10 years of eddy covariance and biometric carbon flux measurements in Croatia

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1.) INTRODUCTION

- Enhanced exploitation of fossil fuels since the beginning of the industrial revolution led to an increase in the atmospheric content of CO_2 from ~280 ppm at the beginning of 18th century to almost 370 pm at the end of the 20th century
- This increase in the atmospheric concentration of CO_2 influenced by human activity is considered as the main driver of the recent climate changes on Earth

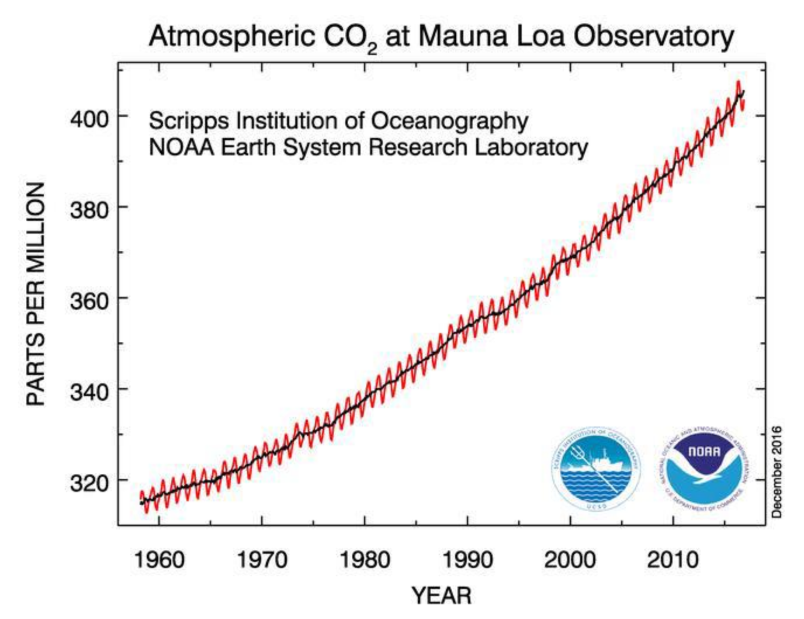


Figure 1: Global average atmospheric CO_2 mixing ratio (red line) with long term trend of growth (black line) [NOAA website 2016]

- Global forests act as a carbon sink [Pan et al. 2011]

- Canadell et al. [2007] have calculated that in the period from 2000 to 2006, global forests were a global sink of carbon of 2.7 Pg C (6 yr)$^{-1}$ what corresponds to approximately 30% of the total anthropogenic CO_2 emissions during that period

- The potential of forest to act as a carbon sink in the future is uncertain, either due to possible saturation effect [Nabuurs et al. 2013], or worse, as a consequences of climate change which would result in directive negative economic impact [Hanewinkel et al. 2013] → Monitoring of global forest productivity and understanding year-to-year variability in carbon sequestration became very important task

- Development of eddy covariance (EC) technique has greatly facilitated calculation of carbon budgets in the global forests and today EC technique is a widely used standard tool for estimation and monitoring of high frequency (typically half-hourly) carbon and water fluxes within the terrestrial ecosystems [Aubinet et al. 2000, Baldocchi et al. 2001, 2003]

1.1 EC method

- EC technique is a micrometeorological method for direct measurement of momentum, heat and mass exchange between a flat horizontally homogeneous surface and the overlying atmosphere [e.g. Baldocchi et al. 2001, 2003, Aubinet et al. 2000, 2012]
- Under this kind of conditions, net transport between the surface and atmosphere is one-dimensional and the vertical flux density can be calculated by the covariance between turbulent fluctuations of the vertical wind speed component and the quantity of interest [e.g. Aubinet et al. 2012]

$$F_c = \overline{w'c'}$$

- Implementation of the EC technique is very complex
- Measurements are not perfect, and thus all measurements are subject to errors or uncertainties
- High frequency raw data often contain spikes, constant and non-physical values, dropouts and noise

1.2 Carbon fluxes in ecosystem

- Gross primary productivity, *GPP*, is the main positive carbon flux in the ecosystem and it denotes CO_2 assimilation by photosynthesis
- The main negative carbon flux, ecosystem respiration – R_{ECO}, denotes the amount of carbon which is released from the ecosystem through the respiration processes. R_{ECO} is a sum of the respiration of the plants (autotrophic respiration, *Ra*) and decomposition of dead organic matter (heterotrophic respiration, *Rh*)
- After subtracting the autotrophic respiration of plants from *GPP*, what remains is called net primary productivity, *NPP*, and it is a measure of carbon stored in biomass within the ecosystem in a given time
- By subtracting R_{ECO} from *GPP* we obtain net ecosystem productivity, *NEP*. *NEP* is the measure of the amount of carbon that is accumulating in (positive *NEP*) or is lost from (negative *NEP*) the ecosystem if in the observed period there was no loss of carbon from the ecosystem due to e.g. harvesting, carbon leaching or fire. *NEP* is equal to negative of net ecosystem exchange, *NEE*, of carbon between the atmosphere and the ecosystem

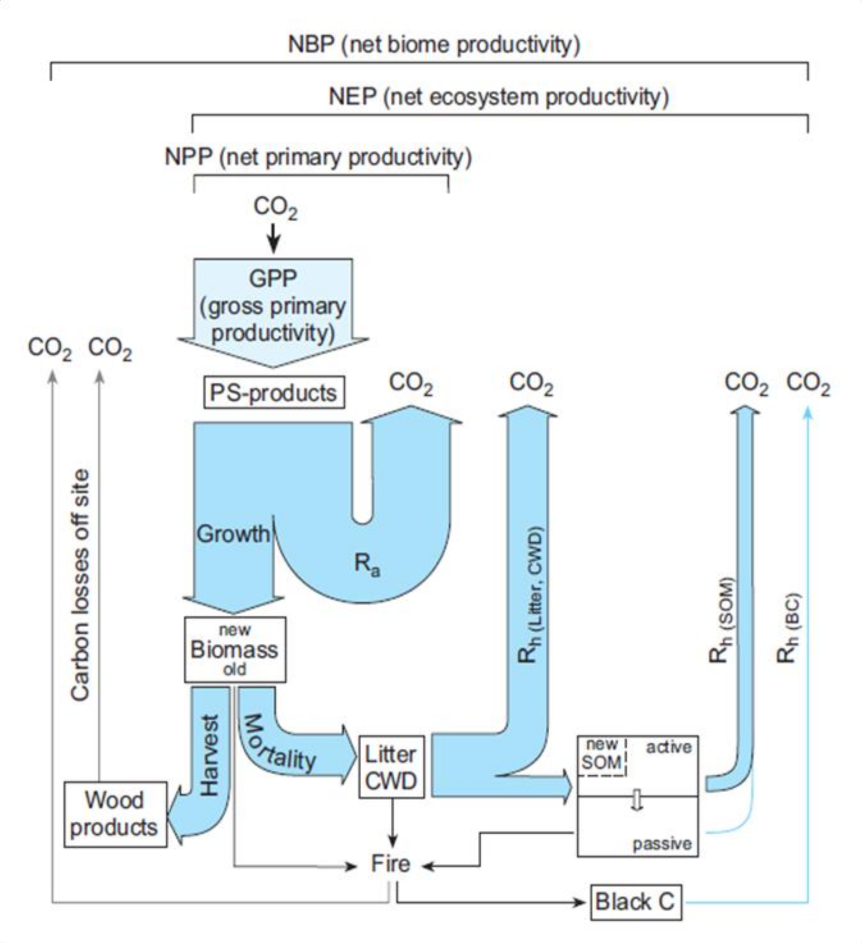


Figure 2. Carbon flow through the ecosystem (from [Schulze 2005], page 435)

2.) MOTIVATION

- The forested area in Croatia amounts to 2.493 million Ha what makes 47.5% of its total land area

- Lowland forests of pedunculate oak (*Quercus robur* L.) are making 32% of growing stock in Croatia [Croatian Forests Ltd. 2017] and they are the most valuable forests in Croatia

- They appear to be the most productive ecosystems in Croatia and represent an important economic resource for the state and local community [Marjanović et al. 2011], thus monitoring of their productivity and response to climate changes is very important

2.) RESEARCH AREA

- The research was carried out in Jastrebarsko forest which is a part of the forest complex of Kupa River basin, located approximately 35 km SW from Zagreb, near the town of Jastrebarsko

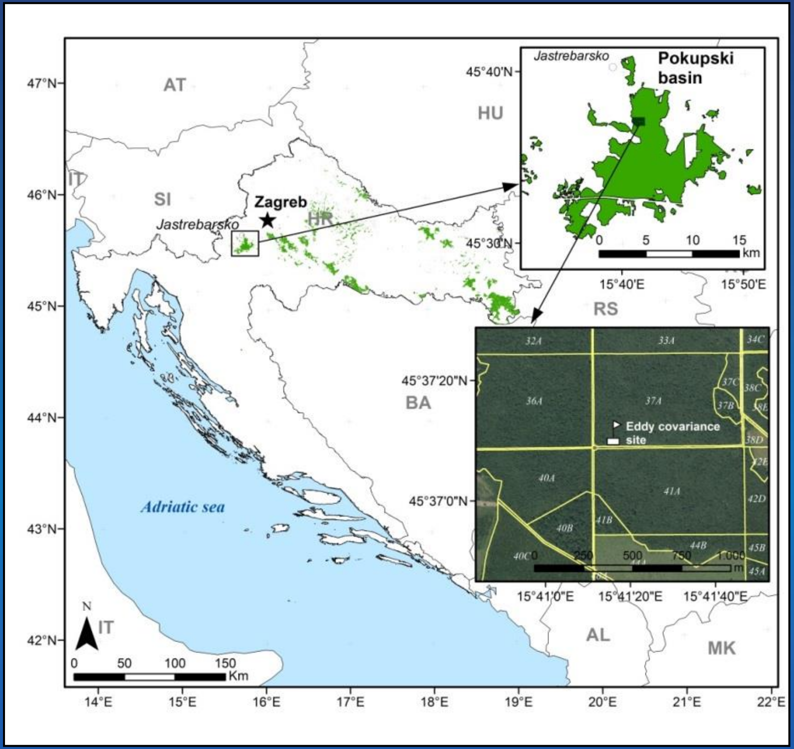


Figure 3. Location of the river Kupa basin within which Jastrebarsko forest is located

Figure 4. EC tower with instruments

- The dominant tree species in the basin is Pedunculate oak, with a significant share of other species, namely Common hornbeam (*Carpinus betulus* L.), Black alder (*Alnus Glutinosa* (L.) Geartn.), and Narrow-leaved ash (*Fraxinus angustifolia* Vahl.). There is also an understory of hazel (*Corylus avellane* L.) and Common hawthorn (*Crataegus monogyna* Jacq.)
- Oak forests in this area are managed in 140 year-long rotations, ending with two or three regeneration cuts during the last ten years of the rotation, which secures a continuous cover of forest soil
- The terrain of the Kupa River basin is mainly flat, with altitudes ranging from 106 m above sea level at the central part of the basin up to 120 m and 130 m above sea level
- According to the Köppen classification, the climate of the area is maritime temperate climate (Csa)
- Experimental station, EC tower is located in young (35-44 years old), managed stands dominated by pedunculate oak
- Tower has been erected in 2007 as a part of project Carbon-Pro [Marjanović et al. 2011] and since then it provides meteorological and EC measurements
- Sampling frequency for EC measurements was 20 Hz
- Meteorological elements were measured at 30 s intervals and then half-hourly averaged by the CR1000 data-logger

- A network of 65 permanent circular plots has been set up in a 100 x 100 m^2 grid in management unit “Jastrebarski lugovi” around EC tower during the year 2007 and winter months of 2008
- A total of 643 dendrometer bands were installed on all trees with DBH (diameter at breast height) > 7.5 cm
- During the vegetation season cumulative stem circumference increment was measured with a precision of 0.01 mm using small callipers with an electronic display

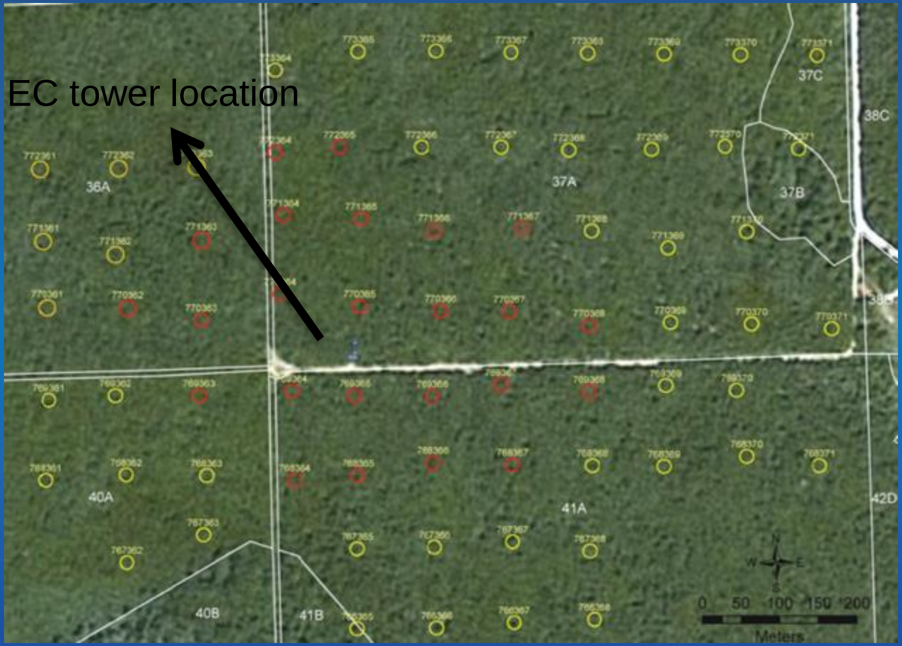


Figure 5. Circular plots network

Figure 6. Tree with dendrometer band

3.) METHODOLOGY

- Before flux calculation bad data was removed from raw EC measurements

- Fluxes of CO_2 were calculated according to EuroFlux standards [Aubinet et al. 2000, 2012]

- For flux calculation EdiRe software developed by Edinburgh University [http://www.geos.ed.ac.uk/homes/jbm/micromet/EdiRe] was used

- Main steps during flux calculation were:

  1.) Data quality control and stationarity test

  2.) Time lag compensation

  3.) Coordinate rotation (planar fit method, Wilczak et al. 2001)

  4.) Spectral corrections

  5.) WPL correction

- CO_2 (*Fc*) and water vapor (*LE* and *H*) fluxes were calculated as half-hourly averages

- Calculated flux data were initially checked for absolute limits and all data which were out of defined range were removed from further processing:

$$Fc < -50\ \mu\text{mol m}^{-2}\ \text{s}^{-1} \text{ or } Fc > 30\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$$

$$LE < -150\ \text{W m}^{-2} \text{ or } LE > 800\ \text{W m}^{-2}$$

$$H < -150\ \text{W m}^{-2} \text{ or } H > 500\ \text{W W m}^{-2}$$

$$Sc < -50\ \mu\text{mol m}^{-2}\ \text{s}^{-1} \text{ or } Sc > 30\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$$

- Carbon storage term (*Sc*) was added to calculated flux to obtain *NEE*

- To obtain high quality fluxes two filtering procedures of *NEE* were performed –> u* filtering and procedure described in Papale et al. 2006

- Gaps in time series of *NEE* were filled using standard MDS (Marginal Distribution Sampling) technique which is available as online tool [http://www.bgc-jena.mpg.de]

- Same online tool was used for partitioning *NEE* into *GPP* and R_{ECO}

- *NPP* was calculated as difference between heterotrophic respiration (Rh) and NEE

- Using data for *Rh* from Marjanović et al. [2011] and R_{ECO} obtained from NEE flux partitioning for 2008 and 2009, Ra and the ratio Rh/R_{ECO} were calculated and the average ratio of 39.19% was then used for the partitioning of R_{ECO} into *Rh* and *Ra* for the remaining years

$$NPP_{EC} = Rh - NEE = 0.3919 \cdot R_{ECO} - NEE$$

- For validation of EC measurements, a biometric estimate of the net primary productivity (NPP_{BM}), which was built on periodic measurement and simple modelling, was compared with NPP_{EC}

- For flux footprint analysis 3D stochastic dispersive Lagrangian model was used [Kljun et al. 2015]

4.) RESULTS

4.1. Meteorological measurements

- During the study period, average air temperature was 11.23°C, while average precipitation was 1058 mm

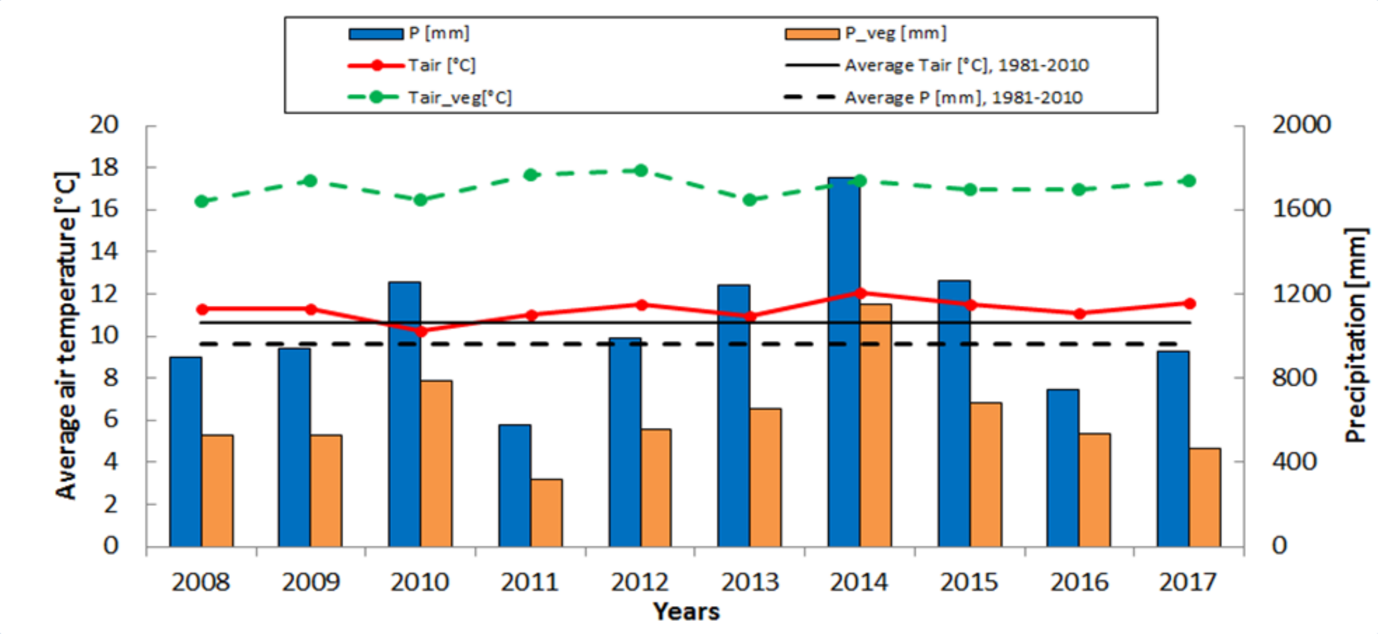


Figure 6. Average annual air temperature and total annual precipitation from 2008-2017.
Black lines mark average air temperature and average precipitation for period 1981-2010 (Data from Croatian Meteorological and Hydrological Service)

4.2 Flux footprint analysis

- Flux footprint analysis showed that the distance from the tower, which encircles the area encompassing 90% of the footprint, was approximately 400 m before the elevation of the tower and 600 m after the tower was elevated

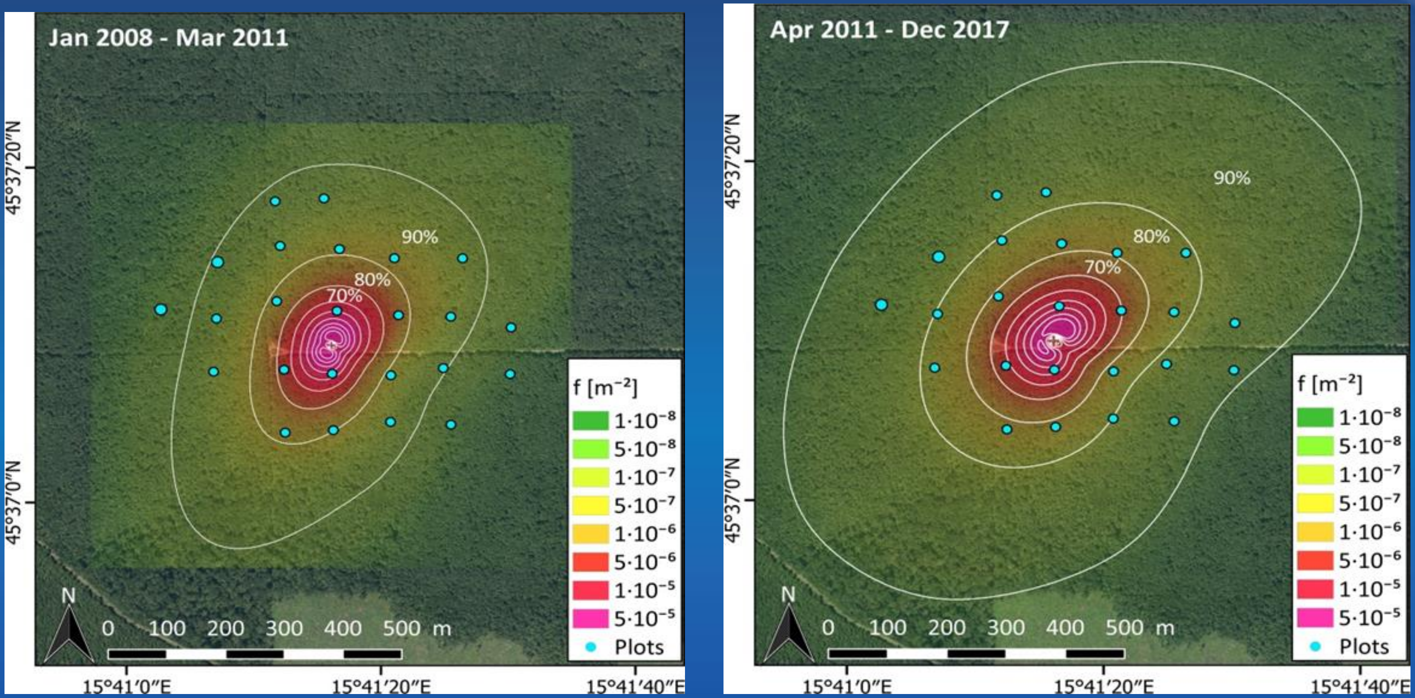


Figure 7. Flux footprint; a) before the elevation of EC tower (23 m); b) after the elevation of EC tower (27 m); little cyan circles mark the location of 24 circular plots

4.2 NEE of CO_2

- To get a closer into how daily cycle of *NEE* varies by months, half-hourly *NEE* values were averaged by time of day, month and year, so every point in Fig. 8 represents a mean of the half-hourly values of *NEE* in the specific month through ten years

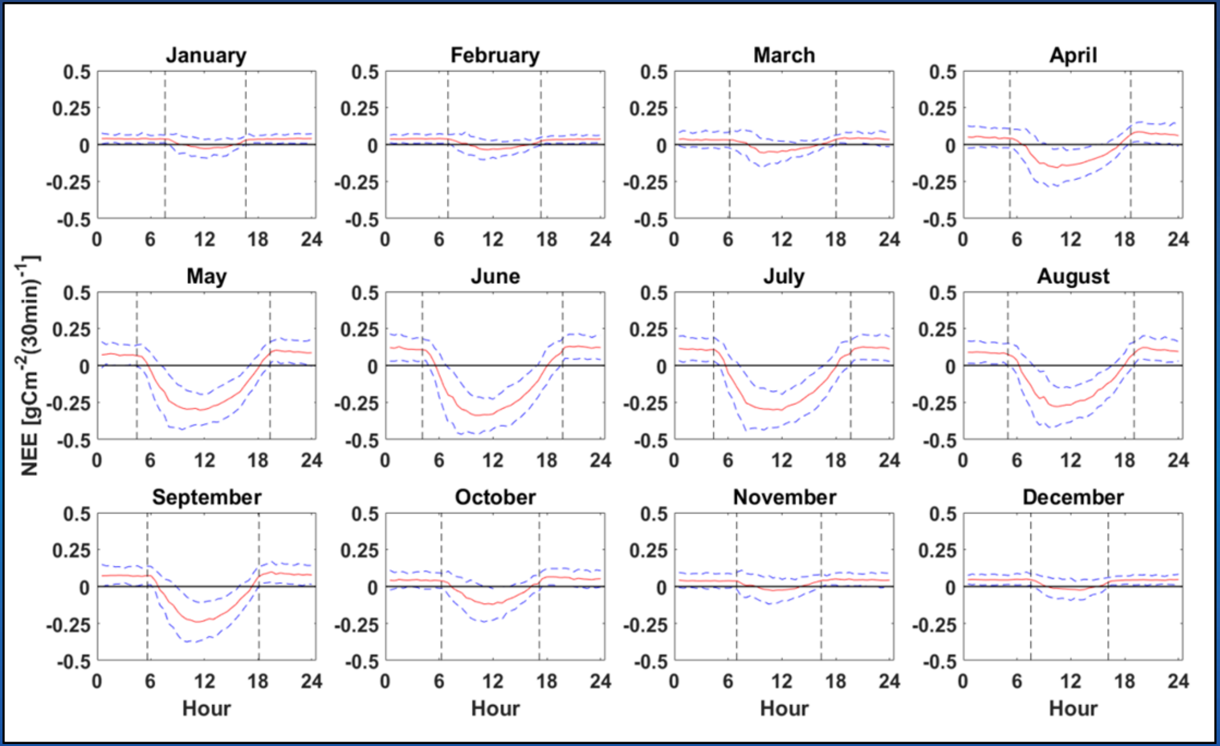


Figure 8. Mean diurnal variation of *NEE* by months during the years 2008 to 2017; blue dashed line marks 1 standard deviation; vertical dashed line marks the time of sunrise and sunset on the 15th day of the month

On average, half-hourly values of *NEE* were lowest during the dormant part of the season which entirely includes months January, February, November and December. With the appearance of leaves at the end of March and the beginning of April, the *NEE* starts to become more negative, especially during May, and reached on average the highest absolute values during June when vegetation is fully developed. *NEE* remained high on average during July and August. During November, after leaves are fully rejected, half-hourly values of *NEE* are small.

- Daily values of *NEE* were summed to obtain annual net carbon budgets
- Annual sums of *NEE* ranged from -147 ± 13 gC m^{-2} yr^{-1} in 2017 to -496 ± 15 gC m^{-2} yr^{-1} in the year 2009
- The average sink of carbon over the study period was -319 ± 30 gC m^{-2} yr^{-1}, while the overall net sink of carbon was -3195 gC m^{-2} $(10yr)^{-1}$.

Table 1. Annual sums of NEE [gC m^{-2} yr^{-1}] for years 2008-2017

Year	NEE ± SE [gC$m^{-2}$$yr^{-1}$]
2008	-352 ± 13
2009	-496 ± 15
2010	-286 ± 14
2011	-353 ± 14
2012	-261 ± 14
2013	-356 ± 13
2014	-232 ± 14
2015	-373 ± 13
2016	-339 ± 13
2017	-147 ± 13
Average value	-319 ± 30
Sum	-3195[gC m^{-2} $(10yr)^{-1}$]

4.3 Partitioned fluxes R_{ECO}, GPP and NPP_{EC}

- Highest daily values of largest negative carbon flux, ecosystem respiration R_{ECO}, were achieved in the summer, while during dormant season daily values of R_{ECO} were significantly lower
- Higher daily R_{ECO} values during some winter days are the consequence of higher air and soil temperatures in that period
- Secondary peaks which occur during autumn are probably the result of decomposition of new litterfall

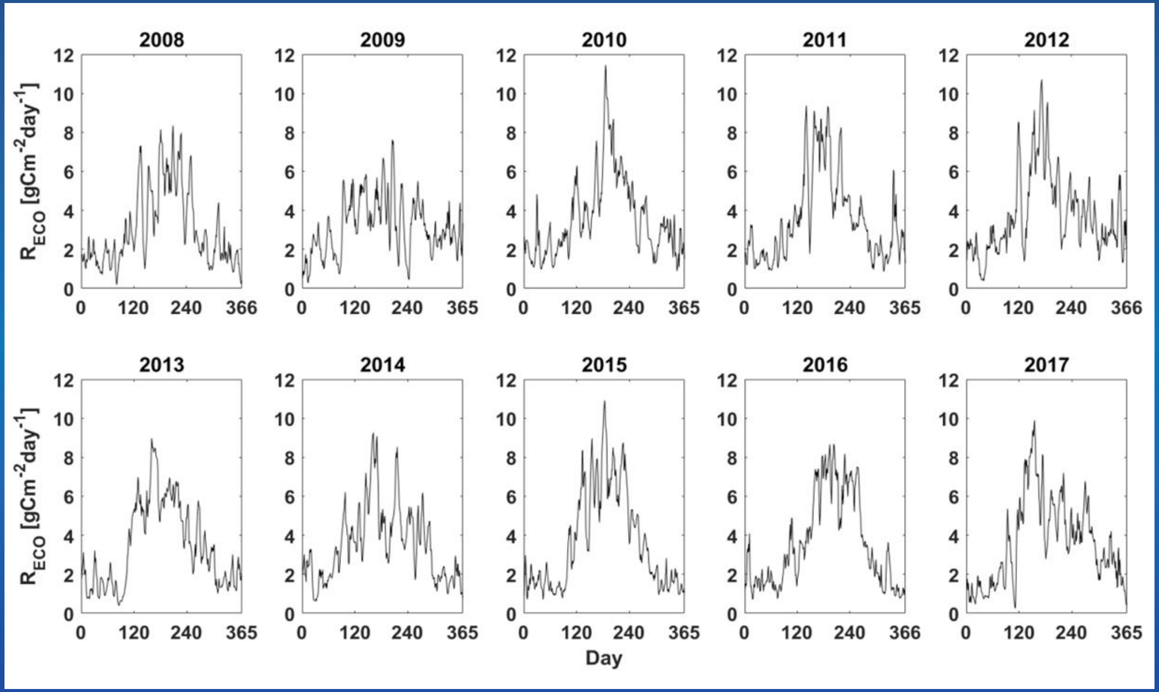


Figure 9. Annual variation of daily sums of R_{ECO} [gC m^{-2} day^{-1}] in Jastrebarsko forest, 2008-2017

- Highest annual sums of R_{ECO} of 1402 gC m^{-2} yr^{-1} were obtained in 2015 what is in good agreement with the higher air temperatures in that year, while the lowest R_{ECO} of 1117 gC m^{-2} yr^{-1} was obtained in 2008.
- The average R_{ECO} over the ten years of measurement was 1275 ± 94 gC m^{-2} yr^{-1}

Table 2. Annual sums of R_{ECO}, R_a and R_h [gC m^{-2} yr^{-1}], 2008-2017

Year	R_{ECO} [gC$m^{-2}yr^{-1}$]	R_a [gC$m^{-2}yr^{-1}$]	R_h [gC$m^{-2}yr^{-1}$]
2008	1117	679	438
2009	1126	685	441
2010	1329	808	521
2011	1289	784	505
2012	1382	840	541
2013	1275	775	500
2014	1290	785	506
2015	1402	852	549
2016	1305	794	512
2017	1236	752	484
Average value	1275 ± 94	775 ± 57	500 ± 37
Sum	12751 [gCm^{-2} $(10yr)^{-1}$]	7754	4997

- During dormant season daily values of *GPP* were small
- Carbon sequestration started with development of leaves in early spring which is manifested with a high increase in daily values of *GPP*
- Maximum rates of *GPP* were achieved during summer months
- After a peak in early summer, *GPP* started to decline slowly and dropped again to near zero after the leaf fall.

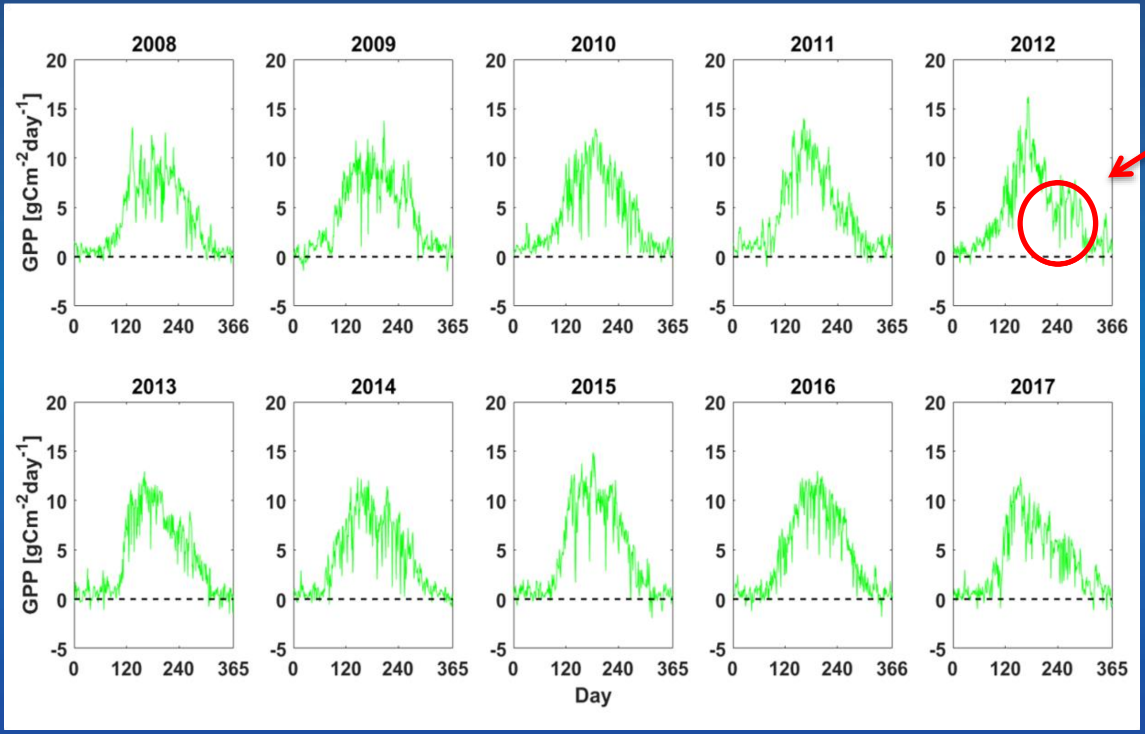
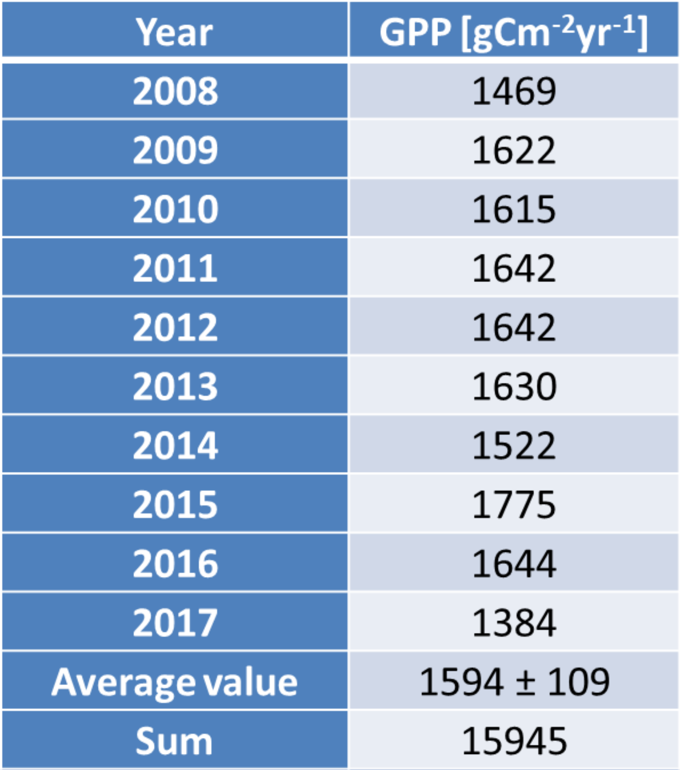


Figure 10. Annual variation of daily *GPP* [gC m^{-2} day^{-1}] in Jastrebarsko forest, 2008-2017

An interesting situation occurred during the summer 2012 when *GPP* has rapidly dropped to small values. This can be explained by a severe drought which occurred in the middle of August 2012.

- Annual sums of *GPP* ranged from lowest of 1384 gC m^{-2} yr^{-1}in 2017 to highest of 1775 gC m^{-2} yr^{-1} in 2015
- Average *GPP* during ten years of measurement was 1594 ± 109 gC m^{-2} yr^{-1}

Table 3. Annual sums *GPP* [gC m^{-2} yr^{-1}], 2008-2017



Year	GPP [gCm^{-2}yr^{-1}]
2008	1469
2009	1622
2010	1615
2011	1642
2012	1642
2013	1630
2014	1522
2015	1775
2016	1644
2017	1384
Average value	1594 ± 109
Sum	15945

- The yearly cycle of *NPP* followed the yearly cycle of *GPP*
- Highest daily values of *NPP* were also achieved in June and lowest during dormant season
- Negative *NPP* is possible and indicates that autotrophic respiration was stronger than *GPP*
- The situation of that kind occurred mainly during the cold part of the year when vegetation was in the state of dormancy

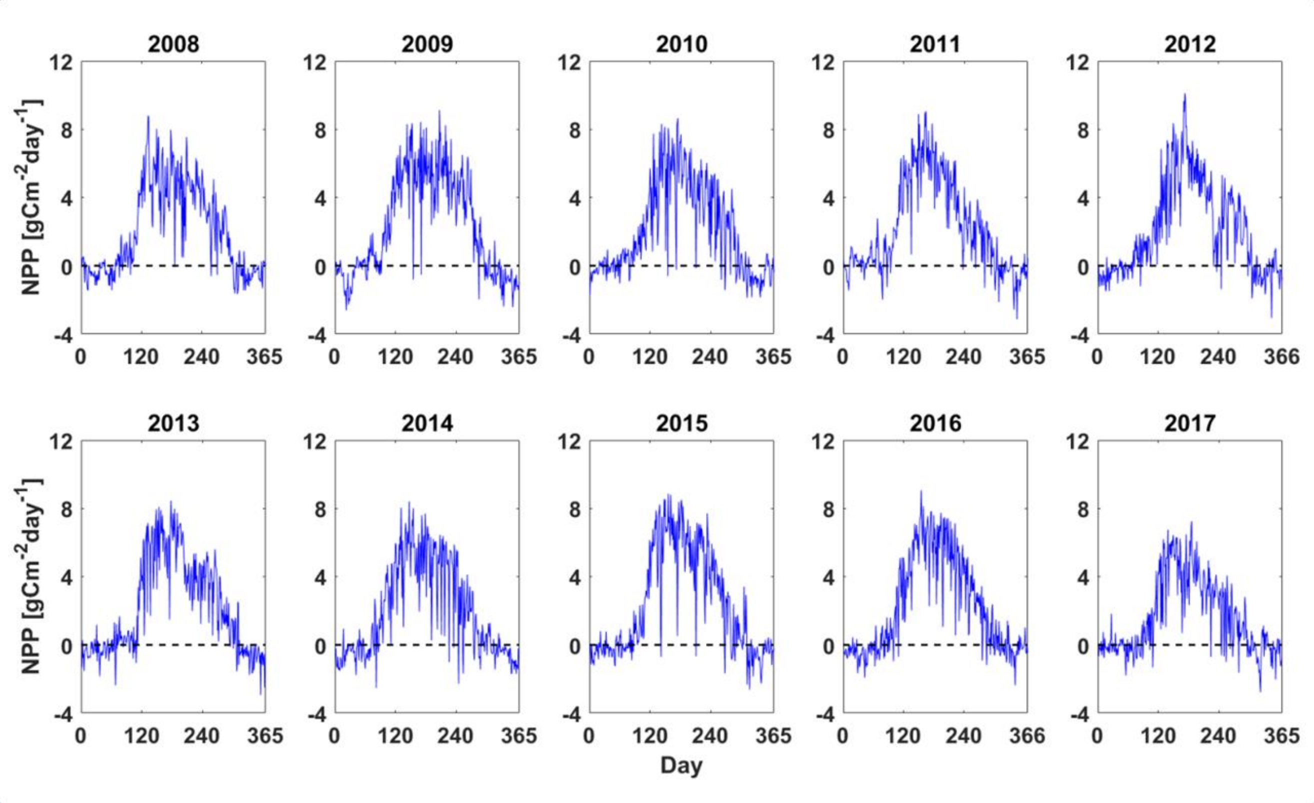


Figure 11. Annual variation of daily *NPP* [gC m-2 day-1] in Jastrebarsko forest, 2008-2017

4.4. Comparison of *NPP* estimates from EC and BM measurements

- The comparison showed good overall agreement (R^2=0.46), although EC estimates were higher in every year than the biometric one -> most probable reason for that -> NPP_{EC} includes the production of whole ecosystem (trees, understory and ground vegetation) with all of its above- and belowground carbon pools, while NPP_{BM} (in our study) includes only the production of trees, excluding fine roots and grasses

Table 4. Comparison of NPP_{EC} with NPP_{BM} for years 2008-2017

Year	NPP_{BM} [$gCm^{-2}yr^{-1}$]	NPP_{EC} [$gCm^{-2}yr^{-1}$]
2008	675 ± 26	790
2009	756 ± 33	937
2010	782 ± 33	807
2011	739 ± 32	858
2012	630 ± 28	802
2013	755 ± 49	855
2014	654 ± 31	738
2015	632 ± 26	923
2016	689 ± 34	850
2017	483 ± 34	632
Average	680 ± 88	819 ± 89
Sum	6795	8192

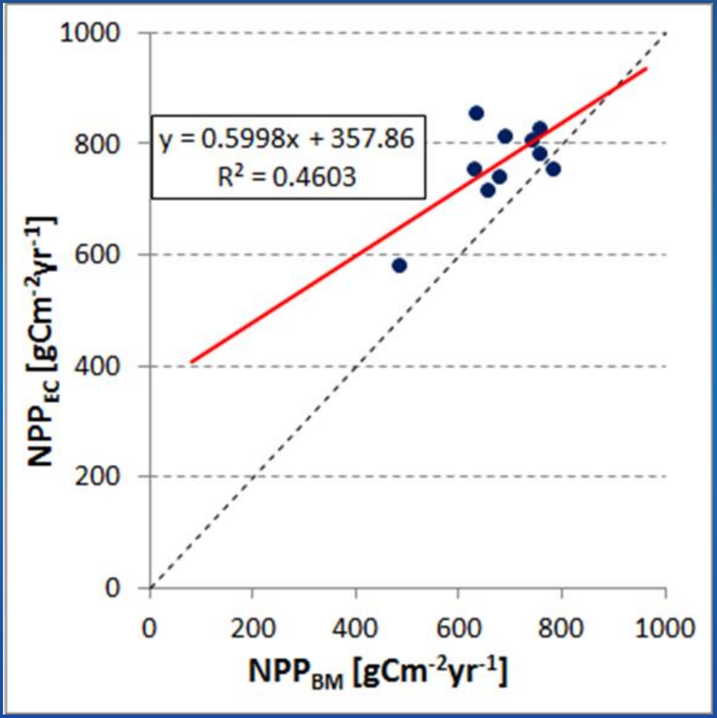


Figure 12. NPP_{EC} vs NPP_{BM}

- When comparing trends of two *NPP* estimates, we can see that NPP_{BM} has a stronger negative trend (-18.7 gC m^{-2} yr^{-2}) then NPP_{EC} (-10.7 gC m^{-2} yr^{-2})
- The probable cause of such trend in *NPP* could be the fact that the stands became denser and competition among trees for resources increased.

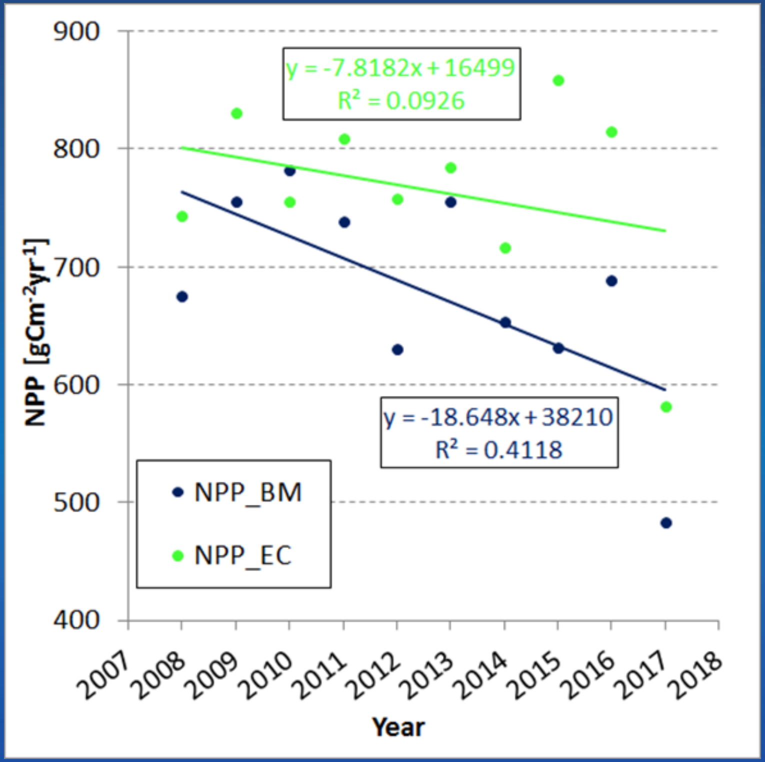


Figure 13. Negative trend of both *NPP* estimates

- Analysis of seasonal dynamic of *NPP* reveals clear difference in seasonal *NPP* dynamics from two independent estimates
- NPP_{BM} estimate represents biomass growth which uses carbohydrates from current assimilation as well as previously stored non-structural carbohydrates (NSC) [Gaudinski et al. 2009, Delpiere et al. 2016, Palacio et al. 2018]
- NPP_{EC} is primarily driven by canopy photosynthesis [Baldocchi 2003], therefore it reflects current accumulation of atmospheric carbon that can further be partitioned into structural growth and labile C storage [Gough et el. 2009]
- This is visible during the spring when NPP_{BM} starts before NPP_{EC} on the account of carbon reserves stored in previous years (Figure 13)
- Later in the vegetation season, stem growth slows down and even ceases, but forest ecosystem continued to absorb carbon, most likely in the NSC pool [Granier et al. 2008].
- NSC represent very important storage/reserve pool of carbon mostly used for spring growth [Delpierre et al. 2016, Palacio et al. 2018], but also important for overcoming unfavourable meteorological conditions, i.e. such as drought

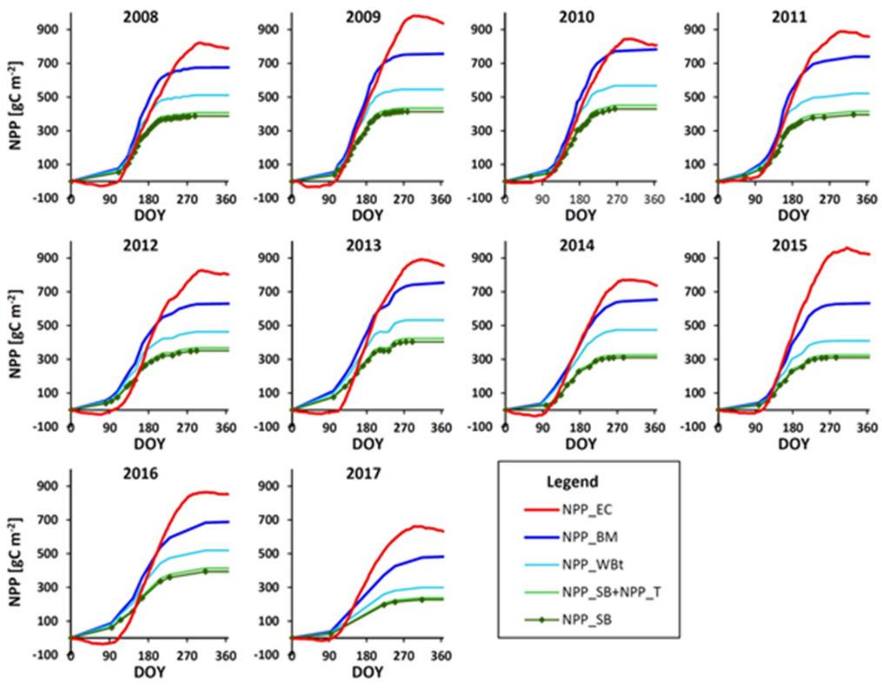


Figure 13. Comparison of cumulative *NPP* determined with EC technique (NPP_{EC}) and with biometric measurements (NPP_{BM})

5. CONCLUSIONS

- Micrometeorological eddy covariance experiment was implemented in young pedunculate oak stands to determine net ecosystem exchange of CO_2 between forest and overlying atmosphere
- Over the study period, young pedunculate oak stands were total sink of carbon of -3195 gC m^{-2} $(10yr)^{-1}$, while the average value of net sink was -319 ± 30 gC m^{-2} yr^{-1}
- High inter-annual variability of *NEE* was driven by meteorological conditions and length of growing season
- To validate EC measurements, *NPP* estimated from EC measurements (NPP_{EC}) was compared with *NPP* estimated from biometric measurements (NPP_{BM})
- The comparison showed good overall agreement (R^2=0.46), although NPP_{EC} was higher than NPP_{BM} in every year of measurement what indicates that NPP components which were not measured in this research (e.g. fine roots, grasses and understory bushes) significantly contribute to the ecosystem NPP
- Further research is needed on the contribution to *NPP* of fine roots and understory vegetation, partitioning of the ecosystem respiration into autotrophic and heterotrophic, as well as on the non-structural carbohydrates dynamics

6. LITERATURE

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