Chapter 4
Long-Term Carbon and Water Vapour Fluxes

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4.1 Introduction

Long-term flux measurements of water vapour and carbon dioxide, as structured within networks like FLUXNET (Baldocchi et al. 2001), are of strong interest for the scientific community for ecosystem level process studies (e.g. Valentini et al. 2000), derivation of regional to global budgets (e.g. Jung et al. 2009) or to evaluation of land surface models (e.g. Bonan et al. 2011).

The Waldstein–Weidenbrunnen site (DE-Bay) has been intensively studied for more than 20 years, starting with the first carbon dioxide flux measurements in 1996. A history of the site including the main activities during the last two decades is given in Chap. 1. The climate at the Waldstein–Weidenbrunnen site is warm-temperate

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in the sense of FLUXNET conventions, and the climate type is Cfb according to Köppen–Geiger classification (Kottek et al. 2006). It has been included in the EUROFLUX sites (Valentini et al. 2000), with eddy-covariance-measured carbon and water fluxes obeying the EUROFLUX methodology (Aubinet et al. 2000, 2003). The site took part in the development of quality standards, especially with respect to eddy-covariance data quality (see Chap. 12), footprint (Rebmann et al. 2005; Göckede et al. 2002, 2008) and gap-filling (Rebmann et al. 2004; Ruppert et al. 2006) for eddy-covariance-measured carbon and water fluxes of the EUROFLUX project.

The first flux data sets from 1997 to 2001 were published by Rebmann (2004), Rebmann et al. (2004), the data has been used for site-specific process studies of carbon and water cycling (e.g. Valentini et al. 2000; Matteucci et al. 2000; Bernhofer et al. 2003). A long-term data set has now been compiled for the Waldstein–Weidenbrunnen site. The present study adds the analysis of the data from 2002 up to 2014. We show the long-term behaviour of the site with respect to evapotranspiration and net carbon uptake, as well as gross primary production and ecosystem respiration derived by flux partitioning algorithms. Furthermore, we investigate the inter-annual variation of evapotranspiration with respect to the Budyko framework, which is a non-dimensional characterization of a region by the relationships between evapotranspiration, potential evaporation and precipitation, and compare our data with the results of Williams et al. (2012). Finally, we put our measurements into the regional context and compare our results to selected examples from related studies.

4.2 Methods

4.2.1 Site Description and Measurement Set-up

The long-term observations of carbon dioxide and water vapour fluxes have been conducted above a Norway spruce forest in the Fichtelgebirge, at the Weidenbrun-

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Table 4.1 Selection of instruments used for the long-term budgets

Parameter	Manufacturer, device	Location	Period
Flux measurements			
Wind vector	Gill, R2 sonic (until May 19, 2003)	MT[a], 33 m	1997–2003
	Gill, R3 sonic	MT[a], 33 m	2003–2006
Water vapour and CO_2	Li-Cor, Li6262 (until April, 2002)	MT[a], 33 m	1997–2002
	Li-Cor, Li7500	MT[a], 33 m	2002–2006
Wind vector	Metek, USA1	TT[b], 36 m	2007–2014
Water vapour and CO_2	LiCor Biosci., Li7500	TT[b], 36 m	2007–2014
Meteorological measurements			
Short-wave radiation	Kipp&Zonen, CM14	MT[a], 30 m	1998–2014
Long-wave radiation	Kipp&Zonen, CG2	MT[a], 30 m	1998–2014
Air temperature and humidity	Friedrichs, Frankenberger Psychrometer	MT[a], 31 m, 2 m	1998–2014
	Vaisala, HMP 45A		
Present weather detector	Vaisala, PWD11	MT[a], 21 m	2002–2014
Precipitation	OMC 212, tipping bucket	Pfl[c], 1 m	1994–2014
	Ott, Pluvio2	Pfl[c], 1.5 m	2012–2014

For a complete instrumentation list of the main tower and Pflanzgarten site see Appendix A
[a]Waldstein–Weidenbrunnen, main tower
[b]Waldstein–Weidenbrunnen, turbulence tower
[c]Waldstein–Pflanzgarten

nen site in the Waldstein measurement area. Chapter 2 provides details about this site including information about location, climate and vegetation. The eddy-covariance set-up has been in operation on the 32 m high walk-up scaffold tower, henceforth called Main Tower or MT (see Chap. 2, Figs. 2.2 and 2.7) since 1996, with a change of instrumentation in 2001 and 2007. A second eddy-covariance complex has been established on a 36 m high slim tower, henceforth called Turbulence Tower or TT in 2007 (see Chap. 2, Figs. 2.2 and 2.8). In this chapter we analyse the data from 2002 up to 2014, with the relevant instrumentation summarized in Table 4.1, while additional information about further routine set-up is given in Appendix A.

4.2.2 Data Processing

4.2.2.1 Turbulent Flux Processing

Turbulent fluxes of carbon dioxide and latent heat have been calculated with the internationally compared software package TK2/TK3 (Mauder and Foken 2011, 2015), obeying micrometeorological standards with respect to corrections and data quality control (Foken et al. 2012). Coordinate rotation has been carried out with the planar-fit method (Wilczak et al. 2001) for each month separately, based on an analysis by Siebicke et al. (2012). The net ecosystem exchange *NEE* is then the sum of the eddy-covariance carbon dioxide flux and the change in storage of the air column below the sensor. As CO_2 profile measurements were only available during intensive observation periods, the storage flux has been calculated from mean CO_2 concentrations at the top of the tower for the whole period. Ruppert et al. (2006) showed for the Waldstein site, that this method captures the canopy storage reasonably well, as long as unrealistic values of the open-path gas analyser were rejected. The evapotranspiration *ET* in mm is the water equivalent of the eddy-covariance latent heat flux.

The flux data has been quality controlled with a flagging system ranging from 1 to 9, combining tests for stationarity and integral turbulence characteristics (Foken and Wichura 1996; Foken et al. 2004). Therefore a u_*-filtering on *NEE* flux measurements has not been applied (Ruppert et al. 2006, see Chap. 12). We kept flux data of best and intermediate data quality (1–6) for the long-term budgets, while the parameterization of the gap-filling routine (this section) was done with data of best quality (1–3) only. In addition, all data during rain or fog events and the following hour have been discarded due to steamed up windows of the open-path gas analyser. No quality checks in terms of advection have been applied, as the relationship between advection and diagnostics of the eddy-covariance flux is still unclear. Especially the night-time u_*-criteria was shown to be not consistent with advection (Aubinet et al. 2010). More details about advection at Waldstein–Weidenbrunnen is given in Chaps. 6, 12 and 14.

The footprint of the eddy-covariance data has been calculated with a Lagrangian stochastic forward model (method presented by Göckede et al. 2006). The calculations for 2003 (Göckede et al. 2008, before Kyrill) and for the IOPs in 2007 and 2008 (Siebicke 2008, after Kyrill) showed that although this significant wind-throw destroyed large forest areas in the further vicinity of the sensors, the contribution from the forest to the flux is in the range of 80–97% (main tower: nearly all of the data; turbulence tower: approx. 75% of the data) and is therefore even slightly larger than the contribution in 2003. This can be explained by the canopy height of a growing forest (2003: 19 m, 2008: 25 m, see Chap. 2), diminishing the average footprint extent. The differences between the footprints of the main tower and the turbulence tower can be attributed to the fact that the turbulence tower is slightly closer to the Köhlerloh clearing (showing larger contribution), and further from the Pflanzgarten clearing (showing less contribution). Twenty-five percent of the data at TT is still not exceeding 80% target contribution, but within a range of approximately 74–80%. All in all, we judged the contribution of the target area as sufficient for the calculation of long-term budgets and did not exclude data on the basis of footprint issues.

4.2.2.2 Meteorological Data

The meteorological data, comprised of the radiation balance (four components) and air temperature, has been used as input for the gap-filling routine, while additional measurements of the precipitation and weather code served for quality checks

(Table 4.1). After visual plausibility checks of the data, gaps have been filled (where possible) by linear regression from measurements at other heights or at the Waldstein–Pflanzgarten site.

4.2.2.3 Gap-Filling

As a last quality check, a multi-step error filter as used by Lüers et al. (2014) has been performed on the meteorological data, the mean CO_2 and H_2O densities as well as on the fluxes. Besides fixed thresholds, adjustable quantile and standard deviation filters have been applied in order to remove physically non-plausible outliers from the data. In addition to the quality checks mentioned earlier in this section, this procedure removed 2.4% of measured *NEE* and 1.3% evapotranspiration records. After all quality checks, and due to longer periods of sensor malfunction and power failures, remaining measured *NEE* (*ET*) in 2007 and 2010 were only 4.1% (4.0%) and 17.4% (17.5%), respectively (Table 4.2). Therefore, these 2 years have been discarded from further analysis. Available measured *NEE* (*ET*) for the remaining years range from 26.5% (26.6%) to 58.4% (56.2%).

Gap-filling of the *NEE* data was then performed with non-linear regression: The Lloyd–Taylor function (Lloyd and Taylor 1994) is used for night-time respiration with the air temperature as the explanatory variable and a Michaelis–Menten type function (Michaelis and Menten 1913) for day-time *NEE*, binned in temperature

Table 4.2 Percentages of observations available for the annual budgets of *NEE* and evapotranspiration after all quality checks (measured), percentages of data gapfilled with non-linear regression (nonlin reg, Ruppert et al. 2006) and percentages of data filled with the half-hourly ensemble average of all years (ens avg); *2007* and *2010* were discarded from further analysis due to low data coverage

	ET			*NEE*		
Year	measured (%)	nonlin regr (%)	ens avg (%)	measured (%)	nonlin regr (%)	ens avg (%)
2002	33.8	60.7	5.5	32.8	62.2	5.0
2003	51.1	47.1	1.8	49.0	50.0	1.0
2004	44.1	53.3	2.6	43.6	54.7	1.7
2005	43.5	55.6	0.9	39.4	60.6	0.1
2006	30.7	65.4	3.9	29.5	69.4	1.1
2007	*7.0*	*76.9*	*16.1*	*7.2*	*70.1*	*22.7*
2008	26.6	66.4	7.0	26.5	71.5	1.9
2009	45.2	50.7	4.0	45.5	53.0	1.6
2010	*17.5*	*71.2*	*11.3*	*17.4*	*76.6*	*6.0*
2011	33.3	42.8	23.9	33.5	55.9	10.5
2012	47.9	48.3	3.8	48.7	48.7	2.6
2013	36.8	52.4	10.8	37.7	53.1	9.2
2014	56.2	41.4	2.4	58.4	41.3	0.3

classes of 2 K width and using global radiation as the explanatory variable. The procedure is explained in detail by Ruppert et al. (2006), and they showed with a data set from 2003 that the explanatory variables used explain most of the variability of *NEE* at the Waldstein site.

Gaps in *ET* measurements have been filled with the help of Priestley–Taylor potential evaporation E_p (Priestley and Taylor 1972). Measured net radiation as well as air temperature was used to calculate E_p, with the ground heat flux being 5% of the net radiation (Rebmann et al. 2004). For gap-filling, E_p has been scaled to measured *ET* by linear regression.

Large gaps in the data in winter-time lead to an under-representation of training data for these conditions. Therefore, regressions have not been performed on an annual basis but for two periods only: 2002–2006 (measurements at the main tower) and 2008–2014 (measurements at the turbulence tower). Further adjustments include a temperature threshold for winter-time assimilation, preventing the occurrence of unrealistic carbon uptake during winter-time. Reasons for these adjustments, and their impact, are presented in Sect. 4.3.2.

After this procedure, some gaps were still left due to missing meteorological input data. Filling these gaps by mean diurnal variation as reviewed by, for example, Falge et al. (2001) seems to be not appropriate, as the gaps occur in larger blocks (due to instrument failures or power outages). An ensemble average annual cycle has therefore been calculated for 2002–2014 on half-hourly basis, and used to fill these gaps. A summary of data availability and gap-filling gives Table 4.2, and a detailed list on a monthly basis is in Appendix B of this book.

4.3 Results and Discussion

4.3.1 Energy Balance Closure of EC Measurements

The non-closure of the observed surface-energy balance introduces a systematic error to the long-term flux measurements (Foken 2008). We calculate the energy balance closure ratio *EBR* as the slope of the geometric mean regression of turbulent fluxes vs. available energy ($R_n - Q_G$, with $Q_G = 0.05 \cdot R_n$). The average closure for the whole period is 81.3 ± 5.2% (mean and standard deviation), while the *EBR* significantly changes from the first to the second period: *EBR* at the main tower (2002–2006) was 75.4 ± 1.9%, while *EBR* at the turbulence tower (2007–2014) increases to 84.9 ± 2.2%. A summary of annual *EBR* is given in Table 4.3, and exemplary scatterplots are displayed in Fig. 4.1. The energy balance closure for the period 1997–1999 was 72.6% (Aubinet et al. 2000), which is similar to the closure from 2002 to 2006. Recent hypotheses as to the reasons for the unclosed energy balance suggest that the missing flux is mainly attributed to the sensible heat flux (Charuchittipan et al. 2014, see Chap. 12). We therefore decided not to correct the latent heat flux (and *NEE*) for missing turbulent energy.

Table 4.3 Annual energy balance closure ratios *EBR* of eddy-covariance data

Tower	Year	*EBR* (slope)	Offset (W m^{-2})	R^2
MT	2002	0.724	8.3	0.74
	2003	0.753	4.0	0.90
	2004	0.762	3.5	0.87
	2005	0.774	6.6	0.90
	2006	0.755	6.9	0.90
		0.754 ± 0.019 (mean ± std)		
TT	2007	0.849	1.3	0.89
	2008	0.828	5.6	0.84
	2009	0.840	5.7	0.80
	2010	0.824	1.0	0.89
	2011	0.840	8.8	0.92
	2012	0.863	7.9	0.75
	2013	0.858	2.9	0.76
	2014	0.892	10.4	0.76
		0.849 ± 0.022 (mean ± std)		
	All	0.813 ± 0.052 (mean ± std)		

4.3.2 Adaptations of the Gap-Filling Method for NEE

With the given set-up, however, the long-term measurements face specific problems during winter-time: data availability is very low due to frequently steamed windows of the open-path gas analyser, and the heating of the sonic anemometer often failed to prevent icing of the sensor head. Moreover, the remaining winter-time data showed carbon uptake in many cases, which is at least not representative for winter-time, and most likely not true, as the respiration components might be subjected to advection, leaving the measured (Reynolds-) flux as an incomplete representation of *NEE*. Utilizing this data for the gap-filling routine (Sect. 4.2.2) would significantly underestimate winter-time respiration. The following adjustments have therefore been made:

Multi-annual parameterization In order to enlarge data coverage in winter-time, non-linear regressions have been performed only for the two periods with different sensor set-up (instead of a parameterization for each year): 2002–2006 and 2008–2014. In order to reduce scatter and to preserve the relative weight of the lower temperature regimes, the regression has been performed on the median of temperature classes (2 K width). All necessary equations and parameters are listed in Table 4.4

Temperature threshold Winter-time assimilation (November–April) is only accepted when the air temperature is above 6 °C. Otherwise, assimilation is set to zero and only parameterized ecosystem respiration is used. A similar method has been applied at a disturbed spruce forest site in the Bavarian Forest by Lindauer et al. (2014), who set *GPP* to zero from December to March, as *GPP* from measurements in this period are zero on average. This is not the

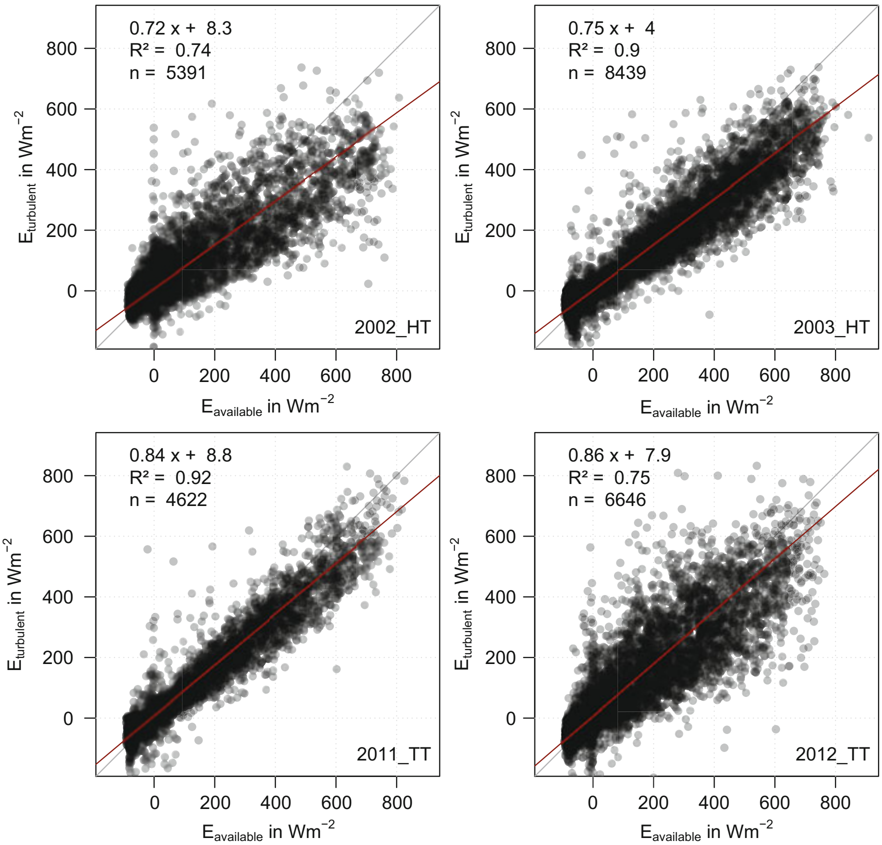

Fig. 4.1 Energy balance closure ratio from available energy ($R_n - Q_G$) vs. turbulent fluxes for 2002/2003 at main tower and 2011/2012 at turbulence tower

case here, as the rare measurements with the open-path gas analyser show, on average, assimilation for November–April. However, these measurements are only available under dry, clear-sky conditions, which are not representative of average winter-time conditions. Excluding these data diminishes annual net carbon uptake ($-NEE$) by $74 \pm 50\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$, on average, in the period 2002–2014.

4.3.3 Carbon and Water Vapour Fluxes

The ecosystem fluxes of net ecosystem exchange *NEE*, gross primary production *GPP* and ecosystem respiration R_{eco} as well as evapotranspiration *ET* and potential evaporation E_p for the calculated period from 2002 up to 2014, as well as the results by Rebmann et al. (2004) from 1997 to 2001, are summarized as annual budgets

Table 4.4 Parameterization of the non-linear regression functions for gap-filling of *NEE* and latent heat Q_E, upper part: Michaelis–Menten type function (Michaelis and Menten 1913) for daytime *NEE*; middle part: Lloyd–Taylor function (Lloyd and Taylor 1994) for ecosystem respiration R_{eco}; lower part: coefficient for Priestley–Taylor function (Priestley and Taylor 1972); grey values displayed in italic type were discarded from the analysis due to low data coverage

Michaelis–Menten: $NEE_{day} = \frac{a \cdot R_G \cdot F_{C,sat}}{a \cdot R_G + F_{C,sat}} + R_{eco,day}$ with global radiation R_G as predictor						
	2002–2006			*2007–2014*		
t_{air} class (°C)	$R_{eco,day}$ (μmol m^{-2} s^{-1})	$F_{C,sat}$ (μmol m^{-2} s^{-1})	a (μmol J^{-1})	$R_{eco,day}$ (μmol m^{-2} s^{-1})	$F_{C,sat}$ (μmol m^{-2} s^{-1})	a (μmol J^{-1})
0	1.18	−8.5	−0.085	4.99	−12.7	−0.919
2	1.69	−10.4	−0.130	0.48	−12.6	−0.152
4	2.84	−17.0	−0.125	0.74	−16.8	−0.110
6	3.08	−22.4	−0.099	2.15	−23.5	−0.108
8	3.18	−25.6	−0.094	3.32	−25.2	−0.151
10	4.13	−27.5	−0.099	3.10	−29.2	−0.117
12	4.60	−27.8	−0.100	4.36	−30.1	−0.125
14	5.10	−31.9	−0.086	5.01	−29.0	−0.131
16	5.75	−27.4	−0.100	5.93	−31.1	−0.106
18	5.21	−25.5	−0.086	6.10	−29.4	−0.099
20	5.28	−24.5	−0.069	8.42	−29.0	−0.117
22	5.21	−22.4	−0.052	5.91	−28.9	−0.058
24	4.28	−20.3	−0.033	10.48	−26.5	−0.097
26	2.23	−21.8	−0.015	9.09	−32.1	−0.047
Lloyd–Taylor: $R_{eco} = F_{R,10} \cdot \exp\left(E_0 \cdot \left[(283.15\,K - T_0)^{-1} - (T_{air} - T_0)^{-1}\right]\right)$						
	2002–2006			*2007–2014*		
	$F_{R,10}$ (μmol m^{-2} s^{-1})	E_0 (K)	T_0 (K)	$F_{R,10}$ (μmol m^{-2} s^{-1})	E_0 (K)	T_0 (K)
	2.973	282.3	227.13[a]	3.004	285.4	227.13[a]
Priestley–Taylor: $Q_E = \alpha \cdot Q_{E,p} = \alpha \cdot \alpha_{PT} \cdot \frac{s_c \cdot (R_n - Q_G)}{s_c + \gamma}$, $s_c = \frac{dq_s}{dT}$, $\gamma = \frac{c_p}{\lambda}$, $\alpha_{PT} = 1.25$						
	2002–2006: $\alpha = 0.396$			*2007–2014*: $\alpha = 0.481$		

[a]Not optimized, but original value taken as done in Ruppert et al. (2006)

in Table 4.5. We analyse these fluxes in more detail in the next sections. Monthly budgets were provided in Appendix B. In the following the data is partly analysed in its whole length, but due to changes in instrument set-up (Table 4.1) and availability of measurements (Table 4.2), three periods were discriminated as well:

1997–2001 MT, Gill R2, LiCor Li6262, data analysis: Rebmann et al. (2004).
2002–2006 MT, Gill R2/R3, LiCor Li7500, data analysis: this chapter.
2008–2014 TT, Metek USA1, LiCor Li7500, data analysis: this chapter.

Table 4.5 Annual budgets of net ecosystem exchange *NEE*, gross primary production *GPP* and ecosystem respiration R_{eco} as well as evapotranspiration *ET* and potential evaporation E_p (Priestley and Taylor 1972); italic values were discarded from the analysis due to low data coverage

Year	*NEE* ($g\,C\,m^{-2}\,a^{-1}$)	*GPP* ($g\,C\,m^{-2}\,a^{-1}$)	R_{eco} ($g\,C\,m^{-2}\,a^{-1}$)	*ET* (mm)	E_p (mm)
1997	−55	−1257	1203	301	–
1998	−41	−1265	1224	299	–
1999	−35	−1314	1279	321	–
2000	−146	−1947	1802	254	–
2001	−24	−1663	1639	211	–
2002	−238	−1271	1033	352	774
2003	−288	−1356	1068	413	946
2004	−377	−1337	960	415	794
2005	−354	−1333	979	412	808
2006	−301	−1329	1027	407	878
2007	*−497*	*−1544*	*1047*	*443*	897
2008	−492	−1510	1018	435	851
2009	−491	−1563	1072	491	852
2010	*−443*	*−1378*	*935*	*408*	771
2011	−608	−1659	1051	488	835
2012	−652	−1726	1075	570	697
2013	−508	−1605	1097	497	757
2014	−692	−1842	1150	562	780

4.3.3.1 Carbon Exchange

The annual sums of *NEE* show a net uptake of carbon throughout the whole time series and a clear trend towards larger uptake (Table 4.5, Fig. 4.2). The three periods differ significantly from each other in both flux magnitudes and variance: 1997–2001 shows low values and variation with $40 \pm 12\,g\,C\,m^{-2}\,a^{-1}$ on average, except for the year 2000 with an uptake of $146\,g\,C\,m^{-2}\,a^{-1}$. The net carbon sink in 2002–2006 ranges from 238 to $377\,g\,C\,m^{-2}\,a^{-1}$, and finally reaches a range of 491–$692\,g\,C\,m^{-2}\,a^{-1}$ in 2008–2014. The highest uptakes were observed for 2011–2014, with $615 \pm 79\,g\,C\,m^{-2}\,a^{-1}$ on average. In comparison with a mean biome flux of $398 \pm 42\,g\,C\,m^{-2}\,a^{-1}$ for evergreen humid temperate forests from a global database (Luyssaert et al. 2007), our numbers seem to be in the same range on average, but low for 1997–2001 and very high in 2008–2014. Nevertheless, all values are within the range for temperate forest sites shown by Luyssaert et al. (2010).

While the trend is significant over the whole period and specifically for 2002–2014 (Mann–Kendall trend test, $p < 0.05$), it is reflected in the latter two sub-periods, but is not significant for 2002–2006 ($p = 0.46$) and is only a tendency for 2008–2014 ($p = 0.13$). This implies a superposition of a real trend and site-specific effects related to the sub-periods, which will be discussed later. The flux partitioning estimates suggest that this increase in carbon uptake can be mainly attributed to an

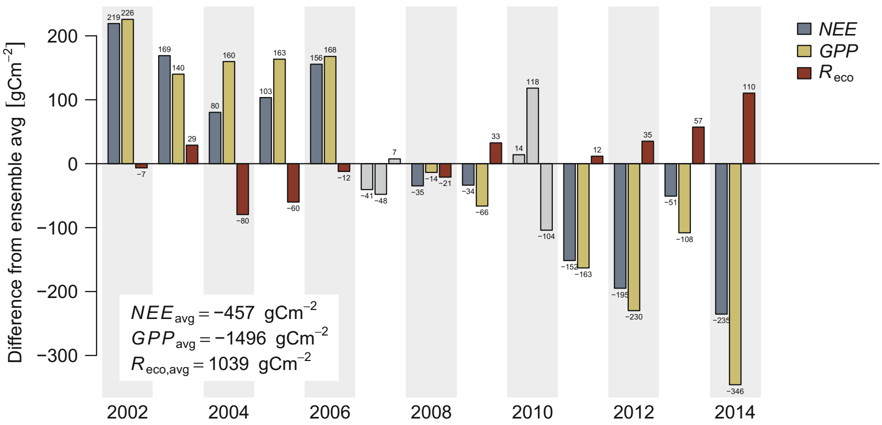

Fig. 4.2 Annual sums of carbon flux components, displayed as absolute deviations from the ensemble average for the whole period; positive values for *NEE* (*GPP*) indicate less net (gross) uptake than on average, positive R_{eco} indicate higher respiration than on average

enhancement in *GPP*, while R_{eco} is increasing as well but to a lesser extent than does *GPP*: a linear regression of R_{eco} vs. *GPP* gives a slope of 0.21, indicating that a rising *GPP* causes an increase in *NEE* by 79% of this growth, while only 21% is consumed by R_{eco} (Fig. 4.3). The coherence between *GPP* and R_{eco} seems to be robust, and is reasonable in an ecophysiological sense as observed for many sites (Fernández-Martínez et al. 2014; Kutsch and Kolari 2015), although to some extent this coherence must be attributed to a spurious correlation resulting from the calculation for $GPP = NEE - R_{eco}$ as a balance residual, see Vickers et al. (2009) and the follow-up discussion (Lasslop et al. 2010; Vickers et al. 2010).

These changes in *NEE*, *GPP* and R_{eco} are reflected in the seasonal patterns as presented in cumulative time series and monthly sums (Fig. 4.4). The ensemble average *NEE* shows net respiration during winter-time from the beginning of November until mid-March, while net uptake takes place in the other months. All years are similar in the winter-time respiration, but the latter periods 2002–2006 and 2008–2014 exhibit subsequently stronger uptake from April to October, especially June, July and August for 2008–2014. The extraordinarily large carbon uptake in 2011, 2012 and 2014 are mainly characterized by an earlier change from net respiration to uptake in March and even stronger uptake from July to October. The time of maximum net uptake shifts from May (1997–2001) to June (2008–2014). Such a shift is reflected in *GPP* (maximum gross uptake in 2002–2006 mainly in June to mainly in July for the period 2008–2014) as well as in R_{eco} (maximum respiration from mainly July to July/August).

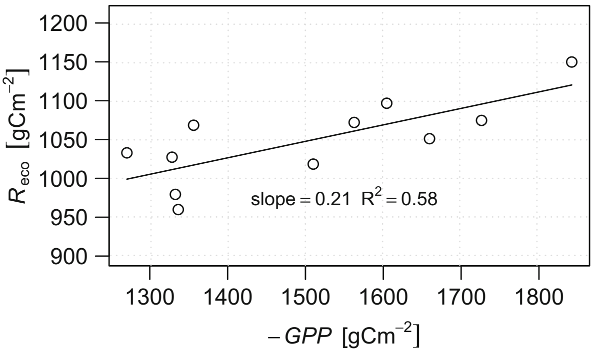

Fig. 4.3 Annual R_{eco} vs. $-GPP$

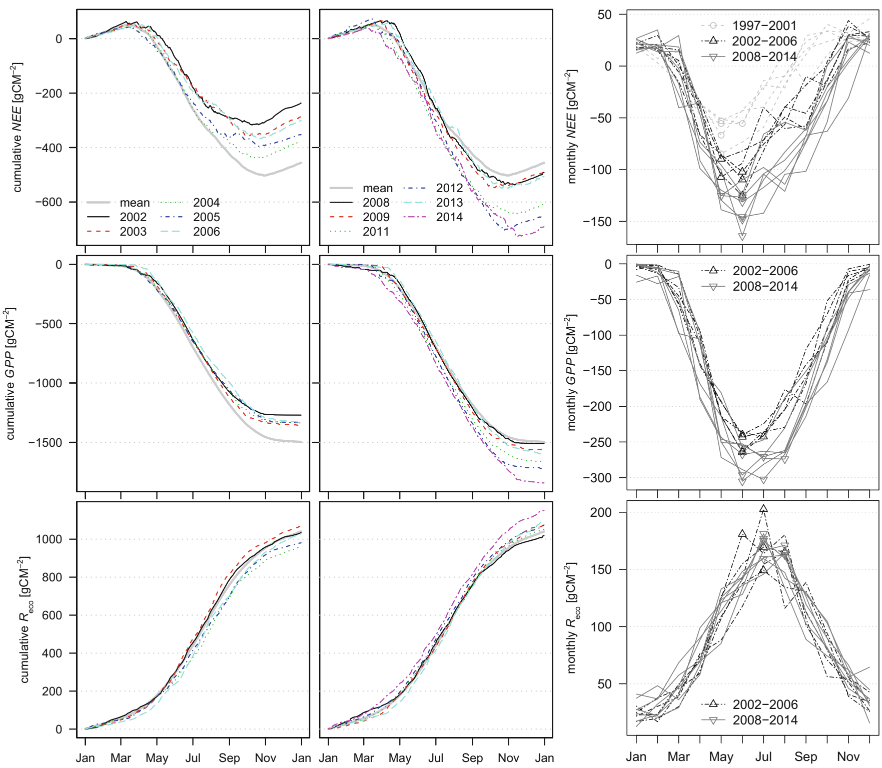

Fig. 4.4 Seasonal carbon exchange at Waldstein–Weidenbrunnen, *left panels*: Cumulative sums of daily net ecosystem exchange *NEE*, gross primary production *GPP* and ecosystem respiration R_{eco} for the period 2002–2006 (*left*) and 2008–2014 (*middle*); the *thick grey line* shows the cumulative sum of the ensemble average for the whole period 2002–2014. *Right panel*: Monthly sums of *NEE*, *GPP* and R_{eco} for 1997–2001 (*light grey*), 2002–2006 (*black*) and 2008–2014 (*darkgrey*); the symbols represent the month with the highest uptake/respiration within the respective year

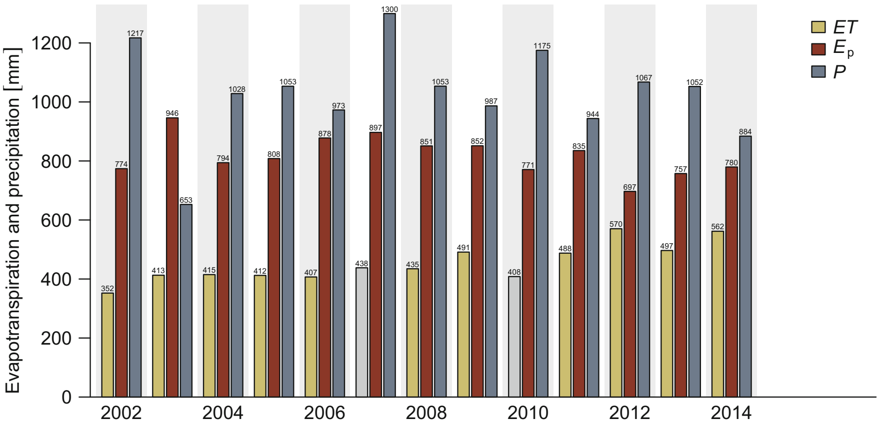

Fig. 4.5 Annual sums of *ET*, E_p and precipitation *P*

4.3.3.2 Water Vapour Fluxes

The annual sums of *ET* show a distinct increase for the whole time series (Table 4.5, Fig. 4.5), with values ranging from 211 to 301 mm a^{-1} (1997–2001), from 352 to 415 mm a^{-1} (2002–2006) and from 435 to 570 mm a^{-1} (2008–2014). The average fluxes increase from 277 ± 44 mm a^{-1} for 1997–2001 to 493 ± 60 mm a^{-1} for 2008–2014. Similar to *NEE*, the trend is significant for the whole period, with no trend visible for 2002–2006 and a tendency apparent for 2008–2014 ($p = 0.13$). Thus the patterns for annual *ET* and *NEE* for all years are consistent, with high correlation ($R^2 = 0.9$). Such increase, however, is not reflected in the potential evaporation E_p, nor in precipitation, which both show variability but no trend, suggesting that *ET* is (still) not strongly limited by these factors.

Budyko (1974) provides an appropriate framework to examine relationships between *ET*, E_p and precipitation with non-dimensional numbers: evaporative index (*ET*, normalized with precipitation) vs. dryness index (E_p, normalized with precipitation). In Fig. 4.6, dashed straight lines denote the supply limit ($ET = P$) and the demand or energy limit ($ET = E_p$). Within this framework, annual values at the Waldstein site suggest not only a trend towards the energy limit (driven by the *ET* trend, while E_p shows no trend), but also a large variability (caused mainly by the variability in *P*, which is not reflected by *ET* or E_p). Although a trend to drier spring seasons has been detected (see Chap. 3), annual *ET* is still not limited by precipitation. Williams et al. (2012) conducted such an analysis for a global set of flux stations. We compared our values with a corresponding subset of numbers from warm-temperate evergreen coniferous forest sites and found a similar range, and the inter-annual variability at the Waldstein site also nearly covers the variation of the station subset chosen from Williams et al. (2012).

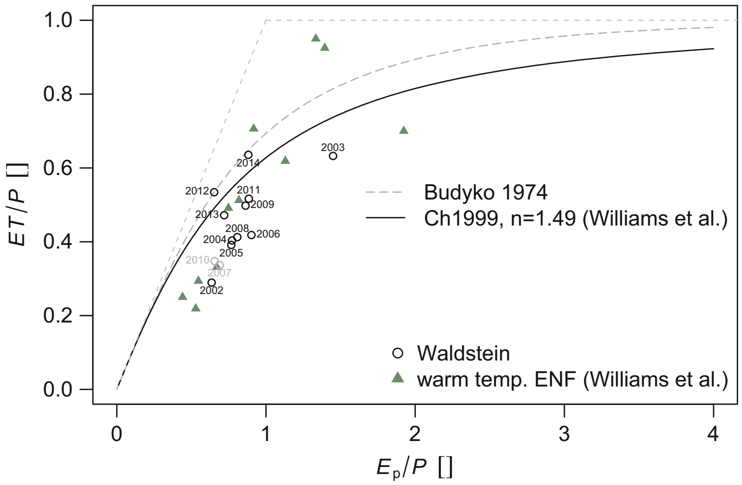

Fig. 4.6 Annual potential evaporation, normalized with annual precipitation vs. normalized evapotranspiration according to the Budyko framework. The *grey dashed line* is the original parameterizations according to Budyko (1974), the *red line* according to Choudhury (1999) with an exponent $n = 1$ and the *black line* also according to Choudhury (1999), but with an exponent $n = 1.49$ as proposed for the sites examined by Williams et al. (2012) (Adapted and completed with kind permission of © John Wiley and Sons 2012, All rights reserved)

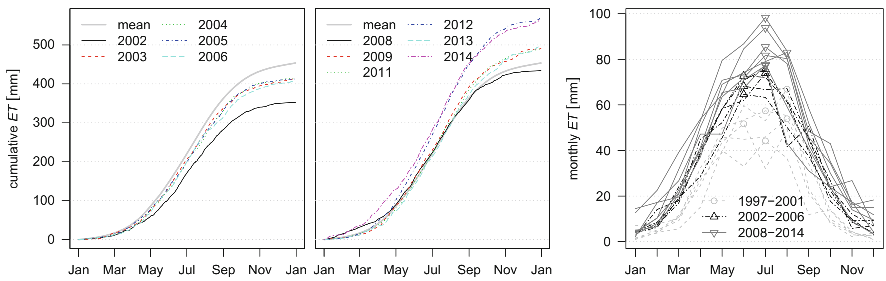

Fig. 4.7 Seasonal water vapour exchange at Waldstein–Weidenbrunnen, *left panels*: Cumulative sums of daily evapotranspiration *ET* for the period 2002–2006 (*left*) and 2008–2014 (*middle*); the *thick grey line* shows the cumulative sum of the ensemble average for the whole period 2002–2014. *Right panel*: Monthly sums of *ET* for 1997–2001 (*light grey*), 2002–2006 (*black*) and 2008–2014 (*darkgrey*); the symbols represent the month with the highest *ET* within the respective year

The inter-annual seasonal variations of *ET* follow the patterns found for *NEE* (Fig. 4.7): a subsequent increase of *ET* from April to October, and only minor changes in winter-time. For *ET*, only 2012 and 2014 were extraordinarily large.

4.3.4 *Factors Influencing the Carbon and Water Vapour Exchange*

In Sect. 4.3.3 we showed remarkable trends of carbon and water vapour exchange with a large range in flux magnitude. There are many possible reasons, which may be attributed either to a gradual shift, or to step changes after breakpoints. Some of them, like instrument set-up and location, are rather local effects, and variations due to these factors are not related to the flux variability of the ecosystem that we wish to characterize and therefore add to the uncertainty of the measurements. The history of the forest's state is site-specific as well, but is certainly relevant for the ecosystem flux. Other factors may have regional to global implication, as, for example, climate change.

4.3.4.1 Development of the Spruce Forest at Waldstein Site

The Norway spruce forest at the Waldstein site has undergone tremendous changes, partly described in Chap. 2, with obvious implications for ecosystem performance. The most important steps are:

- forest visibly suffering from forest decline, with nearly no growth and only slight increase in canopy height from 17.8 m (1995) up to 19 m (2003).
- reconvalescence after a liming application in 2001: re-greening of needles observed and increase in canopy height up to 25 m (2008) and 28 m (2011).
- Increase in heterogeneity of the forest after the wind-throw in 2007 due to the storm "Kyrill", with a clearing south of the site and a reduced tree density west of the site (see Chap. 7), although the percentage of forest in the footprint estimates were not changed significantly. The trees from the blowdown have been removed.

It is obvious that regeneration is accompanied by a large carbon uptake as well as enhanced *ET*. The latter is in agreement with findings in sap-flow measurements (see Chap. 5). Their measurements show that both stand-scale sapwood area and sap flow increased at the Waldstein site, which might be attributed to the effect of liming. The sap-flow measurements made in 1995 at the Waldstein–Weidenbrunnen and five other sites in the area (Alsheimer et al. 1998) always had fluxes below 3 mm d^{-1}, while the measurements in 2007 and 2008 (Chap. 5) also had fluxes larger than 3 mm d^{-1}. The implications of heterogeneity are discussed in a broader perspective in Chap. 19.

4.3.4.2 Instrumental and Methodological Issues

The annual trends of *NEE* and *ET* show distinct jumps in magnitude between the periods 1997–2001, 2002–2006 and 2008–2014. The breakpoints coincide with a change in measurement set-up as summarized at the beginning of Sect. 4.3.3. A potential problem related to the low fluxes in 1997–2001 might arise from the 12-bit digitalization done within the Li6262 in contrast to the 16-bit digitalization within the Li7500. Such digitalization problems also existed for the Gill R2 and R3 sonic anemometer up to 2003 (Foken et al. 2004).

Furthermore, we investigated the impact of the change from R3 to the Metek USA1 sonic anemometer through a comparison of the integral turbulence characteristics for the vertical wind velocity $\sigma_w u_*^{-1}$, as its stability dependence is quite weak in the near-neutral range (Thomas and Foken 2002). Monthly averaged values (March–October, 2002–2014) yield an average $\sigma_w u_*^{-1} = 1.32 \pm 0.026$ for 2002–2006 (R2/R3) and 1.20 ± 0.026 for 2008–2014 (USA1). A larger number indicates a lower momentum flux for the same observed variance σ_w^2 and therefore a possible underestimation of fluxes with the R2/R3. Or, from another perspective, a larger fraction of the variance in R2/R3 observation must be attributed to random noise, which does not contribute to the momentum flux (which likely has an impact on $\overline{w'q'}$ and $\overline{w'c'}$ as well). An exemplary time series is shown for R3, June 2006 and USA1, June 2008 (Fig. 4.8). There is no remarkable difference between R2 and R3 or between the USA1 at the Main Tower and the USA1 at the Turbulence Tower (not shown). The latter indicates that the move of the instrumentation to the Turbulence Tower in 2007 has, at least, no effect with respect to flow distortion by tower elements. On the other hand, the energy imbalance decreased since measurements have been performed on the turbulence tower (Sect. 4.3.1). This suggests that the increase in fluxes is only weakly connected to differences in the sonic anemometer, but might be related to the increased heterogeneity since 2007, which is discussed in Chap. 19.

Another problem arises from the methodological differences between the calculation and gap-filling of the fluxes for 1997–2001 (Rebmann 2004; Rebmann et al.

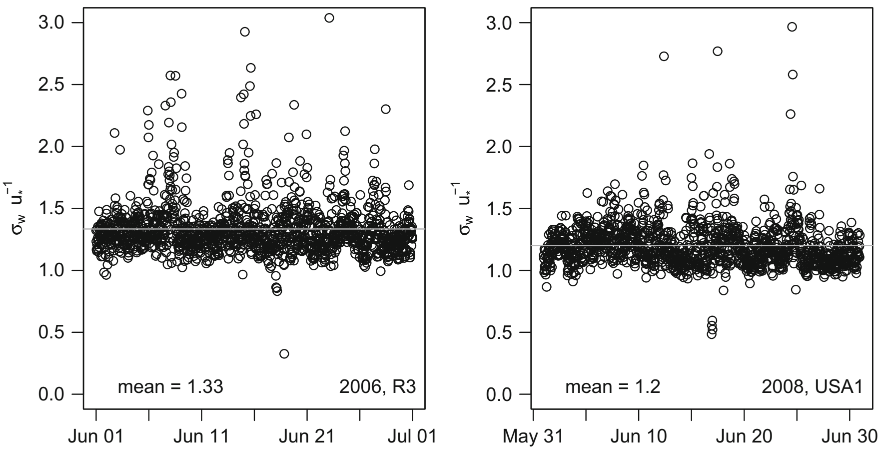

Fig. 4.8 Integral turbulence characteristics for vertical wind velocity $\sigma_w u_*^{-1}$ from ultrasonic anemometer measurements, *left*: June 2006, Main Tower, Gill solent R3; *right*: June 2008, Main Tower, Metek USA1

2004) and the procedure conducted in this chapter. In flux quality assessment, for instance, Rebmann et al. (2004) used the u_*-criterion, while in this chapter the integral turbulence characteristics were utilized. Although similar equations have been used for flux partitioning, parameterization differs in the selection of data subsets for individual regressions. We therefore compared both methods with the data of 2002 (very large fraction of parameterized fluxes, see Appendix B), yielding $NEE = -238\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for the methods used here and $NEE = -326\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ with the methods by Rebmann et al. (2004). While this difference is surely not negligible, it shows that the distinct jump in flux magnitude is reproduced and therefore not a matter of methodological differences. Flux partitioning, however, is affected much more, with differences of $490\,\mathrm{g\,C\,m^{-2}\,a^{-1}}$ for ecosystem respiration. This can be partly explained with a potential overestimation of night-time respiration (and therefore also extrapolated day-time respiration) due to the usage of the u_*-criterion (see Chap. 12), and underlines the huge variability among different approaches.

Although different locations and instrumentations may be one reason for the behaviour of the fluxes in the three periods, modelling approaches in 1998, 2003, 2007, 2008 and 2011 with the ACASA model (see Chap. 16) show similar results of comparisons, at least for day-time data of *NEE* between modelled and measured fluxes in all years. This suggests that the fluxes were reasonable and the differences, attributed either to changes in forest structure or climate, can be reproduced with a process-based model. Also R_{eco} seems to be realistic, as Rebmann et al. (2004) compared the respiration measured using the eddy-covariance method with the sum of the soil efflux (chamber measurements, Subke and Tenhunen 2004) and the modelled wood and foliage respiration for the years 1997–1999, and found good agreement.

4.3.4.3 Influential Factors of Regional Relevance

Another reason for the trends found that has regional relevance is, of course, climate change. It is shown in Chap. 3 that the site is affected by climate change, mainly through an increase of the temperature in all months and drought periods occurring mainly in spring, while the annual precipitation sum is nearly constant. We have observed the largest increase in fluxes in summer, where no significant trend in precipitation could be found. It is reasonable to assume that higher temperatures in summer could increase carbon uptake in this well-watered region, where the mean temperature for the period 1971–2000 is 5.3 °C. On the other hand, the parameterization coefficient α, which we used to scale E_{p} to *ET* in order to gap-fill the measured *ET* series, was 0.396 for 2002–2006 and 0.481 for 2007–2014. This, together with the fact that E_{p} shows no trend (which is also true for summer only), suggests that the increase in *ET* seems to be unrelated to environmental conditions.

Keenan et al. (2013) attribute an observed positive trend of *NEE* to an increasing carbon dioxide concentration. They were able to show an increase in water use efficiency as leaf intercellular CO_2 concentrations rise, which may cause a higher carbon uptake. The authors showed a significant increase of *NEE* for five North

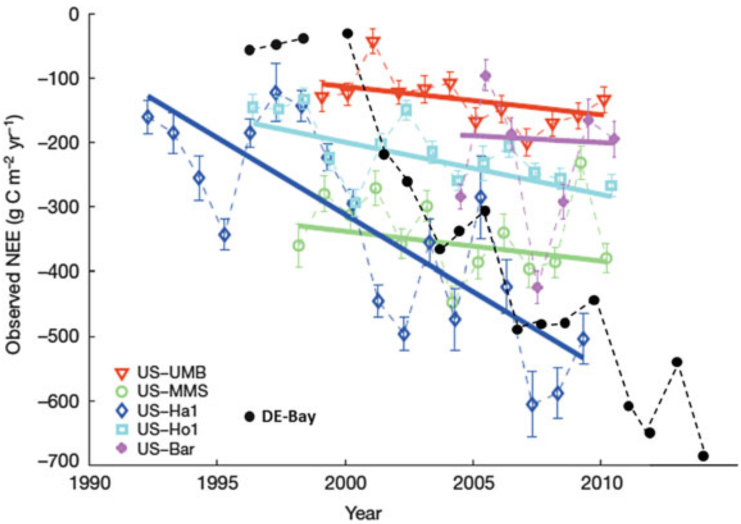

Fig. 4.9 Long-term increase in net ecosystem exchange *NEE* at five natural forest sites in the north-eastern USA according to Keenan et al. (2013) and at the Waldstein–Weidenbrunnen site (DE-Bay). Remark: only the station (US-Ho1, Howland Forest) is an evergreen coniferous forest, the others are deciduous broad-leaf forests (Published with kind permission of © Nature Publishing Group 2013, All rights reserved)

American stations, and the Waldstein–Weidenbrunnen data also fits with their data (Fig. 4.9). Therefore, an increase of the atmospheric carbon dioxide concentration at Waldstein–Weidenbrunnen from 360 to 400 ppm (1997–2015) could potentially contribute to rising fluxes. We assume that the growth at Waldstein–Weidenbrunnen is not limited by nitrogen availability, as this was the case at the beginning of the time series (Matzner 2004), and atmospheric concentrations decreased only slightly (see Chap. 3). We calculated the ecosystem-scale water use efficiency $WUE = GPP/ET$, using only data from April to September, using only measured *ET* (and *GPP* was inferred from measured *NEE* only), and rainy days as well as the days after were excluded to ensure that measured *ET* mainly accounts for transpiration. *WUE* for 2002–2014, however, ranges from 3.5 to $4.2\,\mathrm{g\,C}\,(\mathrm{kg\,H_2O})^{-1}$ with no visible trend, and even a vague decreasing tendency. Similar to the method used by Keenan et al. (2013), we also calculated the inherent water use efficiency by multiplying *WUE* with E_p in order to eliminate the influence of atmospheric demand, but this does not change the situation. This means that reasons other than rising CO_2 levels play an important role.

A very conservative parameter is the carbon use efficiency (*CUE*)—the ratio of net ecosystem exchange and gross primary production. Kutsch and Kolari (2015) made a re-analysis of the investigations by Fernández-Martínez et al. (2014) and found that nutrient availability has some influence on *CUE* (not as large as postulated by Fernández-Martínez et al. 2014), and a strong dependence on the heterogeneity (in altitude) of the area in the vicinity of the station. They further

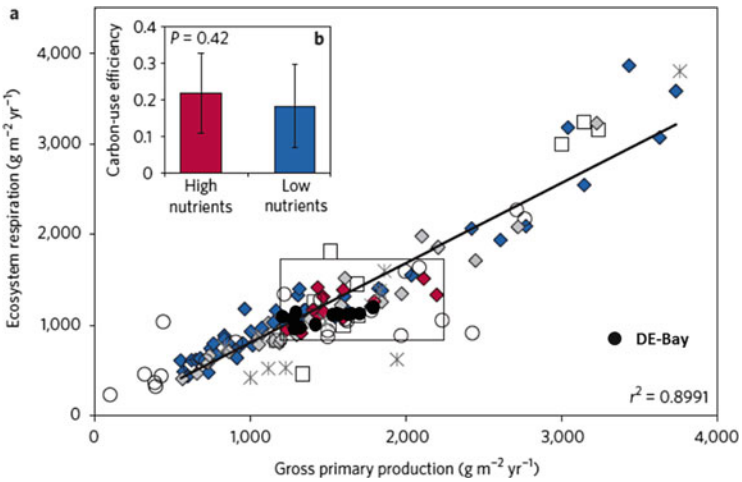

Fig. 4.10 Ecosystem respiration R_{eco} plotted vs. *GPP* for the remaining 82 sites according to Kutsch and Kolari (2015) and for the Waldstein–Weidenbrunnen site (DE-Bay). (**a**) *Red*: sites with high nutrient availability. *Blue*: sites with low nutrient availability. *Grey*: sites with medium nutrient availability. *Open squares*: sites removed owing to bad data quality and unclosed carbon balance that could not be corrected. *Open circles*: removed sites younger than 15 years. *Grey stars*: removed sites with complex terrain. (**b**) Average CUE for sites with low and high nutrient availability with a *GPP* between 1200 and 2300 g C m^{-2} a^{-1} (Published with kind permission of © Nature Publishing Group 2015, All rights reserved)

conclude that a reasonable range of *CUE* is between 0 and 0.3 and a strong relationship exists between *GPP* and R_{eco}. In Fig. 4.10 we add the Waldstein–Weidenbrunnen data to the figure of R_{eco} vs. *GPP* by Kutsch and Kolari (2015). The data from 2002 to 2006 fit well in the relationship found by Kutsch and Kolari (2015), and the data from 2008 to 2014 are still within the observed range, and closer to the data from sites which are rich in nutrients. *CUE* increases significantly at the Waldstein site, with $CUE = 0.23 \pm 0.04$ (2002–2006) and $CUE = 0.34 \pm 0.03$ (2008–2014). This implies that an increase of the heterogeneity in 2007 caused by the wind-throw, and perhaps subsequently enhanced nutrient availability could be responsible for the rising *NEE* and *CUE* at the Waldstein site.

4.4 Conclusion

A long-term data set of eddy-covariance measurements of carbon dioxide and water vapour exchange has been compiled for the Waldstein–Weidenbrunnen site (DE-Bay). While measurements from 1997 to 2001 have already been published, we analysed the years from 2002 until 2014 in a uniform manner with respect to data selection and quality control, processing and gap-filling. Within the latter, gross primary production *GPP* as well as ecosystem respiration R_{eco} has been estimated with standard flux partitioning algorithms.

The Waldstein–Weidenbrunnen site was a carbon sink in all years, while magnitude and variance of net uptake (−*NEE*) increased significantly from values around 40 g C m^{-2} a^{-1} for 1997–1999 up to 615 ± 79 g C m^{-2} a^{-1} for 2011–2014. This is related to a strong increase in *GPP*, while R_{eco} is slightly enhanced. Evapotranspiration *ET* follows the *NEE* trend coherently, with average fluxes ranging from 277 ± 44 mm a^{-1} (1997–2001) up to 493 ± 60 mm a^{-1} (2008–2014), while atmospheric demand does not drive the change.

We discussed various potential drivers for this development, namely instrumentation issues, forest stand history and climate change. Instrumental and methodological problems seem to play a minor role and could not explain the huge flux variability. Climate variability and change do indeed play a role at the site, as warming and rising CO_2-concentrations are consistent with the observed trend. The effects, however, cannot be disentangled from site-specific changes such as the recovery from forest decline after liming and an increase in heterogeneity after a wind-throw, as well as structural change within the under-storey, which are likely primarily responsible for the harsh changes in the observed dynamics. This attempt has been made here using only the flux data as the information source, with a more general discussion given in Chap. 19. Although "know thy site" is already a commonplace aphorism regarding long-term flux stations, there is a more general problem behind it, as a transition from an "ideal" to a disturbed or heterogeneous site is surely not a singular occurrence and therefore a systematic bias in regional studies using multiple sites is likely.

The presented data set suffers from problems in the measurements, creating large and systematic gaps in the winter-time and raising the need for assumptions about a temperature threshold for winter-time assimilation, which cannot be proved with the current data set. The uncertainty in *NEE* measurements therefore by far exceeds the 50 g C m^{-2} a^{-1} error proposed by Baldocchi (2003) for ideal sites. Nevertheless, the visible variation and trends should be robust due to consistent data processing, and the comparisons with other sites show that our estimates are realistic.

The Waldstein–Weidenbrunnen site has been intensively studied for a long time and large, detailed data sets exist from intensive observation campaigns. A long-term flux data set as presented in this chapter offers the opportunity to put these experiments in a temporal context and therefore create a better connection among those campaigns. The data set provides a comprehensive basis for water balance studies (see Chap. 15). Despite the trend found in the series there is a high inter-annual variability in the fluxes of *NEE* and *ET*, presumably following climatic drivers, which should be investigated in more detail. Seasonal trends of precipitation as detected in Chap. 3, however, do not influence the annual *ET* budgets. Furthermore, model studies can be deployed with varying climate and stand structure to quantify the influence of the different drivers at the Waldstein site. Such investigations could bring more generality into a case study at a unique location, having a special history.

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