Ecological Engineering 106 (2017) 369–377

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Weather extremes and tree species shape soil greenhouse gas fluxes in an experimental fast-growing deciduous forest of air humidity manipulation

Raili Torga[a,*], Ülo Mander[a], Kaido Soosaar[a], Priit Kupper[a], Arvo Tullus[a], Katrin Rosenvald[a], Ivika Ostonen[a], Sander Kutti[b], Jaak Jaagus[a], Jaak Sõber[a], Martin Maddison[a], Ants Kaasik[a], Krista Lõhmus[a]

[a] Institute of Ecology and Earth Sciences, University of Tartu, Tartu, Estonia
[b] Tartu College of Tallinn University of Technology, Tartu, Estonia

ARTICLE INFO

Article history:
Received 15 December 2016
Received in revised form 12 May 2017
Accepted 17 May 2017
Available online 20 June 2017

Keywords:
Carbon dioxide
Drought
FAHM
Methane
Nitrous oxide

ABSTRACT

Expected climate change in high latitudes includes increased air temperature, precipitation, and humidity in the coming decades. Simultaneously, climate extremes like heat waves and droughts become more frequent. In the Free-Air Humidity Manipulation (FAHM) experiment in silver birch (*Betula pendula* Roth) and hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) stands in Estonia, we focussed on two questions – how elevated humidity in high temperature and drought conditions influences soil greenhouse gas emissions, and what is the impact of tree species on greenhouse gas emissions.

Soil carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) fluxes were measured using the static chamber method in the 3rd and 4th years of humidification, in 2010 and 2011 respectively. Soil temperature, soil water potential (SWP), relative humidity, and precipitation were monitored; tree and understory growth, litter fluxes, substrate-induced respiration, and basal respiration were measured. During the severe drought in summer 2011 (SWP fell below −250 kPa), aspen stands had higher CO_2 emissions than birch stands and humidification increased CO_2 emission for both tree species. Generally, methane consumption was higher in control than in humidified conditions. Humidification reduced N_2O emission in aspen stands in 2010. Hence elevated humidity, heat wave and drought, and tree species significantly affected soil greenhouse gas emissions, however CH_4 and N_2O fluxes remained small in all cases. The results of this study can be used to infer the future greenhouse gas dynamics from mineral soils in northern forests and to forecast growth conditions for energy forestry in changing climate.

1. Introduction

Many models and long-term observations have predicted climate change that alters air temperature and the water cycle (Huntington, 2006; IPCC, 2012; Wu et al., 2012). Climate models forecast more precipitation and warmer conditions at high latitudes in the coming decades (IPCC, 2012; IPCC, 2013). Warmer air can hold more water vapour, and the average atmospheric water vapour content has already increased over land and ocean since the 1980s (IPCC, 2007). In order to simulate the increased humidity and to predict the response of northern deciduous forests to climate change and the following feedback to the atmosphere, a unique free-air humidity manipulation (FAHM) facility was established in Estonia (Kupper et al., 2011). Test species of the experiment were silver birch (*Betula pendula* Roth), which is financially the most important deciduous tree species with a wide distribution in Northern Europe (Hynynen et al., 2010), and hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.), which is considered to be a highly promising tree species for short-rotation energy forestry (Tullus et al., 2012b). Even in a young age, stands of the both species are effective carbon sinks and suitable also for bioenergy in boreal and temperate regions, and therefore can mitigate the climate change (Weih, 2004; Varik et al., 2015; Lutter et al., 2016).

According to recent FAHM studies, higher relative humidity can change plants' transpiration, photosynthesis, stomatal activity, growth rate, fine root characteristics, and the ratio between plant

Abbreviations: FAHM, free-air humidity manipulation; SIR, substrate induced respiration; SWP, soil water potential; T, soil temperature.

* Corresponding author.
E-mail address: raili.torga@ut.ee (R. Torga).

http://dx.doi.org/10.1016/j.ecoleng.2017.05.025

aboveground and belowground compartments (Kupper et al., 2011; Tullus et al., 2012a; Rosenvald et al., 2014; Sellin et al., 2014; Niglas et al., 2015). For instance Sellin et al. (2014) showed that birches acclimated to elevated humidity exhibited higher sensitivity to drought regarding leaf conductance to water vapour as well as leaf hydraulic conductance. Thus sudden weather fluctuations (heat waves, drought) might be more harmful for northern forests. However, humidification affects forest ecosystem functioning diversely, often in interaction with other abiotic and biotic factors that are not yet fully explored; e.g. tree species-related growth strategies and humidification directly change soil properties through the amount and quality of litter and the activity and composition of soil microbial communities (Parts et al., 2013; Kukumägi et al., 2014). The humidity effect is mainly realized through changes in soil water availability (Sellin et al., 2014), i.e. due to higher soil water potential (SWP) in the humidification treatment. All this has direct or mediated effects on soil greenhouse gas fluxes. In recent publications on soil respiration in FAHM, when the precipitation was average or even excessive, the main environmental factor shaping soil CO_2 emission was the soil temperature (Hansen et al., 2013; Kukumägi et al., 2014). A heat wave and low precipitation in summer 2011 allowed us to study how humidity manipulation in interaction with extreme weather conditions influences soil greenhouse gas emissions under different fast-growing deciduous tree species. Although Hansen et al. (2013) reported soil greenhouse gas emissions in FAHM experimental area in 2009 and 2010, the results for birch and aspen were merged. By now the tree species-specific effect on growth, tree biomass allocation, and leaf life span at elevated humidity has been well established (Godbold et al., 2014; Rosenvald et al., 2014; Sellin et al., 2016); hence in the present paper, we conducted a new statistical analysis for 2010 data, included tree species as a factor and added the results from extremely warm and dry summer of 2011.

Soil gas emissions are influenced by different environmental factors such as soil temperature, moisture, pH, C/N ratio, land use, and fertilization (Steudler et al., 1989; Mosier et al., 2003; Ambus et al., 2006; Mander et al., 2010; Schaufler et al., 2010; Gundersen et al., 2012). CO_2 emission is most strongly affected by soil temperature (Fang et al., 2010; Fenn et al., 2010; Schaufler et al., 2010), whereas soil moisture is a key factor in the dynamics of N_2O and CH_4 exchange in soils (Castro et al., 1994; McLain et al., 2002; Christiansen et al., 2012; Gundersen et al., 2012). In addition, the interaction of soil water content with soil temperature is crucial for CO_2 and CH_4 emissions (Bowden et al., 1998). It is common to find a positive correlation between soil temperature and methane uptake in well-drained soils (Priemé and Christensen, 1997; Del Grosso et al., 2000). For N_2O emissions, Wu et al. (2010) showed that soil temperature had only a limited influence between 2.5 °C to 10 °C, but emissions increased significantly when soil temperatures exceeded 10 °C. This means that soil temperature can have a positive correlation with N_2O flux (Lohila et al., 2010; Morishita et al., 2011), although many investigations have found no clear correlation at all (Mosier et al., 2002; Ullah et al., 2009; Huang et al., 2011). N_2O emissions likely increase when soil is water saturated and during the rapid increase in soil moisture after rainfall (Mosier et al., 2002; Cantarel et al., 2011; Morris et al., 2013). The combination of high soil temperature and a low water-filled pore space during the summer can neutralize each other, and there may therefore be no seasonal pattern in N_2O emissions (Morishita et al., 2011). Previous studies conducted in FAHM study site showed that elevated humidity reduced soil respiration in birch stands in moist summer of 2009 (Kukumägi et al., 2014) and decreased CH_4 uptake in 2009 and 2010 (Hansen et al., 2013). The data about tree species effect on soil greenhouse gas emissions is still scarce (Christiansen and Gundersen, 2011; Benanti et al., 2014; Liu et al., 2014).

As humidity manipulation in the FAHM experiment is a unique and novel approach to simulate future climate change for northern forests at the ecosystem level, many aspects of soil greenhouse gas emissions related to humidity are still unknown. As well as the effects of heat waves and drought in humid and temperate climate zones are insufficiently documented at the ecosystem level (Baldocci, 2008). In this paper, the main aim was to analyse how artificially elevated humidity, interactively with extreme weather conditions (high temperature and drought in summer) and tree species, influences soil CO_2, CH_4, and N_2O emissions.

The hypotheses of the study were: (i) the effect of elevated humidity on greenhouse gas emissions varies with tree species; (ii) an extremely hot and dry summer decreases CO_2, CH_4, and N_2O fluxes.

2. Materials and methods

2.1. Study site

The FAHM experiment was conducted in south-eastern Estonia (58°14′N 27°18′E) on abandoned agricultural land with Endogleyic Planosol soil (IUSS Working Group, 2007; Hansen et al., 2013). The study site covers 2.7 ha and the measurements were carried out in three humidified and three control plots. All hexagonal experimental plots ($14 \times 14\,m^2$ in size) were divided into four segments: according to tree species and understory vegetation. In spring 2006 one-year-old silver birch (*Betula pendula* Roth) seedlings were planted with 1 × 1 m spacing on half of each plot and micropropagated hybrid aspens (*Populus tremula* L. × *P. tremuloides* Michx.) on the other half of the experimental plots; hybrid aspens in the surrounding buffer zone were planted with 2 × 2 m spacing; however aspens had to be replanted in autumn as the planting material used in spring had a poor quality (Kupper et al., 2011). Each plot contained two types of understory: early successional community with low diversity and recently disturbed forest community, described thoroughly in Parts et al. (2013) and Kukumägi et al. (2014).

Humidification started in 2008. Humidity was increased by misting small droplets of water (10 μm) into the air up to one meter over the canopy in the humidified plots. The water use for nebulisation was $0.1\,m^3$ per hour per plot. Humidification occurred during the vegetation period (May – September), when ambient relative humidity was <75% and wind speed $<4\,m\,s^{-1}$ (Kupper et al., 2011). The FAHM facility is thoroughly described in Kupper et al. (2011), and Tullus et al. (2012a).

2.2. Soil and meteorological factors

Soil temperature, measured with a ST1 soil temperature probe (Delta-T Devices, Burwell, UK), and SWP, measured with an EQ2 equitensiometer (Delta-T Devices, Burwell, UK) at a depth of 15 cm, and relative humidity, measured with a HMP45A humidity probe (Vaisala, Helsinki, Finland), were recorded continuously with up to four sensors per plot (Kupper et al., 2011). Precipitation was measured in 10-min intervals with an automatic weather station (Campbell Scientific, Logan, UK) in the study site. Long-term meteorological data originated from the Tartu-Tõravere Meteorological Station (58°15′55′′ N, 26°27′58′′ E), which is located 50 km west of the study site.

2.3. Tree growth and litter measurements

Tree height and stem diameter at 30 cm height of all of the trees in the experimental plots were measured after the growing seasons in both years. For the measurement of tree heights, a Nedo mEssfix-S telescopic measuring rod (Nedo GmbH & Co.KG, Dornstetten, Germany) was used, whereas for stem diameter, a LIMIT