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Soil surface CO_2 efflux measurements in Norway spruce forests: Comparison between four different sites across Europe — from boreal to alpine forest

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ABSTRACT

Extensive measurements of soil surface (including vegetation cover) CO_2 efflux were carried out on 80 positions at four different forest sites (Sweden, Germany, Czech Republic and Italy) using a closed dynamic chamber technique. The period of measurement was 4–5 consecutive days per site. Two approaches were used to analyze the measured data, the Q_{10} parameter and the Arrhenius relationship. Basic environmental factors such as soil temperature and moisture were measured. All the four investigated sites showed a positive dependence of the soil surface CO_2 efflux on soil temperature. The four datasets generally resulted in good agreement (up to 93%) between the approaches and residual analysis showed no significant difference between approaches (less than 8%). The Q_{10} ranged between 2.0 and 2.3 among the sites. The highest spatial variation of the soil surface CO_2 efflux at 10 °C (expressed by the coefficient of variation CV) ranged from 30 to 65% between sites.

1. Introduction

The efflux of CO_2 from soil surface is one of the largest and most important fluxes of carbon in terrestrial ecosystems (Davidson et al., 2002; Raich and Schlesinger, 1992). Soil CO_2 efflux results from the combination of biological processes (i.e. production of CO_2 by roots, soil micro-organisms and soil macro fauna) and physical processes (i.e. CO_2 diffusion from sources to soil surface) (Le Dante et al., 1999), and is thought to account for 60–80% of ecosystem respiration (Davidson et al., 1998; Epron et al., 1999). Soil CO_2 efflux, also called "soil respiration", is the main pathway for carbon moving from the ecosystem to the atmosphere and can strongly influence net carbon uptake from the atmosphere, or net ecosystem production (Valentini et al., 2000; Ryan and Law, 2005). However, as the efflux of CO_2 from the soil is typically characterized by a large temporal and spatial variability, a high heterogeneity introduces an uncertainty in the estimations.

Several studies regarding factors influencing temporal and spatial variabilities of soil CO_2 efflux at local or multi-site scale have been published, the most common are related to soil temperature and moisture (Buchmann, 2000; Janssens et al., 1999; Kosugi et al., 2007; Vodkin et al., 2006), vegetation characteristics (Chojnicki et al., 2010; Law et al., 2001; Widén, 2002), root density or biomass (Fang et al., 1998; Rodeghiero and Cescatti, 2006; Stoyan et al., 2000), quantity–quality of organic matter and microbial biomass (Rayment and Jarvis, 2000; Ryan et al. 1996; Taylor et al. 1989), nitrogen status and soil carbon (Bowden et al., 2004; Robertson et al., 1999), tree photosynthesis (Tang et al., 2005) and net primary production (Janssens et al., 2001; Korari et al., 2009; Moyano et al., 2008). Nevertheless, among all above mentioned environmental factors, temperature is still a key factor influencing soil CO_2 efflux and other processes involved in the production of soil CO_2.

The dependence of soil CO_2 efflux on soil temperature has been frequently described (Lloyd and Taylor, 1994). Soil temperature is the best predictor of soil CO_2 efflux in most of the ecosystems when no water stress occurs (Janssens et al., 1999). Usually, soil moisture is the other dominant factor influencing the soil CO_2 efflux (Epron et al., 1999). Numerous models have been developed to express the temperature sensitivity of soil CO_2 efflux (Reichstein et al., 2003; Tuomi et al., 2008). On the other hand, exponential relationships, especially the Q_{10} relationship, are the most frequently used to predict respiration rates using temperature (Davidson et al., 1998; Raich and Potter, 1995). The use of the Q_{10} relationship has often been

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criticized because Q_{10} decreases with increasing temperature and depends on soil moisture conditions (Davidson et al., 2006). Another widely used approach to determine the relationship between soil CO_2 efflux and temperature is the Arrhenius relationship in which the activation energy (E_a) depends on soil temperature as proposed by Lloyd and Taylor (1994).

Generally, the chamber technique has been used for the direct measurement of soil surface CO_2 efflux. Different chamber methods and types of chamber have been employed mainly depending on the type of investigated ecosystem (Davidson et al., 2002; Fang and Moncrieff, 1996; Janssens et al., 2000; Juszczak et al., 2012; Pumpanen et al., 2004; Acosta et al., 2004; Saiz et al., 2006). Although there are advantages and disadvantages associated with chamber measurements, the chamber technique is generally considered as a useful tool for the determination of soil CO_2 efflux spatial heterogeneity and a complementary tool for eddy covariance measurements. Chamber technique is not affected by CO_2 advection (Welles et al., 2001); on the other hand, chambers can modify the soil environment (e.g., temperature, humidity, CO_2 concentration) if they cover the measured area for long periods, and therefore may introduce biases (Livingston and Hutchinson, 1995). Another issue related to the chamber technique is a common problem in across-ecosystem comparison in that soil surface CO_2 efflux rates are often measured with different systems introducing an important source of uncertainty (Pumpanen et al., 2004).

In our study, we measured and compared the soil CO_2 efflux at four different sites across Europe. Three identical soil CO_2 efflux systems were transported to each investigated site and the same measuring methodology (including man power) was applied in all sites in order to eliminate any uncertainty regarding to equipment and methodology across-ecosystem comparison, thus, doing this study was unique and challenging. This study deals with short-term temporal variability as well as within-site spatial variability of the soil surface CO_2 efflux. Our objectives were: (1) to provide a reliable estimate of the short-term soil surface CO_2 efflux at the four forest sites with different locations in Europe applying the same chamber measurement system, (2) to determine spatial variation in the soil surface CO_2 efflux, (3) to construct a map of the soil surface CO_2 efflux on the base of measurements done for each investigated site and (4) to identify possible factors controlling spatial variation of the soil surface CO_2 efflux.

2. Material and methods

2.1. Site description

The four sites were investigated during this study. Three sites were from the CarboEurope-Integrated Project (CE-IP) advection activities ADVEX performed from 2005 to 2006: Renon (Italy), Wetzstein (Germany), and Norunda (Sweden). The fourth investigated site was Bílý Kříž (Czech Republic), (for more details on the experimental set-up and first results of ADVEX, see Feigenwinter et al., 2008).

Renon (RE) site is influenced by an alpine, windy and humid climate. The unevenly aged forest is heterogeneous with gaps between groups of older and younger trees, and sparse understorey vegetation is dominated by blueberries (*Vaccinium myrtillus* (L.)) and grasses, (for more details about the site, see Marcolla et al., 2005). Wetzstein (WS) site is situated nearly on the crest of ridge with steep slopes to the ESE and WNW directions. The climate is temperate humid. The forest is a managed homogeneous stand and ground vegetation is sparse with occasional areas covered by blueberries and mosses, for more details about the site see Anthoni et al. (2004). Norunda (NO) site is a flat area located in a cold-temperate to boreal climate. It is a managed forest and the forest floor is mainly covered by boulders, rocks (with a diameter of up to 1.5 m), dwarf shrubs and mosses. For more details about the NO site see Morén and Lindroth (2000). Bíly Kríž (BK) site is located on a gentle slope with SSW exposure. The climate is cold-temperate. The forest is a managed homogeneous stand. The ground vegetation is dominated by blueberries, for more details about the site see Urban et al. (2007). Main characteristics of the sites are presented in Table 1.

2.2. Soil surface CO_2 efflux measurements

Extensive measurements of the soil surface CO_2 efflux (including vegetation cover — low growing plants covering the ground) were carried out for 80 positions at all the investigated sites. At each position a PVC collar (19 cm in diameter, height 8.5 cm) was placed and inserted into the soil at about 3 cm depth one day before measurements began. During the installation of the ring a cutting effect could be generated a paulatim increase in the soil CO_2 efflux that could last for weeks or months depending of the impact due to the cut of root biomass. However, installation of rings one day before measurements is the minimum time necessary to obtain reliable soil CO_2 efflux measurements (see Heinemeyer et al., 2011 for more information about collar insertion). At WS, NO and BK sites a grid design was used in order to investigate the soil CO_2 efflux spatial variation. In this design a collar was installed at each intersecting point of the grid with 5 m distance between positions at sites WS and BK since both sites present a homogeneous soil surface, and with 10 m distance at NO due to the presence of boulders and rocks on the forest floor. Because the forest stand in RE was heterogeneous with gaps between groups of older and younger trees, collars were installed in

Table 1
Main characteristics of the investigated sites.

Site name	Renon	Wetzstein	Norunda	Bílý Kříž
Country	Italy	Germany	Sweden	Czech Republic
Region	South Tyrol	Thuringia	Uppland	Beskydy
Latitude	46° 35′ N	50° 27′ N	60° 05′ N	49° 30′ N
Longitude	11° 26′ E	11° 27′ E	17° 28′ E	18° 32′ E
Elevation (m)	1730	785	45	908
Topography	Alpine slope (11°)	Top of a hill	Flat	Slope (13 °C)
Mean annual temperature (°C)	4.1	5.9	5.5	5.5
Mean annual precipitation (mm)	1010	840	527	1200
Forest type	Evergreen needleleaf forest (*Picea abies* 85%)	Evergreen needleleaf forest (*Picea abies*)	Evergreen needleleaf forest (Picea abies, Pinus sylvestris)	Evergreen needleleaf forest (Picea abies)
Stand age	Uneven	50	50–100	27
Stand density (trees/ha)	745	670	600	2000
Mean canopy height (m)	25	22	28	12
Mean DBH (cm)	17	27	29	13
LAI ($m^2\ m^{-2}$)	4–5.5	4	3–6	10.5
Soil description — FAO	Haplic podzols	Dystric cambisol and podzols	Dystric regosol	Haplic podzols
Soil depth (m)	0.3	0.4	2.0	0.6
Depth of the main rooting zone (m)	0.2	0.3	0.4	0.2