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Monsoon rains, drought periods and soil texture as drivers of soil N_2O fluxes – Soil drought turns East Asian temperate deciduous forest soils into temporary and unexpectedly persistent N_2O sinks

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ABSTRACT

To quantify N_2O fluxes between soil and atmosphere and understanding those processes driving them, is crucial if we aim to reliably predict one of earth's important greenhouse gases' origin and fate. Soil moisture has been identified as one major driver of N_2O fluxes, drought has been observed to decrease soil N_2O emissions and accounts for soil N_2O consumption. We monitored N_2O fluxes occurring at the soil/atmosphere interface of three temperate deciduous Korean forest sites experiencing a pronounced early summer drought followed by heavy East Asian monsoon rains. Because soil texture can enhance or mitigate soil drought effects, we selected sites which were different in topsoil texture. Therefore, we took closed chamber measurements of N_2O fluxes during the growing season 2010 and determined N_2O concentrations and $\delta^{15}N$ values along soil profiles in the dry and monsoon season for a sandy-loam site. We observed N_2O consumption at all of our study sites during early summer drought, which turned into N_2O emission during the monsoon season. The N_2O balance of the sandy-loam site remained slightly negative during the entire vegetation period. Soil moisture explained most of the measured N_2O fluxes. For a sandy-loam forest soil we calculated a switch between N_2O emission and consumption at an intermediate soil moisture (pF level of 3.02) which corresponds to a water filled pore space (WFPS) of 36%, but at half an order of magnitude moister soil (pF level: 2.57; WFPS 50%) at a loamy site. N_2O concentration and $\delta^{15}N_{N_2O}$ values along the soil profiles suggest that those processes driving the N_2O fluxes at the soil/atmosphere interface most likely occurred in the topsoil. Our results contribute to our knowledge on the global N_2O budget, because monsoon affected forests cover large areas worldwide and their soils' N_2O emissions have so far been uninvestigated.

1. Introduction

N_2O is a powerful greenhouse gas which contributes to the global warming effect (WMO, 2006) and is also involved in the destruction of the stratospheric ozone layer (Cicerone, 1987). Important sources of N_2O are mainly agriculturally managed soils but also include (semi-) natural forest soils (Potter et al., 1996; Davidson and Kingerlee, 1997; Pilegaard et al., 2006). Microbial denitrification, nitrification and nitrifier denitrification are the N_2O producing processes (Kool et al., 2011). However, a significant N_2O sink function has recently been observed in managed northern forests in Canada (Kellman and Kavanaugh, 2008), and in European forests (Goldberg and Gebauer, 2009a, 2009b; Inclán et al., 2012). Those findings are now of importance for further improvement of predictions on Earth's climate specifically under conditions of global climate change (Billings, 2008), as soils as N_2O sinks had not been taken into account for global N_2O balances before.

Still little is known about the underlying processes of this N_2O sink function, which can temporarily be observed in different soils. Soil moisture and temperature have been identified as the most important drivers of N_2O fluxes between forest soils and atmosphere (Butterbach-Bahl et al., 2004; Pilegaard et al., 2006; Kesik et al., 2006). It is also known that an increasing amount of rainfall as well as increasing soil temperature enhance N_2O emissions (Potter et al., 1996; Skiba et al., 1998; IPCC, 2001). IPCC (2007) predicted changes in precipitation and temperature regimes,

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which raised the question how such changes actually affect N_2O emissions from forest soils. Goldberg and Gebauer (2009b) showed that an experimentally induced drought of 46 days could temporarily turn the soil of a coniferous forest in Germany from a source into a transient N_2O sink. East Asian climate is even more extreme than the simulated one: yearly recurring heavy monsoon rainfall periods after eight months of fair to extreme drought (Qian et al., 2002; Yihui and Chan, 2005). This provides an extreme case of drying and rewetting cycles of soils and therefore we considered it as an adequate framework to field-test the above mentioned experimental results. And we intended to go one step further by investigating the effects of those long drought and heavy rainfall periods on forest soils distinguished by different soil textures, which appears of great importance especially when considering most recent findings by Wlodarczyk et al. (2011), who explicitly reported on loamy soils having a greater capacity to N_2O production and consumption than sandy soils.

Here we report on a monitoring study, to our knowledge investigating for the first time, how the N_2O fluxes of East Asian forests respond to the extreme fluctuations in soil moisture which we expected to be caused by heavy monsoon rains. Over and above the N_2O fluxes, we determined several additional parameters such as soil moisture, soil temperature, soil and vegetation properties, N deposition and C/N ratio to see if there were any relationships with the occurring N_2O fluxes. Because the soil texture can enhance or mitigate drought effects, due to differences in water holding capacity, aeration and O_2 availability etc., the measurements were carried out on three forest sites differing in their topsoil texture characteristics: each one predominantly consisted of sand, sandy-loam or loam, respectively. We hypothesized that the sandy site as the location with the most aerated and most quickly drying soil would show the least N_2O fluxes whereas the loamy soil with a greater water retaining capacity was expected to show higher emissions and less declining N_2O emissions during the drought period. Furthermore, we attempted to identify the switching point from N_2O emission to consumption and *vice versa* for each one of these soils.

2. Materials and methods

2.1. Experimental sites

The measurements were taken in three forests in the Haean Basin which is located northeast of the city of Chuncheon in Yanggu County, South Korea, between longitude 128°5′ to 128°11′E and latitude 38°13′ to 38°20′N, with a range in altitude from ca. 400 to 1100 m a.s.l. The average annual air temperature is ca. 10.5 °C at valley sites and ca. 7.5 °C at the northern ridgeline. Average precipitation is estimated at 1200 mm with 70% falling during the summer monsoon (Lee et al., 2010, unpublished).

The most important characteristics of the three sites are summarized in Table 1. The solar radiation (provided by the TERRECO-site (http://www.bayceer.uni-bayreuth.de/terreco/), downloaded on 10 January 2011) at the sites is shown in Fig. 1. According to the FAO soil classification (IUSS Working Group WRB, 2006) the soils of our research sites can be classified as Cambisols, even though they are different in soil texture of the first 20 cm topsoil layer.

2.2. Measurement of soil moisture and soil temperature and determination of pF levels

On the sandy-loam site two ECH_2O loggers and one ECH_2O logger at both sandy and loamy site (EM50 Data logger, Decagon Devices, WA, USA) were installed at 10 cm depth logging volumetric soil water content [%] and soil temperature [°C] every 30 min from 10 May until 31 October 2010. Afterwards the mean daily water content and mean temperature of the soils at 10 cm depth were calculated.

In addition, on all of the three sites three topsoil samples were collected using a soil corer. The samples' sand-, silt- and clay contents as well as their bulk densities were determined in the laboratory of the Soil Physics Department at the University of Bayreuth. The analysis method was wet sieving for sand and laser particle analyzer "Mastersizer S MAM5004" (Malvern Instruments, Herrenberg, Germany) for silt and clay. The samples were prepared by humus destruction (H_2O_2) and dispersion ($(NaPO_3)_6$). Based on the texture and bulk density data the computer program ROSETTA estimated the soil hydraulic parameters θ_r, θ_s, α and n which then defined the pF − water content − curve described by the Van-Genuchten function (Schaap et al., 2001) for each site. The pF level for each corresponding mean daily soil water content value was read out of that curve.

pF levels were determined because the topsoil characteristics of the study sites differed a lot and in order to make soil moisture site comparisons possible, a more independent factor stating soil moisture was needed. pF levels serve that purpose because they include soil characteristics such as soil texture and bulk density.

2.3. N_2O flux measurements

N_2O fluxes were measured from 14 May to 24 October of 2010 twice a week at the sandy-loam site and in weekly intervals at the

Table 1
Site characteristics of the studied forests, in Haean basin, South Korea.

Site	Location	Aspect	2010 monsoon precip. & mean air temp.	Soil characteristics	Dominant species basal area	Subdominant species basal area	Understory basal area	Average tree height
Sandy-loam	128°8′27.13″E 38°18′57.067″N 650 m a.s.l.	220°	1223 mm 8.5 °C	60% sand 31% silt 9% clay BD: 0.90 g cm^{-3}	10.3 m^{-2} ha^{-1} (*Quercus mongolica*)	10.15 m^{-2} ha^{-1} (*Quercus dentata*, *Tilia mandshurica*, & others)	2.46 m^{-2} ha^{-1} (*Q. dentata*, *Q. mongolica* & others)	9.9 m
Sandy	128°6′0.86″E 38°14′43.374″N 950 m a.s.l.	70°	1616 mm 7.5 °C	80% sand 15% silt 5% clay BD: 1.11 g cm^{-3}	16.13 m^{-2} ha^{-1} (*Q. mongolica*)	6.25 m^{-2} ha^{-1} (*Fraxinus rhynchophylla*, *Euonymus hamiltonianus*, & others)	1.02 m^{-2} ha^{-1} (*Acer pseudosieboldianum*, *Acer mono* & others)	4.9 m
Loamy	128°7′50.091″E 38°17′18.636″N 450 m a.s.l.	70°	1326 mm 10.5 °C	45% sand 42% silt 13% clay BD: 1.07 g cm^{-3}	11.43 m^{-2} ha^{-1} (*Quercus serrata*, *Q. mongolica*, *Q. aliena*, *Alnus japonica*)	4.38 m^{-2} ha^{-1} *Q. dentata*, *Ulmus laciniata* & others)	8.28 m^{-2} ha^{-1} (*Rhododendron yedoense*, *Euonymus alatus*, *Lespedeza cyrtotrya* & others)	9.6 m

As dominant species we identified those which accounted for at least half of the canopy area.
Temperature and rainfall data were downloaded from the TERRECO-site (http://www.bayceer.uni-bayreuth.de/terreco/) on 31st of January, 2011. Sand, silt and clay were classified according to EN ISO 14688.