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# Net ecosystem productivity and its environmental controls in a mature Scots pine stand in north-western Poland

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ABSTRACT

Although there have been many studies of the net ecosystem productivity (NEP) of different types of forests around the world, the $CO_2$ dynamics in afforested pine stands of Central Europe are poorly understood. To fill this gap, continuous eddy-covariance (EC) measurements of net ecosystem exchange (NEE) were made from January 2008 to December 2013 in a 62-year-old temperate afforested Scots pine stand near Tuczno. The site is located in north-western Poland, where forests account for almost 30% of the land area and are dominated by Scots pine. Weather conditions during this 5-year period were mostly warm and wet. In all 5 years, air temperature ($T_a$) was higher than the 30-year (1983–2013) mean and by 3.3 °C during winter 2008, while precipitation ($P$) was noticeably higher only in summer months. The high productivity of the forest, which sequestered 118 Mg of $CO_2$ per ha over the 5-year period, is likely because it was planted on fertile meadowland. Annual net ecosystem productivity (NEP = −NEE) ranged from 494 g C $m^{-2}$ in 2012 to 765 g C $m^{-2}$ in 2009, with an average of 645 g C $m^{-2}$. The interannual variation in NEP was attributed more to the interannual variation in gross ecosystem photosynthesis (GEP) than to ecosystem respiration ($R$). Moreover, both annual NEP and GEP significantly decreased over the 5 years. This was the result of increasingly drier springs and wetter summers as time progressed during the 5-year period, as compared to the 30-year averages, which resulted in a gradual reduction in the growing season NEP and consequently the annual values. Seasonal values of NEP were highly correlated with $T_a$, photosynthetic photon flux density and vapor pressure deficit. The sensitivity of NEP to $T_a$ was largely due to the much higher sensitivity of GEP to $T_a$ compared to that of $R$. Although the interannual variability in NEP for separate seasons could not be explained using seasonal values of individual meteorological variables, a hygrothermal index, defined as $P/10T_a$, explained a large proportion of the interannual variability in NEP in spring and summer.



## 1. Introduction

Global forest inventory data and long-term ecosystem carbon (C) studies indicate that the global forest C sink is large ($2.4 \pm 0.4$ Pg C $y^{-1}$) and increasing (Pan et al., 2011). The same study revealed that in comparison to tropical and boreal zone forests, temperate forests have shown the highest rate of increase in the C sink over the past two decades: from 0.67 (1990–1999) to 0.78 (2000–2007) Pg C $y^{-1}$. In addition to the forest inventory-based approach, many eddy-covariance (EC) flux studies have shown that temperate forests are C sinks worldwide (e.g., Barford et al., 2001; Pilegaard et al., 2001; Kolari et al., 2004; Zielis et al., 2014; Danielewska et al., 2015). Furthermore, according to comprehensive quantification of the C balance of different forests, using EC and biometric measurements, temperate evergreen forests sequester from $133 \pm 47$ up to $389 \pm 42$ g C $m^{-2}$ $y^{-1}$ depending on climatic conditions (Luyssaert et al., 2007). In general, the large contribution of forests to the total terrestrial C sink, ca. 26% for the period 2000–2007 (Pan et al., 2011), will have a strong influence on future climate due to its effect on $CO_2$ exchange between the land surface and the atmosphere. Thus, there is an urgent need to investigate the effects of different climate variables in the various forest types on $CO_2$ exchange processes. There has been considerable research into the response of evergreen forests' C exchange to climate conditions and their variation in North America, e.g. in Douglas-fir stands (Morgenstern et al., 2004; Chen et al., 2009), black spruce forests

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(Krishnan et al., 2008; Gaumont-Guay et al., 2014), white pine plantations (Arain and Restrepo-Coupe, 2004), ponderosa pine (Law et al., 2000), jack pine (Zha et al., 2009) and Europe (Ceulemans et al., 2003; Falge et al., 2002; Law et al., 2002; Baldocchi et al., 2001). Empirical relationships between C fluxes and climatic factors have been developed using different approaches: simple linear and nonlinear regressions, multiple regression analysis, residual analysis, etc. (Chen et al., 2002; Chen et al., 2009). In most studies the main factors, controlling $CO_2$ exchange are air and soil thermal and wetness characteristics and solar radiation (e.g. Chen et al., 2002; Carrara et al., 2003; Dunn et al., 2007; Barr et al., 2009; Chen et al., 2009). Therefore, in this study some of previously mentioned, commonly measured variables were chosen to investigate whether they are similarly important controlling factors of net ecosystem productivity (NEP) in Tuczno pine forest.

In Europe, where the majority of the forest area has been deforested during the past century, special afforestation policies have been implemented to compensate for this loss. This region is the only one that has had an increase in forest area (both afforestation and natural regeneration) over the past 20 years gaining ca. 0.7 M ha $y^{-1}$ since 2005, which is slightly less than 0.9 M ha $y^{-1}$ in the 1990s. This has resulted in an increase in total forested area in Europe to 196 M ha in the period 1990–2010 (excluding the Russian Federation), which accounts for 34% of total land area (Food and Agriculture Organization of the United Nations (FAO, 2010). The role of afforestation in the change in total forest area differs among countries, e.g. in Poland, the Czech Republic, Ireland and the UK, the contribution from natural regeneration is so small that it can be neglected, while in the Mediterranean region natural regeneration plays a major role (Zanchi et al., 2007). In this paper, it is assumed that "afforestation" means planting and/or seeding to establish forests or plantations on land not previously vegetated, classified and/or utilized as forest (Food and Agriculture Organization of the United Nations (FAO, 2010). Before World War II, Poland's forest area was depleted mainly as a result of both the expansion of agriculture and the demand for timber, but it decreased even more rapidly by 1945 when it accounted for only 20.8% of the area of Poland (Forest Research Institute, 2006). To prevent any further decrease, the National Program of Afforestation was introduced by the government, so that during the period 1945–1970 Poland's forested area increased to 27.0% of the country's area, as a result of the afforestation of 0.9 M ha (Forest Research Institute, 2006), and recently constitutes up to 29%. Since mainly Scots pine was planted in the newly established forests, this species currently accounts for almost 60% of the forest trees, and thus has become a major species in the restoration of Polish forests. (Forest Research Institute, 2013).

To fill the existing gap in the potential production assessment of a mature temperate pine forests in Central Europe, a study focusing on the controlling factors of $CO_2$ exchange between an afforested pine stand and the atmosphere was conducted in north-west Poland. The main objectives of this study were: (1) to determine the NEP of this stand and compare it with other pine-dominated European forests; (2) to identify the main factors controlling NEP in this stand by examining the responses of gross ecosystem productivity (GEP) and ecosystem respiration ($R$) to environmental variables at the seasonal scale.; and (3) to determine the cause of interannual variability of seasonal and annual NEP of the stand over the past five years.

## 2. Material and methods

### 2.1. Site description

The study site is located in north-western part of Poland in the Tuczno Forest District (Regional Directorate of State Forests in Piła, Forestry Martew, 53°11′N, 16°05′E, 180 m a.s.l.), which is under the management of the State Forests National Forest Holding (SF NFH). The even-aged Scots pine (*Pinus sylvestris* L.) stand (tree age ranging from 60 to 65 years) is approximately 22.7 ha in size (approximately 500 m × 450 m) and is located on level ground (2–4% slope) on the Drawsko Plain. The forest was planted in 1953 on a meadowland, commonly used by local farmers for cattle grazing since 1945 and formerly as farmland when it was part of Germany. The stand is surrounded by 40–80 years old pine forest, which spreads for several kilometers in all directions. No forest treatments (except for the removal of dead trees and branches when needed) were carried out at the study site since 2008 when EC tower observations began. In 2012 a few trees within 20 m of the tower were removed but had no noticeable effect on measured $CO_2$ exchange. The main tree species in the stand was Scots pine, which accounted for 99% of the trees, with an admixture of birch (*Betula pendula Roth*). The understory was dominated by beech (*Fagus sylvatica* L.) and hornbeam (*Carpinus betulus* L.). Forest floor flora within approximately 500 m of the EC tower consisted of grasses (*Deschampsia flexuosa* and *Calamagrostis epigejos*), mosses (*Pleurozium schreberi),* ferns *(Dryopteris spinulosa)* and berries (*Rubus idaeus*). As derived from hemispherical photographs, taken in 2008, the leaf area index (LAI) of the overstory canopy ranged from 0.83–1.5. Average height and the diameter at breast height (DBH) of the pine trees measured in 2013 were 26 m and 25 cm, respectively. At that time, the stand density was estimated to be 900 trees $ha^{-1}$. The average tree height during the period 2008–2013 increased by approximately 5 m. According to the classification in the World Reference Base for Soil Resources (2006), the soil in the study area was classified as a Brunic Arenosol (Dystric). This soil, which has historically been used for agricultural purposes, has surface organic (O), A and B horizon thicknesses of about 2–5, 14–25 and 37–90 cm, respectively. The texture of the mineral soil layers was sand to loamy sand. The average organic C content, measured at 6 locations in 10 plots (ca. 20 × 20 m each) surrounding the tower, ranged from 103 to 505 g C $kg^{-1}$ soil in the O horizon and from 7 to 49 g C $kg^{-1}$ soil in the A horizon.

### 2.2. Climate

The mean annual air temperature and precipitation in this region were 8.06 °C and 553 mm respectively as obtained for the 30-year period (1983–2013) from the nearest meteorological station, which is in Piła, about 50 km from Tuczno. Values from Piła were used to fill gaps in the records at the research site. Based on site data, the average length of the growing season, the aggregate period of days with mean air temperature ≥5 °C, was estimated to be 232 days and ranged from 216 to 251 days (over the 5 years of the study). This is consistent with the report by Koźmiński et al. (2007), which shows that average growing season length in this region is 220 days using similar methodology. The prevailing wind direction at the site was from the southwest-west to north (245–360°).

### 2.3. Eddy covariance measurements

A 38-m-tall steel scaffold flux tower (2 m × 2 m) was located about 100 m from the eastern edge of the stand. The eddy-covariance (EC) system, which was installed in January 2008, comprised a three-dimensional (3-D) non-orthogonal sonic anemometer (model CSAT3, Campbell Scientific Inc. (CSI), UK) and an open-path infrared gas analyzer (IRGA, model LI-7500. LI-COR Inc., Nebraska, USA). Both instruments were positioned above the highest platform (34 m above the ground) on a 4-m-long mast mounted vertically to the tower frame, so that the height of the EC instruments was 38 m. This ensured that measurements were made >1.5 times the mean height of the trees as recommended by Burba (2013) for tall vegetation. The location of the tower ensures