIS data. Upcoming data from new satellite platforms may provide an exciting and unexplored opportunity. Criteria of the small-scale heterogeneities should be documented for each site in addition to the target area within the footprint, which is available for many FLUXNET sites (Göckede et al., 2008). The increase of the carbon uptake at many sites should be studied in the context of such heterogeneity or disturbance criteria.

Because NEE and ET fluxes increase and the water use efficiency is nearly constant, the fertilisation due to higher carbon dioxide concentrations cannot be a significant factor for the trends (Fig. 5). The finding disagrees with Keenan et al. (2013), however, an increase of ET may be possible with a greater amount of leafs (needles) and a greater active evaporative surface. For respiration – except single breakpoints – no trends in respiration were found in agreement to many other sites (Fernandez-Martınez et al., 2017).

The paper has analysed the significant influences of heat waves and droughts of individual sites had in the year of the event and probably also in the following year. Especially extreme weather periods may have a significant influence on annual sums of carbon and water budgets. Old natural forest and boreal forest are probably less influenced by such events.

Investigations of trends of carbon and water fluxes should be undertaken with care. Not only good climate data and meta data that characterise the site, the sensors, and data handling but also the aerodynamic structure of the ecosystem should be documented and taken into account.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplementary data

The data of DE-Bay site are available in Foken (2017), https://link.springer.com/content/pdf/bbm%3A978-3-319-4 9389-3%2F1.pdf, and the data of the other sites on the data portal serving the FLUXNET community (https://fluxnet.fluxdata.org).

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