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*Supplement of*

## **Prediction of photosynthesis in Scots pine ecosystems across Europe by a needle-level theory**

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## S1 The measuring stations

### S1.1 SMEAR I

The Värriö Subarctic Research Station is located just below the current northern altitudinal treeline in north-eastern Finnish Lapland. CO<sub>2</sub> flux measurements of Scots pine (*Pinus sylvestris*) are carried out at the nearby Station for Measuring  
5 Ecosystem-Atmosphere Relations (SMEAR I, 67°46' N, 29°35' E, 400 m a.s.l.). The region is characterised by fells, a hilly landscape with fells higher than 400 m in altitude with lower areas covered by Scots pine and Norway spruce (*Picea abies*) forests. The location of the measuring station is extremely remote: nobody is permanently living within 10 km. The mean annual temperature for the climatological normal period (years 1981–2010) was –0.5 °C and mean annual precipitation 601 mm (Pirinen et al., 2012). The average end of snow cover period has been 20th May, and the length of the growing season 114  
10 d.

SMEAR I is located on the summit plateau of Kotovaara hill dominated by Scots pines with an average height of 8.8 m and an average diameter of 14 cm. The fell was naturally populated by Scots pine consisting of very young and old trees of various age with a density of approximately 750 trees ha<sup>-1</sup>. The ground vegetation is comprised of a variety of mosses, lichens and dwarf shrubs such as *Vaccinium myrtillus*, *Empetrum nigrum* and *V. vitis-idaea*.

15 The eddy covariance (EC) system at SMEAR I includes the METEK-USA1 ultrasonic 3D anemometer (METEK, Elmshorn, Germany) and the enclosed-path LI-7200 CO<sub>2</sub>/H<sub>2</sub>O gas analyser (LI-COR Biosciences, Lincoln, NE, USA) installed 5 m above the forest canopy.

Automatic chambers attached to single shoots at the top of four Scots pine trees close to the EC tower measured the shoot scale CO<sub>2</sub> and H<sub>2</sub>O exchange. Each chamber was closed one after another for 60 seconds. During a closure, CO<sub>2</sub> and water vapour  
20 concentrations were recorded at 10 s intervals. The hourly CO<sub>2</sub> exchange was determined by processing resulting five CO<sub>2</sub> exchange measurements for each chamber. Simultaneously, we measured photosynthetically active radiation (PAR) and air temperature at every chamber.

### S1.2 SMEAR II

The SMEAR II measuring station (Hari and Kulmala, 2005) is situated at the Hyytiälä Forestry Field Station. The SMEAR II  
25 is in a Scots pine stand established by sowing in 1962. It is located in southern Finland (61°46' N, 24°17' E, 170 m a.s.l.) on a medium fertile site, classified as *Vaccinium* type (Cajander, 1926). Small hills characterise the surroundings of the station. In 2012, the dominant height and mean stem diameter at 1.3 m were 17.5 m and 19.6 cm (Bäck et al., 2012) with density of 700 trees ha<sup>-1</sup>. Norway spruce grows in understory. Dwarf shrubs *Vaccinium myrtillus* and *V. vitis-idaea* dominate the ground layer with feather mosses such as *Pleurozium schreberi* and *Dicranum polysetum*.

The site belongs to the middle boreal zone and has a harsh boreal climate with long cool days in the summer and short cold days in the winter. The mean annual temperature is 3.5 °C and mean monthly temperature varies from -7.7 °C in February to 16.0 °C in July (mean for 1981–2010) (Pirinen et al., 2012). Mean annual rainfall (711 mm) is distributed evenly throughout the year.

- 5 The ecosystem net exchange was measured with a closed-path eddy covariance measuring system (Vesala et al., 2005). The net exchange was partitioned into gross primary production (GPP) and total ecosystem respiration (TER) that was modelled from nighttime observations using an exponential function (Kolari et al., 2009). The evapotranspiration and sensible heat fluxes were calculated using standard methodology with stability filtering (Launiainen, 2010; Mammarella et al., 2009).

### **S1.3 Norunda**

- 10 The Norunda forest site (60°05'11''N, 17°28'46''E, 45 m a.s.l.) is located in central Sweden, ca 90 km north of Stockholm. The forest consists of patches with different ages (60–110 years) and is dominated by Scots pine and Norway spruce, with a canopy height of approximately 25 m. The mean annual temperature is 5.5 °C, and mean annual precipitation is 527 mm.

- A closed-path eddy covariance system with an LI-6262 gas analyser (LI-COR Biosciences, Lincoln, NE, USA) and a Gill R2 sonic anemometer (Gill instruments, Hampshire, UK) is located on a flux tower at a height of 35 m, approximately 10 m above  
15 the canopy. The site has been in operation since 1994. A detailed description of the eddy covariance setup and the flux calculations is given in Grelle and Lindroth (1996) and Grelle et al. (1999).

- The GPP flux was obtained by correcting the observed net exchange of CO<sub>2</sub> from the eddy covariance system for storage of CO<sub>2</sub> in the canopy (determined from profile measurements of the atmospheric CO<sub>2</sub> concentration) and by subtracting respiration determined from the nighttime measurements of net exchange. The site and data processing is described in more  
20 detail by Lundin et al. (1999) and Schurgers et al. (2015).

### **S1.4 Loobos**

- The Loobos site in the Netherlands was established at the end of 1994 in a stand of Scots pine on a sandy soil with a relatively deep groundwater table in the centre of the Netherlands (52°10'04.286 N, 05°44'38.252 E). Mean annual temperature is 10.1 °C (1997–2015). The eddy covariance measurements started at the end of 1996 with a Windmaster Pro sonic anemometer  
25 (Gill, Lymington, UK) and a LI-6262 gas analyser (LI-COR Biosciences, Lincoln, NE, USA). The instruments were mounted on a mast extending 3 m above a 23 m scaffolding tower. Tree height was around 17 m. In 2001, the eddy covariance instruments were replaced by a R3 sonic anemometer (Gill, Lymington, UK) and a LI-7500 gas analyser (LI-COR Biosciences, Lincoln, NE, USA). For more information on the site and instrumentation, see <http://www.climatexchange.nl/sites/loobos> (10/06/2017, current setup), Dolman et al. (2002, initial setup) and Schelhaas et al. (2004, inventory based carbon budgeting).

The Loobos site is located near Kootwijk on the Veluwe. The trees were planted on sand dunes and are widely spaced with some open spots. In a radius of 500 m around the flux tower, 89 % of the area is covered with Scots pine, 3.3 % with Corsican or black pine (*Pinus nigra*), 2.3 % with birch (*Betula* spp.), 1.3 % with Douglas fir (*Pseudotsuga menziesii*), 0.6 % with oak (*Quercus* spp.) and 3.5 % of the area is open and mostly covered with heather (*Calluna vulgaris*) and grass. The undergrowth of the forest is a closed cover of mainly grass (*Deschampsia flexuosa*). Because of the local topography caused by the sand dunes, the distance to the ground water table depends on the location. At the base of the tower, the ground water table is at a depth of  $\pm 6.5$  m below the surface. In the valleys, the ground water table reaches  $\pm 3.5$  m. More information of the site can be found in Elbers et al. (2011).

### **S1.5 Brasschaat**

10 The experimental forest “De Inslag” is located in Brasschaat, 20 km NE of Antwerp in the Belgian Campine region (51°18’ N, 4°31’ E). The study site consists of a 2.0 ha, 80-year-old even-aged Scots pine stand situated within a 150 ha mixed coniferous–deciduous forest dominated by Scots pine. The stand is part of the ICP Forests level II and Fluxnet/CarboEurope-IP networks. Historic inventory data showed a tree density of 538 trees ha<sup>-1</sup> in 1995 (Janssens et al., 1999). However, a thinning in the winter of 1999 and a storm in the autumn of 2002 decreased the density to 375 and 360 trees ha<sup>-1</sup>, respectively (Gielen et al., 2013; Xiao et al., 2003).

The region has a temperate maritime climate, with a long-term mean annual temperature of 11 °C (Carnioli et al., 2011). The long-term mean temperatures of the coldest and warmest months are 3 and 19 °C, respectively, and mean annual precipitation is 830 mm. The study site is subject to an atmospheric nitrogen deposition of on average 48 kg N ha<sup>-1</sup> (Neiryneck et al., 2008). The site has a flat topography (slope 0.3 %) with an elevation of 16 m a.s.l.

20 The eddy covariance system was set up in August 1996. It consists of a sonic anemometer (model SOLENT 1012R2, Gill Instruments, Lynton, UK) to measure turbulence and an infrared gas analyser (IRGA) (model LI-6262, LI-COR Biosciences, Lincoln, NE, USA) to measure the CO<sub>2</sub> concentration. The measurements were conducted at the top of the tower at a height of 41 m, about 18 m above canopy. Detailed description of the experimental setup can be found in Carrara et al. (2003, 2004).

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