

Growing season length as a key factor of cumulative net ecosystem exchange over the pine forest ecosystems in Europe**

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Abstract. The Scots pine is one of the most important species in European and Asian forests. Due to a widespread occurrence of pine forests, their significance in the energy and mass exchange between the Earth surface and the atmosphere is also important, particularly in the context of climate change and greenhouse gases balance. The aim of this work is to present the relationship between the average annual net ecosystem productivity and growing season length, latitude and air temperature (t_{ay}) over Europe. Therefore, CO₂ flux measurement data from eight European pine dominated forests were used. The observations suggest that there is a correlation between the intensity of CO₂ uptake or emission by a forest stand and the above mentioned parameters. Based on the obtained results, all of the selected pine forest stands were CO₂ sinks, except a site in northern Finland. The carbon dioxide uptake increased proportionally with the increase of growing season length (9.212 g C m⁻² y⁻¹ per day of growing season, R² = 0.53, p = 0.0399). This dependency showed stronger correlation and higher statistical significance than both relationships between annual net ecosystem productivity and air temperature (R² = 0.39, p = 0.096) and annual net ecosystem productivity and latitude (R² = 0.47, p = 0.058). The CO₂ emission surpassed assimilation in winter, early spring and late autumn. Moreover, the appearance of late, cold spring and early winter, reduced annual net ecosystem productivity. Therefore, the growing season length can be considered as one of the main factor affecting the annual carbon budget of pine forests.

Key words: forest, carbon dioxide, eddy covariance, growing season length

INTRODUCTION

In the last decade the atmospheric CO₂ concentration increased about 1.5 ppm per year (NOAA, 2014). From the point of view of climate change, the increase in CO₂ in

the atmosphere is an unfavourable phenomenon, even if for plants growth and productivity stimulation can occur (Keenan *et al.*, 2014). In this context, special attention should be focused on forest ecosystems and their abilities to accumulate a significant amount of CO₂ from the atmosphere, up to 610 g C m⁻² y⁻¹ (Luysaert *et al.*, 2010). However, the amount of uptaken carbon (C) is strongly dependent on weather conditions (air temperature, precipitation, radiation) (Niu *et al.*, 2012), air quality (concentrations of CO₂, O₃ and N compounds) (Ciais *et al.*, 2010), tree species, soil type (Lal, 2005) and forest management practices (Jandl *et al.*, 2007).

The net ecosystem production (NEP), corresponding to the net amount of carbon dioxide exchanged between the forest ecosystem and the atmosphere, is the balance between the ecosystem respiration (R_{ECO}) and overall uptake in the photosynthesis process (gross ecosystem production-GEP). Therefore, to better understand the causes of the changes in the NEP fluxes over time, with respect to the meteorological conditions at particular sites, the authors attempt to determine the time frame of the growing season for each of the selected sites. In literature there are many definitions of the growing season or so-called uptake period (Barr *et al.*, 2009). For example, the growing season could be defined as a period during the year in which the gross ecosystem production (GEP) fluxes are at least 15% of the maximum annual rate (Coursolle *et al.*, 2012). Because of the lack of a standard criterion for determining the starting and the ending date of the growing season, the authors proposed here their own method of determining the growing season time frame.

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Research related to the influence of growing season length (GSL) on the annual (NEP_y) fluxes variability were carried out both across Europe (Churkina *et al.*, 2005) and locally – in such forest ecosystems as: boreal Scots Pine in Finland (Suni *et al.*, 2003), boreal Trembling Aspen (*Populus tremuloides*) in Canada (Chen *et al.*, 1999) we measured CO₂ fluxes using the eddy covariance technique above an old aspen (OA or broadleaf forest in the east of the USA (Dragon *et al.*, 2011). Despite the fact that the GSL for the above ecosystems was assigned by different methods, a positive linear correlation between these two quantities was observed – the GSL prolongation increased the NEP flux values. However, it should also be mentioned, that under some local conditions, which are characteristic in particular locations, the relation between GSL and NEP may show an opposite correlation, like an subalpine coniferous forest ecosystems (Hu *et al.*, 2010). The authors explain this phenomenon of water limitation in the sub-alpine ecosystem, resulting from the early snowmelt and low summer precipitation.

Taking into consideration the location of forest ecosystems on Earth, tropical, temperate and boreal forest ecosystems may be distinguished. Temperate forest ecosystems occur between 40 and 60° latitude, both in the northern and the southern hemisphere. In general, meteorological conditions in these latitudes can be characterised by: the average air temperature in summer months of 18-20°C, around 3-5°C in winter months and the annual precipitation of about 600 mm (Chapin III *et al.*, 2011). In case of boreal forests, which are located between 50 and 70° latitude, local climate is significantly diversified by the influence of the continental and marine air masses. In boreal forest, winter circulation is dominated by polar air masses, and in summer by temperate air masses, resulting in very cold winters (< -60°C temperature minima) and warm summers (> 30°C temperature maxima). The annual precipitation totals ranges from 300 to more than 1000mm, depending on the distance to the nearest ocean (Schulze *et al.*, 2009). Forest ecosystems in Europe, with respect of species composition, consist of pine to the extent of 50% (*Pinus spp.*). Because of described diversification of meteorological conditions in boreal and temperate forests, significant differences in the net ecosystem production can be expected. On the other hand, some species, like the Scots pine trees are well adapted to a wide range of meteorological conditions. Pine forests are spreading from Spain to the north of Finland, therefore, they are a relevant example for analyzing meteorological conditions influence on the annual NEP in forest across Europe, over a long period of time.

As nowadays longer data series and additional sites were available, compared to previous studies Luyssaert *et al.* (2007), we hypothesize that the growing season length could exhibit even stronger influence on the annual carbon uptake of pine-dominated European forest stands as reported in previous works.

MATERIALS AND METHODS

The analysis conducted in this study, involved pine-dominated forest stands only (*Pinus sylvestris* or *Pinus pinaster*) since pine is the most widespread tree genus in the northern hemisphere (Ceulemans *et al.*, 2003). In all selected sites the net CO₂ fluxes were measured by the eddy covariance (EC) technique.

To put it simply, the theory of the eddy covariance method assumes, that in the case of a notionally separated volume (eg a portion of air above a canopy), the molecules of a gas, such as CO₂, move constantly in both directions (eddies are created), and that at the same time the concentration of the gas in that volume remains unchanged. In these conditions one is dealing with a stationary flow, which means that it does not change in time and is equal at different heights inside the analyzed volume. If we assume that this condition is met we can then measure the exchange between the atmosphere and the surface of interest, which is considered as the source area of the measured EC signal. This area is commonly known as a footprint. In a real-life situation a turbulent flow in the atmosphere is chaotic and the eddies propelling turbulence differ in size and speed. In principle, the EC methodology assumes, that at chosen averaging time interval, the product of vertical wind velocity and the quantity of the substance, heat or momentum carried by the air should be equal to the substance, heat or momentum flux respectively. The vertical flux of a scalar constituent (CO₂) is calculated as follows:

$$F = \overline{w' c'}, \quad (1)$$

where: w – is the vertical wind speed (m s⁻¹) and c – is the quantity of interest (mg m⁻³) (gas concentration). The overbar denotes the time averaging, and the prime denotes the fluctuation of the instantaneous value from this average:

$$w = \overline{w} - w'. \quad (2)$$

The EC technique requires fast response instruments, sampling typically at 10-20 Hz (Aurela *et al.*, 1998). In recent years the EC technique has been developed the most in comparison to other measuring methods applied for the assessment of mass and energy fluxes (Aubinet *et al.*, 2000).

In order to compare particular CO₂ fluxes of different ecosystems from the CarboEurope-IP database the following sites were selected: Sodankylä (Finland), Hyytiälä (Finland), Norunda (Sweden), Tuczno (Poland), Loobos (The Netherlands), Brasschaat (Belgium), Le Bray (France), San Rossore (Italy) (Fig. 1). They are located in both temperate and boreal forests. For these sites the correlation between the average seasonal course of NEP (as the average for the period 2003-2007) and meteorological conditions was examined. Furthermore, a seasonal course of 5-years average values of air temperature and precipitation was presented. Additionally, to compare the NEP fluxes across Europe the average net ecosystem exchange total values for



Fig. 1. Location of selected sites from the CarboEurope-IP.

each measurement year were calculated. The same applies to the 5-years average (for the years 2008-2012) NEP values which were later compared with the NEP fluxes from the Tuczno forest site. The data from these periods were selected because of their availability at all sites. We also reduced the number of years to five, because it was the longest reference time at the newest site – Tuczno. Our intention was to give the same weight to each site.

Data concerning fluxes and meteorological variables (completed by using the Marginal Distribution Sampling method) were downloaded from the European fluxes database (Level 4 data-<http://gaia.agraria.unitus.it/home>). Selected sites characteristics are presented in Table 1. The data were collected and processed in accordance with the recommendations of Papale (Papale *et al.*, 2006). Individual data collection methodologies for each site were described in previous studies Carrara *et al.* (2003), Schelhaas *et al.* (2004) and Suni *et al.* (2003).

The analyses presented in this assessment are based on the daily means and sums of data provided by the database. The average values of raw data were computed in Microsoft

Table 1. General description and site characteristics of the selected pine forest stands

Localization	Le Bray ¹	San Rossore ²	Hyttiälä ³	Sodankylä ⁴	Brasschaat ⁵	Loobos ⁶	Norunda ⁷	Tuczno ⁸
Species composition (%)	<i>Pinus pinaster</i>				<i>Pinus sylvestris</i>			
Air temperature (°C) long term	13.5	15.1	3.8	-1.0	9.8	9.8	5.5	7.8
Air temperature (°C) 5 years average	13.1	15.3	4.5	0.9	11.5	10.4	6.7	9.8
Precipitation (mm) long term	900	918	709	500	750	786	530	625
Precipitation (mm) 5 years average	926	642	488	346	696	854	560	583
Forest stand age (years)	42	45	46	65	83	103	114	54
LAI	2.6-3.1	4.0	3.0	1.2	1.3	1.9-2.2	5.0	1.1-1.2
Tree height (m)	17	18	12	13	23	15	25	23
Forest stand density (trees ha ⁻¹)	500	567	2500	2100	375	360	600	900
NEPy (g C m ⁻² year ⁻¹)	350	532	228	-57	122	450	21	645
GEPy (g C m ⁻² year ⁻¹)	1731	1870	1013	569	1178	1567	1350	2071
R _{ECO} (g C m ⁻² year ⁻¹)	1384	1338	785	626	1056	1117	1321	1426
Related literature	(Stella <i>et al.</i> , 2009)	(Chiesi <i>et al.</i> , 2005)	(Suni <i>et al.</i> , 2003)	(Köster <i>et al.</i> , 2013)	(Nagy <i>et al.</i> , 2006)	(Elbers <i>et al.</i> , 2011)	(Lundin <i>et al.</i> , 1999)	(Ziemblińska <i>et al.</i> , 2013)

Localization (latitude/longitude, elevation): 1 – France 44°5'N 0°5'E, 60 m a.s.l.; 2 – Italy 43°43'N 10°17'E, 6 m a.s.l.; 3, 4 – Finland 61°5'N 24°17'E, 170 m a.s.l.; 67°21'N 26°38'E, 180 m a.s.l.; 5 – Belgium 51°18'N 4°31'E, 16 m a.s.l.; 6 – Netherlands 2°10'N 5°44'E, 25 m a.s.l.; 7 – Sweden 60°5'N 17°29'E, 45 m a.s.l.; 8 – Poland 53°11'N 16°05'E, 180 m a.s.l.

Excel (2007). Statistical analyses of the annual averages and totals, were performed using dynamic scripts in R statistical software, version 3.1.1, R Core Team (2014). At the outset using last square method, linear models coefficients (slope and intercept), was calculated. For each model, coefficients of determination (R^2), defined as the square of the Pearson correlation coefficient, was also computed. In order to verify the slope of the lines are not equal 0, the F-test for each model was performed, and the p-value for the F-test was determined. It was assumed that the limit value for the level of significance for the test-F is 0.05.

For the GSL designation, the authors divided each site-year into a 10-days periods and the GEP averages values were calculated for these periods. The end of the first 10-days period, in which a GEP flux exceeds an average annual value by 15%, was treated as an indication of the beginning of a growing season. Similarly, the end of a growing season was defined as the end of the first 10-days periods, in which a GEP flux dropped under the average annual value by 15%. A half-hourly averaged data of air temperature were used to calculate the annual average values (for each site), then the average of the selected five-years air temperature (*tay*) was calculated for each site. The annual totals of the net ecosystem exchange (NEPy), precipitation (*Py*) and photosynthetic photon flux density (PPFDy) were calculated in a similar way. Obtained results were then used to perform a linear relationship between the NEPy and the *tay* (Fig. 2a), *Py* (data not shown) and the PPFDy (data not shown), for all selected sites. In addition, linear regressions were made for the NEPy and LAI (data not shown), as well as the NEPy and the latitude (*lati*) (Fig. 2b), and the NEPy and the GSL relationship (Fig. 2c). Some regression models are not presented here because of their poor performance ($R^2 < 0.2$) and any statistical significance ($p < 0.05$).

RESULTS AND DISCUSSION

Estimation of NEPy by a simple model, based on statistically significant correlations with any of easily measurable habitat parameters, was found to be difficult. It comes from the differences of climatic conditions variability (temperature, radiation, humidity) as well as soil properties (soil type, moisture, fertility, *etc.*) among analyzed sites. It is well known that NEP is a balance value of two fluxes: GEP and R_{ECO} . The main weather factor influencing GEP, via an impact on photosynthesis process, is solar radiation, whereas soil properties and air temperature are the drivers of ecosystem respiration. The intensity of CO_2 uptake during photosynthesis is also dependent on plant phenology (Wu *et al.*, 2013). However, in this paper we focus on the relationships between easily accessible parameters only derived from the European database and the cumulative NEP values at the annual time scale.

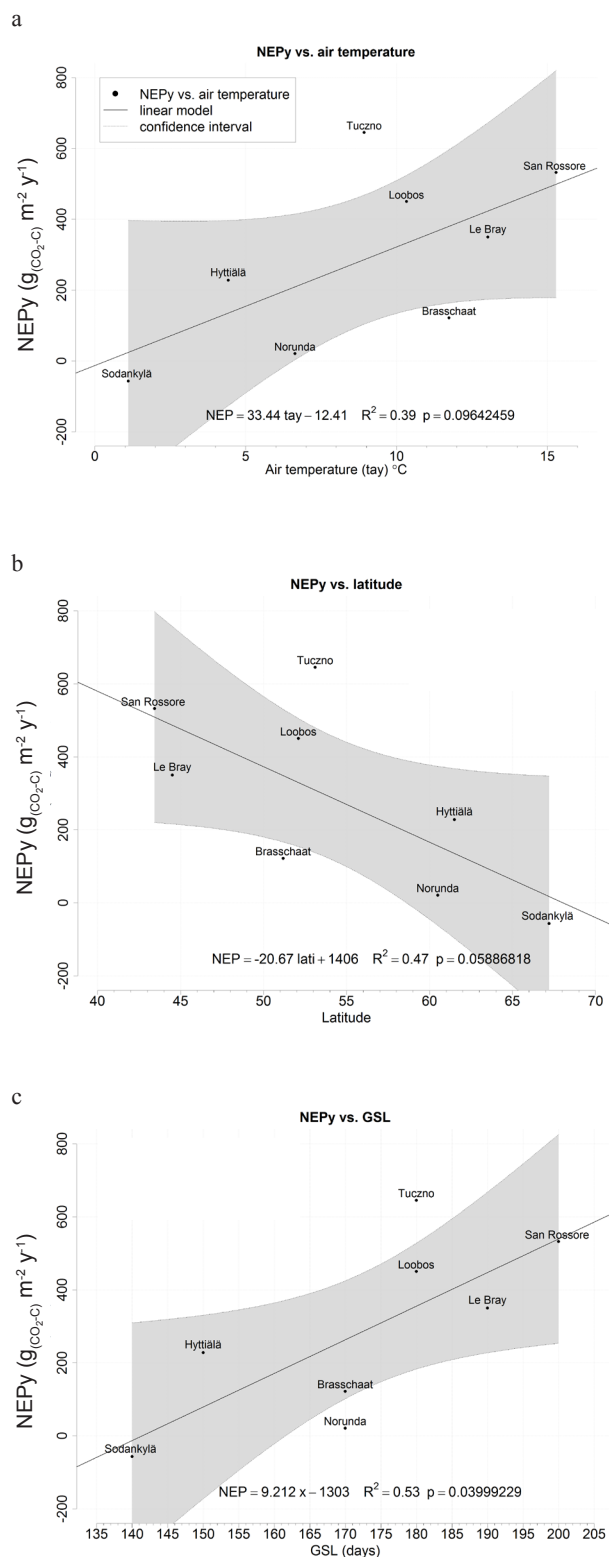


Fig. 2. The relationships between 5-years average annual NEP fluxes (NEPy) and a – air temperature, b – latitude, c – growing season length (GSL), of selected European forest research stations.

Prior to the analysis described above, special attention was paid to the Sodankylä station (located in the north of Finland in a boreal forest ecosystem) which act as a CO₂ source. The observed NEP totals were negative – both in particular years and the 5-years average (-57 g CO₂-C m⁻² y⁻¹). This relatively long-term tendency at this site was difficult to explain. For some reasons, the annual R_{ECO} outweighs the GEP every year in the whole five-years period. It was quite logical in the past, since the CO₂ assimilation must have been bigger than the CO₂ release, because some organic matter was deposited there. There is some explanation of this phenomenon in the literature (Köster *et al.*, 2013). Sodankylä is situated on a sandy soil with about 0.5 cm thick layer of humus. Moreover, the region of the site is among the five largest reindeer herding districts of Finland. The number of reindeers has increased three times during the last 50 years. The authors showed, that the total ground vegetation biomass was 62% higher in the ungrazed area as compared to that in the grazed region. Generally, in high latitudes the less radiation comes in, causing GEP to be low. It reduces also the R_{ECO}, although respiration process still takes place even if soil temperature comes near to 0°C (Juszczak *et al.*, 2012, 2013). For these reasons, the other two Scandinavian sites (Norunda and Hyytiälä) are also characterized by low annual NEP. Besides, the decomposition rate of organic matter is lower in a boreal forest compared to a temperate one, due to lower temperature and (unlike at other sites) a thin organic layer. In such conditions the soil microorganisms are not so active, what cause the decrease in heterotrophic respiration.

The influence of air and soil temperature on the intensity of photosynthesis and respiration, and therefore, also on the NEP fluxes in Finnish boreal forests, was observed especially in early spring and late autumn (Vesala *et al.*, 2010). In these periods, freezing temperatures on the one hand delay the beginning of vegetation season (spring), thus decreasing the intensity of CO₂ assimilation, and on the other accelerate the end of tree growth in autumn. The attention should also be directed to the NEP fluxes in very cold periods, when the air temperature drops below 0°C (even up to -15°C). As indicated at the Sodankylä and Norunda sites the net CO₂ exchange in winter was close to zero. A similar influence of meteorological conditions on the annual NEP fluxes, as described for a boreal forest, can be found also for temperate forest ecosystems (Poyatos *et al.*, 2007).

In comparison with the sites in the presented analysis the middle-aged Scots Pine forest stand in Poland show some of the highest annual NEP flux values equals to 645 g C m⁻² year⁻¹. We assume, that the Tuczno forest is currently achieving the highest rate of its growth. Moreover, at the majority of the growing season (summer time) the litter layer is probably too dry to be decomposed. Therefore, the respiration intensity might be not as high as in the forests of higher average annual temperatures and annual sum of precipitation in western and southern Europe. This can be one of the cause of the largest annual value of the NEPy.

Our analyses indicate that NEP variation can be explained by the average air temperature, the latitude and the growing season length differences (Fig. 2). Other parameters, such as precipitation, soil water content, stand density, water table level and photosynthetic photon flux density totals, were excluded from the analysis because they showed very weak, non-statistically significant correlation, with the NEPy. In presented studies the annual variability of NEP fluxes in different forest ecosystems across Europe can be explained by the mean annual air temperature, latitude and growing season length (GSL) changes in 39, 47, and 53%, respectively. Nevertheless, only the relationship between NEPy and GSL was statistically significant at chosen 0.05 significance level ($p = 0.04$) (Fig. 2c).

The poor linear regression between the NEPy and the τ (Fig. 2a) can be explained by the fact, that it was probably of curvilinear type. However, with such a small amount of data the application of any non-linear formula seems risky, although in the literature such formulas for at different time scales are known (Falge *et al.*, 2001) phenology patterns, and stress conditions. The comparisons are usually performed on annual sums of FNEE; however, the average data coverage during a year is only 65%. Therefore, robust and consistent gap filling methods are required. We review several methods of gap filling and apply them to data sets available from the EUROFLUX and AmeriFlux databases. The methods are based on mean diurnal variation (MDV). Despite the fact that described regression is not statistically significant, it is worth noting that its tendency seems to be reasonable and the intercept was around -12.41, which is very close to the expected value of 0, due to the reduction of biological activity (and CO₂ fluxes) in cold conditions. This value can be also an artefact, an effect of using annual mean air temperature versus NEPy, but analysis based on daily data shows that the value of intercept is also near 0.

The results of the second relationship presented below (NEPy versus latitude) seems to be quite interesting. The course of this simple linear correlation indicates that the NEPy value approaches zero at the latitude of around 68 degree north. This is consistent with reality. In general, as derived from described relationship annual NEPy shows growing tendency with decreasing latitude (Fig. 2b).

The last analyzed linear relationship seems to be the best model for estimating NEPy of the Scots pine in European climatic conditions. Unfortunately, the interpretation of the formula obtained by the regression is not as simple as in the previously discussed cases. It is notice worthy, that when the GSL equals 0 the NEPy reaches up to -1 303 g (CO₂-C) m⁻² y⁻¹. The negative value indicates the net emission results from ecosystem respiration only. Since NEP is the balance between the GEP and the R_{ECO}, the absence of the growing season means that the GEPy is equal to 0. As a result, our model indicates that when there is no photosynthesis the amount of respired CO₂ will be around 1 303 g (CO₂-C) m⁻² y⁻¹. This is definitely not true, because without growing

season there would be no plants, and as consequence would be no organic matter in the soil. Thus, both the absorption and respiration would amount to 0. This tendency is visible in Table 1, the R_{ECO} and GEP decreases with the growing season shortening. It is the effect of the low air and soil temperature which is mostly responsible for the reduction of biological activity, and consequently the reduction in both CO_2 effluxes – from soil and plants respiration.

Therefore, an extrapolation using the proposed model (despite the significance of the regression) is impossible. On the other hand, the data presented in this work fully covers the entire range of the Scots pine occurrence in Europe, so that there is probably no need for extrapolating the proposed formula.

CONCLUSIONS

1. The assigned growing season length and the latitude of a particular forest stand in Europe can be the parameters which allow the approximate estimation of the average annual total of the net ecosystem production flux.

2. Presented models are though not perfect, as there are limitations to their use. Their application requires caution, and as it was pointed out, prediction capabilities are limited only to the range of the GSL, which has been presented in the paper.

3. The models were created involving a relatively small population of data, which limited our ability to put forward other (non linear) formulas. Bigger dataset could presumably significantly improve some relationships performance.

4. Large residuals (for Tuczno, Norunda) in different models can sometimes be an effect of the influence of the factors which could not be determined in this work. Our analysis attempts were limited to those presented above, mainly because of the data availability issue.

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