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Impact of extreme precipitation and water table change on N₂O fluxes in a bio-energy poplar plantation

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Abstract

A large fraction of the West European landscape is used for intensive agriculture. Several of these countries have very high nitrous oxide (N_2O) emissions, because of substantial use of fertilizers and high rates of atmospheric nitrogen deposition. N_2O production in soils is controlled by water-filled pore space (WFPS) and substrate availability (NO_3^-). Here we show that extreme precipitation (~ 80 mm rainfall in 48 h) after a long dry period, led to a week-long peak in N_2O emissions (up to about $2200 \mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$). In the first four of these peak emission days, N_2O fluxes showed a pronounced diurnal pattern correlated to daytime increase in temperature and wind speed. It is possible that N_2O was transported through the transpiration stream of the poplar trees and emitted through the stomates. However, during the following three high emission days, N_2O emission was fairly stable with no pronounced diurnal trend, and was correlated with wind speed and WFPS (at 20 and 40 cm depth) but no longer with soil temperature. We hypothesized that wind speed facilitated N_2O emission from the soil to the atmosphere through a significant pressure-pumping. Successive rainfall events and similar WFPS after this first intense precipitation did not lead to N_2O emissions of the same magnitude. These findings suggest that climate change-induced modification in precipitation patterns may lead to high N_2O emission pulses from soil, such that sparser and more extreme rainfall events after longer dry periods could lead to peak N_2O emissions. The cumulative effects of more variable climate on annual N_2O emission are still largely uncertain and need further investigation.

1 Introduction

Nitrous oxide (N_2O) is one of the major greenhouse gases, with a global warming potential ~ 300 times higher than CO_2 , and that plays also a role in the destruction of stratospheric ozone (Cicerone, 1989). Approximately two thirds of the atmospheric N_2O originates from the biogenic processes of nitrification and denitrification

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(Davidson, 2010). As previously suggested (Kramer et al., 1999; Boeckx and Van Cleemput, 2001; Kroon et al., 2010a) N₂O emissions from agricultural soils are very important in European countries with a long history of fertilizer use. In addition to agricultural soils, forest soils in Western Europe could also present very high N₂O emissions (Pilegaard et al., 2006; Wu et al., 2010), caused by the high nitrogen deposition rates (Kristensen et al., 2004). The total emission of N₂O from forest soils in Germany (expressed as CO₂ equivalents) could reach up to 53% of the total emission of greenhouse gases (CO₂, CH₄, and N₂O) (Jungkunst et al., 2008). However, there are still large uncertainties on the estimates of N₂O fluxes from the biosphere (Houghton et al., 1996; Kroeze et al., 1999; Schindlbacher et al., 2004; Neftel et al., 2007).

The mechanisms responsible for N₂O emission and the environmental controls over its production are complex. For instance, increases in soil water content initially have a positive effect, but further increases have a negative effect on N₂O emissions; how soil water controls N₂O fluxes is not yet fully understood (Davidson et al., 2000; Jungkunst et al., 2008; Castellano et al., 2010). Dry, well-aerated soils favor the oxidative process of nitrification (with transformation of NH₄⁺ into NO₃⁻ and NO emission), wet soils favor NO₃⁻ and NO reduction, and N₂O emission, and finally extremely wet soils favor the complete N₂O reduction to N₂ by denitrifiers (Davidson, 1991; Davidson et al., 2000). A water-filled pore space (WFPS) of ~60% corresponds to the maximum N₂O emission (Davidson, 1991). However, N₂O emission is also strongly dependent on soil compaction, soil texture and bulk density (Ruser et al., 2006; Ball et al., 2008; Castellano et al., 2010). Water is a transport medium for NO₃⁻ and NH₄⁺, both substrates for the nitrifying and denitrifying microbes (Davidson et al., 2000). Soil aeration also affects gas diffusivity in the soil and increases N₂O release into the atmosphere (Davidson et al., 2000; Smith et al., 2003).

Previous studies highlighted the complexity in predicting N₂O fluxes from environmental variables, where similar soil water content could lead to very different emission rates (Schindlbacher et al., 2004; Castellano et al., 2010; Wu et al., 2010). Even long-term measurements (Hellebrand et al., 2003; Wagner-Riddle et al., 2007; Wu et

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al., 2010) were not able to unequivocally explain the processes responsible for N₂O release. Moreover, the processes leading to N₂O consumption within the soil are still largely unknown (Chapuis-Lardy et al., 2007). Nitrous oxide uptake has been observed in different ecosystems, such as grasslands (Glatzel and Stahr, 2001; Neftel et al., 2007) and forests (Cavigelli and Robertson, 2001; Butterbach-Bahl et al., 2002), and it has been connected to anaerobic microbial denitrification (Zumft, 1997).

N₂O release mostly occurs in short peak emissions connected to fertilization and precipitation events (Wagner-Riddle et al., 2007; Eugster et al., 2007; Jungkunst et al., 2008; Neftel et al., 2010). The short-term nature of the N₂O release and the difficulties in modeling N₂O emission generate the need for continuous monitoring to estimate annual N₂O emission from ecosystems. Unfortunately most studies have been of discontinuous nature (from weekly to monthly) (Kavdir et al., 2007; Neftel et al., 2007; 2010; Mammarella et al., 2010) and/or involved the use of soil chambers (Hellebrand et al., 2003; Kroon et al., 2010b; Wu et al., 2010), with associated spatial scaling issues, and with resulting uncertainties in annual estimates of more than 50% (Flecharde et al., 2007). Small spatial and discontinuous temporal resolution of chamber measurements prevent the accurate capture of some of these peak events-based N₂O release. Thus far, few studies have been performed at ecosystem scale with eddy covariance (Neftel et al., 2007; 2010; Eugster et al., 2007; Mammarella et al., 2010; Kroon et al., 2010a) or gradient techniques (Wager-Riddle et al., 2007). Neftel et al. (2007) reported that N₂O emission measured with eddy covariance exceeded that obtained by the chamber technique threefold.

Understanding the impact of climate and soil hydrology on N₂O emissions is particularly important, because the frequency and magnitude of drought and precipitation events are expected to increase with climate change (Kunkel et al., 2008). Future changes in rainfall patterns are predicted to increase N₂O emission by 45% even with reduced fertilizer application (Hsieh et al., 2005). As soil water content is believed to be among the most important controls on N₂O emission, altered precipitation patterns could significantly affect the emission of this greenhouse gas (Davidson et al., 1991;

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Groffman et al., 2009; McClain et al., 2003; Castellano et al., 2010).

The main objective of this study was to investigate the impact of soil hydrological changes (e.g. WFPS and water table change) on N₂O emission in a high-density bio-energy poplar plantation, recently converted from cropland and pasture. We hypothesized that increases in water table and WFPS connected to rain events lead to increases in N₂O emissions. We also hypothesized that increases in soil temperature stimulate N₂O production and thus increase N₂O emissions if adequate water is available in the soil.

2 Materials and methods

2.1 Site description

The research site is located in Lochristi, Belgium (51°06'44" N, 3°51'02" E), 11 km from the city of Ghent at an altitude of 6.25 m above sea level (Fig. 1). The long-term average annual temperature is 9.5 °C and the average total annual precipitation is 726 mm (Royal Meteorological Institute of Belgium). The soil has a sandy texture with a clay-enriched deeper soil layer. The soil C:N ratio (measured in February–March 2010) in the first 90 cm of the soils was on average 13.3 ± 1.4 ($n = 110$) and the bulk density was $\sim 1.482 \pm 0.075 \text{ g cm}^{-3}$. The soil pH was on average 5.51 ± 0.66 ($n = 42$). Nitrogen deposition in northern Belgium (Flanders) is $\sim 30\text{--}40 \text{ kg N ha}^{-1} \text{ y}^{-1}$ (Official report of the Flemish Environment Agency, Environmental Assessment Report).

A total of 18.4 ha were planted on 7–10 April 2010, with different poplar clones (belonging to the species *Populus deltoides*, *P. maximowiczii*, *P. nigra*, and *P. trichocarpa* and interspecific hybrids) in a double-row planting scheme (with 0.75 m and 1.5 m in between rows; 1.1 m within the rows, and a planting density of 8000 plants ha⁻¹). The canopy height of the plantation (measured in front of the eddy covariance mast) increased from ~ 1.3 m on 2 August to 2.1 m on 29 September 2010. Ditches of ~ 80 cm depth were established by the previous land users around the field to drain excess

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water. These ditches were draining water into deeper canals (1.5 m depth) at the outer edges of the field site. As a consequence the soil surface was mostly dry and drainage of standing water was fairly rapid.

The previous land uses were pasture and cropland (ryegrass, wheat, potatoes, beets, and most recently monoculture corn with regular fertilization, 200–300 kg N ha⁻¹ y⁻¹ liquid animal manure and chemical fertilizers). Before establishment of the plantation the agricultural land was ploughed in March 2010, to 40–70 cm depth. Several herbicide treatments were applied between the end of March and the beginning of April 2010, and between 25 June and 7 July 2010. Mechanical weeding was conducted, both manually and by tilling, from June until the end of August 2010. No fertilization or irrigation were applied during this experiment.

The site is surrounded by intensively managed croplands (mostly monoculture corn, and potatoes) with regular fertilizer application (170–250 kg N ha⁻¹ y⁻¹; K. Mouton, personal communication, 2010; S. Overloop, Flemish Environment Agency, personal communication, 2010). The N concentration in the water in the ditch around the field (measured on 29 October 2010) was on average 2.37 ± 0.005 mg N l⁻¹ (the sum of NO₃⁻-N and NO₂⁻-N) and 0.31 ± 0.0416 mg N l⁻¹ (NH₄⁺-N).

2.2 Environmental variables

A complete set of meteorological variables were recorded continuously from the beginning of June 2010 to the present day. Soil water content was measured at different depths (0–30 cm, 0–20 cm, 0–10 cm in different locations), and across a vertical transect (at 1 m, 60 cm, 40 cm, 30 cm, and 20 cm) in the proximity of the eddy covariance mast using 8 Time Domain Reflectometry (TDR, model CS616 Campbell Scientific, Logan, UT, USA) moisture probes. Soil water content was then converted to water-filled pore space (WFPS) according to Wu et al. (2010). Soil temperature was recorded by temperature probes which provided the average temperature of a soil layer of 8 cm

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depth (model TCAV-L averaging thermocouples, Campbell Scientific, Logan, UT, USA). These probes parallel four type-E thermocouples together into one, 24-gauge wire, and were inserted in proximity of each of the soil water content sensors. Surface temperature was recorded using an Apogee infrared sensor (Apogee Instruments, Inc., Logan UT, USA) pointing into the footprint of the eddy covariance mast at an angle of $\sim 45^\circ$ with the ground (with field of view 22° , height above the surface of 4.8 m, corresponding to a footprint of $\sim 7.7 \text{ m}^2$). Air temperature and relative humidity was recorded both on the eddy covariance mast using Vaisala probe (model HMP45C, Vaisala, Helsinki, Finland) at a height of 5.4 m above the ground surface. The air temperature profile was also measured at a meteorological tower at three different heights (50 cm, 1 m, and 2 m above the ground) with type-T thermocouples. Air pressure was measured with an electronic barometer (model PTB 101B, Vaisala, Helsinki, Finland). Incoming photosynthetically active radiation (PAR) (400–700 nm) was recorded above the canopy using quantum sensors (Li-190, Li-COR, NE, USA). Net radiation (0.2 to $100 \mu\text{m}$) was recorded using a net radiometer (NR Lite Kipp & Zonen, Delft, The Netherlands). The incoming and reflected shortwave solar (0.3 to $3 \mu\text{m}$) and longwave (far infrared 4.5 to $42 \mu\text{m}$) radiation were collected using two pyranometers and two pyrgeometers (model CNR1, Kipp & Zonen, Delft, The Netherlands). Diffuse radiation was monitored with a shadow-band pyranometer (model LP PYRA 02, Delta Ohm, Padova, Italy). The PAR sensor, the net radiometer, the pyranometers and pyrgeometers, and the diffuse radiation sensors were all mounted on the meteorological tower (where also sensors for measuring air temperature profile were installed) at 2 m above the surface and at $\sim 10 \text{ m}$ distance from the eddy covariance mast. Eight heat flux plates (HFT3, REBS Inc., Seattle, WA, USA) were installed in the soil at 6–8 cm depth. Precipitation was recorded using a tipping bucket rain gauge (model 3665R, Spectrum Technologies Inc., Plainfield, IL, USA) installed on top of the cabin where the gas analyzers were installed. Water table was recorded with a pressure transducer (model PDCR1830, Campbell Scientific, Logan, UT, USA) installed in a pipe inserted into the ground to a 1.85 m depth. All instruments were connected to two data loggers (model CR5000

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and model CR1000, Campbell Scientific, Logan, UT, USA) and each environmental variable was read once every 0.1–10 s and the 30 min averages are output to a PC.

2.3 Eddy covariance measurements

An eddy covariance mast was installed at the beginning of June 2010 and it was continuously been operated to the present day. The eddy covariance mast was positioned in the northeast part of the plantation (Fig. 1) including areas with both previous land use types (cropland and pasture). The eddy covariance mast included a sonic anemometer for the measurement of the three-dimensional wind components, wind speed, wind direction, and the energy fluxes (Model CSAT3, Campbell Scientific, Logan, UT, USA), and several fast-response analyzers, among them a closed-path Los Gatos N₂O/CO analyzer (model 908-0014, Los Gatos Research, Mountain View, LGR, CA, USA) and a closed path CO₂/H₂O infrared analyzer (LI-7000, LI-COR, Lincoln, NE, USA). The sonic anemometer and the inlet of the sampling lines were positioned at 5.8 m above the surface. The mast location was chosen according to the prevalent wind direction (from southeast, Fig. 1), to maximize the footprint of the tower. The sonic anemometer was oriented to 175° from true north. The large majority of wind directions were between 198° and 252° from north (Fig. 1).

The Los Gatos N₂O analyzer employs a cavity enhanced laser absorption technique in which an optical cavity is used as the measurement cell. This allows for a longer optical pathlength (400 ± 10 m) compared to conventional laser absorption techniques, resulting in increased sensitivity. The analyzer utilizes a room temperature mid-infrared quantum cascade laser and detector at a specific narrow band (4.6 μm). The internal pressure of the optical cell is fixed at 10 kPa. The analyzer has a 1 s 1σ precision of 0.3 ppbv for both N₂O and CO. A scroll pump (model XDS-35i, Edwards, MA, USA) was used to draw air through the N₂O analyzer. A two-meter long vacuum tubing was used to dampen the air flow and pressure in the air stream. The flow rate in the sampling line of the N₂O analyzer was ~25 l min⁻¹.

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The N₂O analyzer was calibrated at the LGR Company on 6 July 2010 using a NOAA primary standard at 322.24 ppbv N₂O in air (uncertainty less than 0.1 ppbv). The linearity of the analyzer was then tested by diluting a higher concentration bottle (440 ppbv N₂O) by known amounts and measuring the analyzer response. This dilution test proved that the accuracy of the instrument was better than 1% over the range of 40–440 ppbv N₂O (R. Provencal, Los Gatos Research, personal communication, 2010). We calibrated the N₂O analyzer again on 31 August 2010 with 733 ppbv (ultra high purity ≥ 99.997 vol% with 10% accuracy, limited by dilution system).

The LI-7000 (LI-COR, Lincoln, NE, USA) was used to measure CO₂ and H₂O fluxes. A vacuum pump was positioned at the outlet of the LI-7000 analyzer, generating a flow of ~ 22 l min⁻¹. Two buffer volumes of 0.5 l each respectively were positioned between the pump and the outlet of the analyzer to dump the fluctuations of the pump. Here we describe only calibration procedure for the H₂O fluxes as they were used to correct the N₂O fluxes (see following sections). CO₂ fluxes are presented and discussed elsewhere. The H₂O vapor was calibrated every week using ultra-high purity nitrogen for the zero, and a dew point generator (LI-610, LI-COR, Lincoln, NE, USA) to produce an air stream with a known water vapor dew point (typically 7 °C lower than the ambient air temperature) for the H₂O span.

Fluxes of H₂O, N₂O, and momentum were measured using eddy covariance, a micrometeorological method that quantifies the net exchange of a scalar between the biosphere and the atmosphere (Swinbank, 1951; Desjardins and Lemon, 1974; Baldocchi, 2003).

Teflon tubing (~ 15 m long and 8 mm inner diameter) was used for two separate sampling lines for the LI-7000 and for the N₂O analyzer. The two inlets were positioned 10 cm from the center of the sonic anemometer. A 1 μ m teflon filter (Gelman) was used at the inlet of the sampling line of the LI-7000 analyzer. A stainless steel Swagelok™ filter (60 μ m pore size SS-4FW4-60) was positioned at the inlet to protect the sampling line of the N₂O analyzer. Another stainless steel Swagelok™ filter (2 μ m pore size, SS-4FW4-2) was also present at the input of the sampling line to prevent dust from

entering the sample cell.

The H₂O, N₂O fluxes, and sonic wind components were recorded at 10 Hz using a data logger (model CR 5000, Campbell Scientific, Logan, Utah, USA). All the analyzers, the data loggers, and the PC were positioned inside a wooden cabin maintained at a stable temperature (21 °C).

2.4 Post-processing of the eddy covariance data

Fluxes of N₂O, H₂O, sensible heat, and momentum were calculated using the EdiRe software (version 1.4.3.1169, R. Clement, University of Edinburgh, UK; <http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/>) and averaged over 30 min.

A two-components rotation was applied to set mean vertical (w) and lateral (v) velocity components to zero. Time delays (on average 1.6 s for N₂O and 1.8 s for H₂O) were calculated using a cross-correlation function of the scalar fluctuation and the vertical wind velocity. A frequency response correction was applied to the eddy covariance fluxes following Moore (1986) and using theoretical attenuation functions and Kaimal model spectra to account for high frequency and low frequency fluctuations in signal losses (Kaimal et al., 1972). We also applied a correction for density change (WPL) according to Webb et al. (1980). We only applied the water vapor term of the WPL correction as we assume the long tube attenuated the temperature fluctuation. It should be noted that N₂O and H₂O fluxes were measured by different instruments (N₂O fluxes with the Los Gatos analyzer and H₂O fluxes with the Li-7000) with separate lines but similar flow rates.

Data quality was assessed by analysis of energy budget closure and by comparison of co-spectra of $\overline{w'Ts'}$, $\overline{w'H_2O'}$, $\overline{w'N_2O'}$ (Kaimal et al., 1972). Obvious data outliers were removed, which were values more than 30 standard deviations from the 30 min mean for H₂O vapor, N₂O and for the wind velocity components, u , v , and w . The remaining N₂O fluxes were filtered according to the following procedures: when N₂O concentration was < 0 (due to instrumental failure), in correspondence of error of the

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sonic anemometer (reported by the diagnostics of the CSAT-3D), when failing the stationarity test with a threshold of 30% as suggested by Foken and Wichura (1996). A footprint model was applied to the data (Klijun et al., 2004) indicating that the 90% of the fluxes were coming from the first ~200 m upwind of the eddy mast. Data with wind direction between 285° and 135° (from the north, back, and from the right of the tower) were removed.

Only N₂O fluxes are being presented in this manuscript, but CO₂ fluxes were used to derive u^* (defined as $\sqrt{u'w'}$) threshold, then applied to the N₂O fluxes. CO₂ fluxes for a solar radiation < 10 Wm⁻² were regressed with u^* and a u^* threshold was set to 0.15 m s⁻¹ (data not shown). H₂O fluxes were used for the WPL correction of the N₂O fluxes. As no standard procedure exists for gap-filling of the N₂O fluxes, we did not gap-fill them. The cumulative N₂O emission during 19–25 August 2010, was estimated from the daily average of the available data. The temperature sensitivity of N₂O emission (R) was investigated by fitting the following equation to the data:

$$R = BR \times Q_{10}^{((soil\ T - 10)/10)} \quad (1)$$

Where BR is the basal respiration and Q_{10} describes the response of respiration to temperature (soil T) increase.

2.5 Statistical analyses

General linear modeling (GLM) was used to identify the most important predictors of N₂O fluxes (Systat version 13, Systat Software Inc., 2002, Chicago, IL, USA). A single variable and a forward stepwise multiple regression approach were used to discriminate among and rank the most important variables (surface temperature, soil temperature at 0–8, 20, 30, 40, and 60 cm, WFPS at 0–10, 20, 30, 40, and 60 cm, water table depth, wind speed, u^*) in explaining the variability in N₂O fluxes. Models were applied to the instantaneous N₂O fluxes during the peak emission days (for 19–25 August, and separately for 19–22 August and 23–25 August 2010).

3 Results

3.1 Environmental conditions

Atmospheric conditions at the experimental field site during August 2010 were exceptional. From 11–14 August 2010, a depression over the North Sea brought maritime air over the European continent. From 15 to 17 August 2010, the depression moved toward Germany causing very active rain zones over Belgium (Royal Meteorological Institute of Belgium). At the field site the total measured rainfall on 16–17 August was 81 mm. The normal monthly total precipitation is 75 mm (at Ukkel, ~50 km from Lochristi, Royal Meteorological Institute of Belgium), less than what we measured in only 48 h. During the second decade of August the total precipitation reported for Ukkel was 111 mm (the long-term average for that decade is 25 mm), which was the highest value since 1901 (the second largest occurred in 1951 and was 71 mm).

Over the entire month of August 2010 the total precipitation at our site was 185 mm (187 mm at Ukkel, classified as an “exceptional event” by the Royal Meteorological Institute of Belgium, a denomination used for events that occur once every 30 yr). The record high total monthly precipitation at Ukkel was measured in 1996 (231 mm).

This extreme precipitation event led to a steep increase in water table and WFPS (Fig. 2). Prior to the precipitation event the water table was at ~136 cm below the surface and it was below 80 cm for the entire summer season (Fig. 2). The heavy rain on 16–17 August caused flooding of the field site (in several locations there was standing water) and overflowing of the ditches. The weekly total precipitation from 20 June to 16 August 2010 was on average 13 ± 11 mm while from 16 August to 3 October it was on average 37 ± 27 mm, not allowing the shallower soil layers (0–10 cm) to become drier than ~60% WFPS after 17 August (Fig. 2).

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3.2 N₂O fluxes

The spectral analysis showed that the co-spectra of $\overline{w'Ts'}$, and of $\overline{w'N_2O'}$ presented a reasonable comparison, demonstrating the good performance of the instruments (Fig. 3). The co-spectra of $w'N_2O'$ showed a slight loss at the high frequencies (typical for closed path analyzers) (Fig. 3). The energy budget closure for the presented data averaged 85%.

During the days immediately following the large rainfall event and the steep increase in water table and WFPS on 16–17 August, a steep increase in N₂O emission from the plantation was observed (Fig. 4). This large N₂O emission started on 19 August when the water table and WFPS progressively decreased (Fig. 4 and Fig. 5). From 19 to 22 August the N₂O emission presented a pronounced diurnal trend following the daytime increase in soil temperature (Fig. 5), and wind speed (or u^*) (Fig. 6). From 23 to 25 August when the wind speed was generally $> 2 \text{ m s}^{-1}$ (and the u^* was mostly $> 0.3 \text{ m s}^{-1}$) N₂O emissions did not present a diurnal pattern any more (Fig. 6).

To identify the most important environmental variables controlling N₂O emission during these peak release days, a general linear model was applied to the half hourly averaged N₂O fluxes. The results of the single variable model for 19–25 August, and for 19–22 and 23–25 August separately, are shown in Table 1–3. If the entire peak N₂O emission period was modeled together (19–25 August), the best single variable model included surface temperature that explained 48% of the variability in N₂O fluxes (Table 1). A multi-variable model that included surface T , u^* , and WFPS (at 60 cm) presented a slightly higher explanatory power of the N₂O fluxes ($R^2 = 51\%$, F-ratio 74, $p < 0.001$).

Similar results were found for the N₂O fluxes from 19 to 22 August (Table 2). During this period surface temperature and the shallow soil temperature (0–8 cm) explained 56% and 54% of the N₂O fluxes, respectively (Table 2). At this time wind speed and u^* were also important but presented lower explanatory power (29% and 33% respectively) than temperature (Table 2). The relation between N₂O emission (from

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19–22 August) and soil temperature (0–8 cm) was exponential and exhibited a Q_{10} of 3 (Fig. 7). The multi-variable model that presented the highest explanatory power of the N_2O fluxes from 19–22 August included surface temperature, soil T (60 cm depth), and wind speed, and it was able to explain 68% of the variability in N_2O emissions (F-ratio 67, $p < 0.001$).

N_2O emissions between 23 and 25 August did not present a diurnal trend (Fig. 5). During 23–25 August, soil and surface temperature were no longer significant predictor of N_2O fluxes (Table 3). During these days, wind speed and u^* were the variables with the highest explanatory power of N_2O fluxes and they explained 38% and 42% of the variability in N_2O fluxes, respectively, (Table 3). A multi-variable model that included u^* , WFPS (20 cm), and WFPS (40 cm) was able to explain 79% of the variability in N_2O fluxes (F-ratio 148, $p < 0.001$). Interestingly, we noticed that the WFPS at intermediate depth in the soil profile (20 cm) was sometimes lower than in the shallower and deeper layers. The water content in the shallower layers increased due to the mist and light rainfall (a clear example is shown on 7 July, Fig. 2 when WFPS at 0–10 cm increased right after a small rainfall, even while WFPS at 20 cm increased later only after a larger rainfall event).

The low turbulence at night ($u^* < 0.1 \text{ m s}^{-1}$) and moderately turbulent conditions during daytime ($u^* \sim 0.5 \text{ m s}^{-1}$), during the first four days (19–22 August), led to N_2O concentration increases at night, ranging from ~ 325 ppb to ~ 340 ppb over a few hours period (Fig. 6). The last three days (23–25 August) exhibited higher turbulent conditions, with u^* spanning from $\sim 0.3 \text{ m s}^{-1}$ at night to $\sim 0.8 \text{ m s}^{-1}$ during daytime, and presented a lower variability of N_2O concentration with no marked diurnal cycle (Fig. 6).

The daily total N_2O -N emission from 19–22 August was fairly stable, on average 0.26 ± 0.01 (SD) $\text{kg } N_2O\text{-N ha}^{-1}$, while the total daily emission from 23–25 August was also fairly stable (e.g. on average $0.13 \pm 0.014 \text{ kg } N_2O\text{-N ha}^{-1}$). We also estimated the approximate N present in the soil water using the average sum of NO_3^- -N, NO_2^- -N (their sum was $\sim 90\%$ of the total inorganic nitrogen) and NH_4^+ -N in the water from the ditch around the site and the average soil water content in the different soil layers on 19–

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25 August 2010. According to this calculation the total nitrogen present in the soil water was 9.7 kg N ha^{-1} . The total N emitted as N_2O from 19 to 25 August ($\sim 1.44 \text{ kg N}_2\text{O-N ha}^{-1}$) thus represented 15% of this soil water N content.

Rain events that occurred after 25 August 2010 led to similar increases and decreases in water table (and WFPS), but did not lead to N_2O emissions of the same magnitude of the one observed on 19–25 August (Fig. 4). Overall, N_2O fluxes before and after the peak emissions of 19–25 August, were mostly close to zero.

4 Discussion

The emission of N_2O differed dramatically between the week following the first extreme rain event and the rest of the study period. The low N_2O emission observed before the large rainfall on 16–17 August, could be related to the fact that under normal conditions well aerated sandy-loam soils are unlikely to develop the large number of anaerobic micro-sites necessary for N_2O production by denitrification (Skiba et al., 1993).

In contrast, a first extreme rain event induced production and release of substantial amount of N_2O . The maximum N_2O emission observed after the large rain fall in this study was several orders of magnitude higher than what is usually observed (Pilegaard et al., 2006; Davidson et al., 2000; Schauffler et al., 2010). Our maximum emission of about $2200 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ was comparable to reported peak emissions (Jungkunst et al., 2008; Kroon et al., 2009; Kroon et al., 2010a; Wu et al., 2010). Some of the highest N_2O peak emissions reported were recorded in a managed fen meadow (with a maximum of about $3200 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ in The Netherlands, Kroon et al., 2009), in spruce forests in Germany (a maximum of about $800 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$, Wu et al., 2010, and almost $3000 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$, Jungkunst et al., 2008), and in a bio-energy poplar plantation (in Germany, up to $900 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$, Hellebrand et al., 2003). The average daily emissions during 19–25 August resulted in a cumulative $\text{N}_2\text{O-N}$

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loss of 1.44 kg N₂O-N ha⁻¹ (~10% of the emission from agricultural soils in European countries, estimated to be ~15 kg N₂O-N ha⁻¹ y⁻¹; Boeckx and Van Cleemput, 2001).

Peak N₂O emission with re-wetting of dry soils has been observed in several ecosystems (Sexstone et al., 1985; Wagner-Riddle et al., 1996; Hsieh et al., 2005; Wagen-Riddle et al., 2007). The large release in N₂O emissions observed on 19–25 August may have been connected to multiple mechanisms. The flooding of the land could have transported NH₄⁺ and NO₃⁻ from the ditches or from surrounding agricultural fields to the plantation at a rate that exceeded the uptake of plants and microorganisms, leading to significant rates of denitrification and N₂O emission. It is likely that the extreme rain event probably also caused the reactivation of water-stressed bacteria following the dry period, which decomposed and mineralized the labile organic matter fraction, suddenly available in the soil (Birch, 1964). Additionally, the prolonged drier conditions before 16 August could have led to death of the microbial population in the shallower soil layers and the release of nitrogen in the soil, emitted as N₂O once the intense rain event suddenly increased moisture availability.

The observed lag between the rain event (16–17 August) and N₂O emission (19–25 August) was probably related to the rate of water infiltration through the soil profile (Fig. 5). The sustained high N₂O emission that we observed for a week was accompanied by the drop in the water table from the surface until about 60 cm below the surface from 16 to 23 August 2010 (Fig. 4). We observed the highest N₂O emission when the soil profile became less anoxic (e.g. WFPS 0–10 cm between 60–72%, Fig. 5) preventing the complete reduction of N₂O into N₂ (Davidson, 1991), but leaving sufficient anaerobic micro-sites available for denitrification (Rolston et al., 1982; Sexstone et al., 1985). Deeper soil layers presented a stable and higher WFPS (80%, Fig. 5) where probably N₂ production was dominant instead (Davidson, 1991; Davidson et al., 2000).

While N₂O fluxes from 19–22 August presented a pronounced diurnal trend with increased emission during daytime, the following days (23–25 August) presented stable emissions and no diurnal trend. This could be related to the interaction of different processes responsible for the N₂O emission. The observed diurnal pattern in N₂O

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emission between 19–22 August could be related to the N₂O release through poplar leaves. N₂O could be transported by the transpiration stream and emitted to the atmosphere (Chang et al., 1998; Mc Bain et al., 2004). Poplar seedlings emit N₂O when extremely high soil N₂O concentration was applied to the root zone (Chang et al., 1998; McBain et al., 2004). The dependence of N₂O emission on temperature on the 19–22 August could suggest the dependence of N₂O release from daytime increase in stomatal conductance and transpiration (Chang et al., 1998; McBain et al., 2004). The increase in transpiration with increasing wind speed, with abundant water in the soil and high stomatal conductance (Campbell and Norman, 1998), could explain the dependence of N₂O fluxes from wind speed at this time.

As N₂O emission from poplar leaves has been observed only under extremely high soil N₂O concentration (McBain et al., 2004), it was probably connected to the observed nighttime decrease in wind speed (and u^*) and increase in N₂O concentration (Fig. 6). This decrease in turbulence probably led to high N₂O concentration in the soil during 19–22 August. On the other hand, the high diffusion rates (Chang et al., 1998) and pressure pumping between 23–25 August prevented an N₂O concentration increase (Fig. 6), and probably an increase in concentration in the soil profile, thus reducing the importance of N₂O emission through leaves.

From 23–25 August, soil temperature lost its importance in explaining N₂O fluxes and the main environmental variables controlling N₂O release were wind speed (or u^*) in combination with moisture content in deeper soil layers (WFPS at 20 and 40 cm depth). At this time the main mechanism of N₂O emission was probably mass flow through the soil layers, not transpiration through the poplar leaves anymore. The wind pumping effect (Gu et al., 2005) probably pushed N₂O from deeper soil layers (where temperature was more stable, not presenting a diurnal trend) into the atmosphere, thus reducing the residence and the travelling time of N₂O in and from deeper soil profiles, and preventing its reduction to N₂. The occurrence of a more aerobic layer between 20 and 40 cm depth into the soil may have been either the site of production or storage of N₂O, that was released once the wind speed (or u^*) increased (Fig. 5).

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in previous studies (Rolston et al., 1982; Smith and Patrick, 1983). The intense precipitation event after a long dry period could also have been responsible for higher NO_3^- leaching than the one occurring under lower and more frequent precipitation events (Rolston et al., 1982).

5 Conclusions

Intense precipitation events after extended dry periods could have a large impact on N_2O emission; weekly or monthly monitoring schemes of N_2O fluxes could largely underestimate these emissions. In this study we showed that water table and soil water content could affect N_2O fluxes, but that an increase in soil water content does not necessarily lead to peak N_2O emissions, leaving large uncertainties on the controls of N_2O fluxes. Notably, the use of eddy covariance allowed capturing the effect of pressure pumping and increase in turbulence on N_2O emissions. Overall the results presented here explore multiple important mechanisms responsible for peak N_2O emission. The first peak emission days presented a diurnal increase in N_2O emission which suggested that N_2O was transported through the transpiration stream of the poplar trees and emitted through their stomates. However, during the last days of high emission, N_2O loss was fairly stable with no pronounced diurnal trend. Overall, wind speed, and increasing gas flow through the soil, played a major role on the N_2O emission. These results confirm the complexity in modeling N_2O emission and the need for continuous larger-scale studies.

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References

- Arah, J. R. M. and Vinten, A. J. A.: Simplified models of anoxia and denitrification in aggregated and simple-structured soils, *Eur. J. Soil Sci.*, 46, 507–517, 1995.
- Baldocchi, D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, *Glob. Change Biol.*, 9, 479–492, 2003.
- Ball, B. C., Crichton, I., and Horgan, G. W.: Dynamics of upward and downward N_2O and CO_2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence, *Soil Till. Res.*, 101, 20–30, 2008.
- Birch, H. F.: Mineralisation of plant nitrogen following alternate wet and dry conditions, *Plant Soil*, 20, 43–49, 1964.
- Boeckx, P. and Van Cleemput, O.: Estimates of N_2O and CH_4 fluxes from agricultural land in various regions of Europe, *Nutr. Cycl. Agroecosys.*, 60, 35–47, 2001.
- Butterbach-Bahl, K., Breuer, L., Gasche, R., Willibald, G., and Papen, H.: Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands: 1. Fluxes of N_2O , NO/NO_2 and CH_4 at forest sites with different N-deposition, *Forest Ecol. Manag.*, 167, 123–134, 2002.
- Campbell, G. S. and Norman, J. M.: *An Introduction to Environmental Biophysics*, Springer-Verlag, New York, 1998.
- Castellano, M. J., Schmidt, J. P., Kaye, J. P., Walker, C., Graham, C. B., Lin, H., and Dell, C. J.: Hydrological and biogeochemical controls on the timing and magnitude of nitrous oxide flux across an agricultural landscape, *Glob. Change Biol.*, 16, 2711–2720, 2010.
- Cavignelli, M. A. and Robertson, G. P.: Role of denitrifier diversity in rates of nitrous oxide consumption in a terrestrial ecosystem, *Soil Biol. Biochem.*, 33, 297–310, 2001.

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- Chang, C., Janzen, H. H., Cho, C. M., and Nakonechny, E. M.: Nitrous oxide emission through plants, *Soil Sci. Soc. Am. J.*, 62, 35–38, 1998.
- Chapuis-Lardy, L., Wrage, N., Metay, A., Chotte, J. L., and Bernoux, M.: Soils, a sink for N₂O?, a review, *Glob. Change Biol.*, 13, 1–17, 2007.
- 5 Christensen, S.: Nitrous oxide emission from a soil under permanent grass: Seasonal and diurnal fluctuations as influenced by manuring and fertilization, *Soil Biol. Biochem.*, 15, 531–536, 1983.
- Davidson, E. A.: Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems, in: *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes*, edited by: Rogers, J. E. and Whitman, W. B., American Society for Microbiology, Washington, DC, 219–236, 1991.
- 10 Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L.V., and Veldkamp, E.: Testing a conceptual model of soil emissions of nitrous and nitric oxides, *BioScience*, 50, 667–680, 2000.
- Davidson, E. A., Janssens, I. A., and Luo, Y. Q.: On the variability of respiration in terrestrial ecosystems: moving beyond $Q_{(10)}$, *Glob. Change Biol.*, 12, 154–164, 2006.
- 15 Desjardins, R. L. and Lemon, E. R.: Limitations of an eddy-correlation technique for the determination of the carbon dioxide and sensible heat fluxes, *Bound.-Lay. Meteorol.*, 5, 475–488, 1974.
- Dowdell, R. J. and Smith K. A.: Field studies of the soil atmosphere ii. occurrence of nitrous oxide, *J. Soil Sci.*, 25, 231–238, 1974.
- 20 Eugster, W., Zeyer, K., Zeeman, M., Michna, P., Zingg, A., Buchmann, N., and Emmenegger, L.: Methodical study of nitrous oxide eddy covariance measurements using quantum cascade laser spectrometry over a Swiss forest, *Biogeosciences*, 4, 927–939, doi:10.5194/bg-4-927-2007, 2007.
- 25 Flechard, C. R., Ambus, P., Skiba, U., Rees, R. M., Hensen, A., Van Amstel, A., Van den Polvan Dasselaar, A., Soussana, J.-F., Jones, M., Clifton-Brown, J., Raschi, A., Horvath, L., Neftel, A., Jocher, M., Ammann, C., Leifeld, J., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K. J., Levy, P.E., Ball, B. C., Jones, S. K., Van de Bulk, W. C. M., Groot, T., Blom, M., Domingues, R., Kasper, G., Allard, V., Ceschia, E., Cellier, P., Laville, P., Henault, C., Bizouard, F., Abdalla, M., Williams, M., Baronti, S., Berretti, F., and Grosz, B.: Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe, *Agr. Ecosyst. Environ.*, 121, 135–152, 2007.
- 30

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- Foken, T. and Wichura B.: Tools for quality assessment of surface-based flux measurements, *Agric. Forest Meteorol.*, 78, 83–105, 1996.
- Glatzel, S. and Stahr, K.: Methane and nitrous oxide exchange in differently fertilized grassland in southern Germany, *Plant Soil*, 231, 21–35, 2001.
- 5 Groffman, P., Butterbach-Bahl, K., Fulweiler, R., Gold, A., Morse, J., Stander, E., Tague, C., Tonitto, C., and Vidon, P.: Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models, *Biogeochemistry*, 93, 49–77, 2009.
- Grundmann, G. L., Rolston, D. E., and Kachanoski R. G.: Field soil properties influencing the variability of denitrification gas fluxes, *Soil Sci. Soc. Am. J.*, 52, 1351–1355, 1988.
- 10 Gu, L. H., Falge, E. M., Boden, T. A., Baldocchi, D. D., Black, T. A., Saleska, S. R., Suni, T., Verma, S. B., Vesala, T., Wofsy, S. C., and Xu, L. K.: Objective threshold determination for nighttime eddy flux filtering, *Agric. Forest Meteorol.*, 128, 179–197, 2005.
- Hellebrand, H. J., Kern, J., and Scholz, V.: Long-term studies on greenhouse gas fluxes during cultivation of energy crops on sandy soils, *Atmos. Environ.*, 37(12), 1635–1644, 2003.
- 15 Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K.: *Climate Change 1995; The Science of Climate Change*, Cambridge University Press, New York, 1996.
- Hsieh, C. I., Leahy, P., Kiely, G., and Li, C.: The effect of future climate perturbations on N₂O emissions from a fertilized humid grassland, *Nutr. Cycl. Agroecosys.*, 73, 15–23, doi:10.1007/s10705-005-7129-4, 2005.
- 20 Cicerone, R.: Analysis of sources and sinks of atmospheric nitrous oxide, *J. Geophys. Res.*, 94, 18265–18271, 1989.
- Jungkunst, H. F., Flessa, H., Scherber, C., and Fiedler, S.: Groundwater level controls CO₂, N₂O and CH₄ fluxes of three different hydromorphic soil types of a temperate forest ecosystem, *Soil Biol. Biochem.*, 40, 2047–2054, 2008.
- 25 Kaimal, J. C., Wyngard, J. C., Izumi, Y., and Cote, O. R.: Spectral characteristics of surface-layer turbulence, *Q. J. Roy. Meteor. Soc.*, 98, 563–589, 1972.
- Kavdir, Y., Hellebrand, H. J., and Kern, J.: Seasonal variations of nitrous oxide emission in relation to nitrogen fertilization and energy crop types in sandy soil, *Soil Till. Res.*, 98, 175–186, 2008.
- 30 Kljun, N., Calanca, P., Rotach, M. W., and Schmid, H. P.: A simple parameterisation for flux footprint predictions, *Bound.-Lay. Meteorol.*, 112, 503–523, 2004.

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- Kramer, K. J., Moll, H. C., and Nonhebel, S.: Total greenhouse gas emissions related to the Dutch crop production system, *Agr. Ecosyst. Environ.*, 72, 9–16, 1999.
- Kristensen, H. L., Gundersen, P., Callesen, I., and Reinds, G. J.: Throughfall nitrogen deposition has different impacts on soil solution nitrate concentration in European coniferous and deciduous Forests, *Ecosystems*, 7, 180–192, 2004.
- Kroeze, C., Mosier, A., and Bouwman, L.: Closing the global N₂O budget: A retrospective analysis 1500–1994, *Global Biogeochem. Cy.*, 13, 1–8, 1999.
- Kroon, P., Hensen, A., van den Bulk, W. C. M., Jongejan, P., and Vermeulen, A.: The importance of reducing the systematic error due to non-linearity in N₂O flux measurements by static chambers, *Nutr. Cycl. Agroecosyst.*, 83, 97–98, 2009.
- Kroon, P. S., Schrier-Uijl, A. P., Hensen, A., Veenendaal, E. M., and Jonker, H. J. J.: Annual balances of CH₄ and N₂O from a managed fen meadow using eddy covariance flux measurements, *Eur. J. Soil Sci.*, 61, 773–784, 2010a.
- Kroon, P. S., Hensen, A., Jonker, H. J. J., Ouwersloot, H. G., Vermeulen, A. T., and Bosveld, F. C.: Uncertainties in eddy covariance flux measurements assessed from CH₄ and N₂O observations, *Agric. Forest Meteorol.*, 150, 806–816, 2010b.
- Kunkel, K. E., Bromirski, P., Brooks, H., Cavazos, T., Douglas, A. V., Easterling, D. R., Emanuel, K. A., Holland, G. J., Knutson, T. R., Kossin, J. P., Komar, P. D., Levinson, D. H., and Smith, R. L.: Observed changes in weather and climate extremes, in: *Weather and Climate Extremes in a Changing Climate, Regions of Focus: North America, Hawaii, Caribbean, and US Pacific Islands*, edited by: Karl, T. R., Meehl G. A., Hassol S. J., Murray W. L., and Waple A. M., A Report by the US Climate Change Science Program and Subcommittee on Global Change Research, Washington, DC, 2008.
- Mammarella, I., Werle, P., Pihlatie, M., Eugster, W., Haapanala, S., Kiese, R., Markkanen, T., Rannik, Ü., and Vesala, T.: A case study of eddy covariance flux of N₂O measured within forest ecosystems: quality control and flux error analysis, *Biogeosciences*, 7, 427–440, doi:10.5194/bg-7-427-2010, 2010.
- Maag, M. and Vinther, F. P.: Nitrous oxide emission by nitrification and denitrification in different soil types and at different soil water content contents and temperatures, *Appl. Soil Ecol.*, 4, 5–14, 1996.
- McBain, M. C., Warland, J. S., McBride, R. A., and Wagner-Riddle, C.: Laboratory-scale measurements of N₂O and CH₄ emissions from hybrid poplars (*Populus deltoides* X *Populus nigra*), *Waste Manag. Res.*, 22, 454–465, 2004.

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5 Moore, C. J.: Frequency response corrections for eddy correlation system, *Bound.-Lay. Meteorol.*, 37, 17–35, 1986.

Neftel, A., Flechard, C., Ammann, C., Conen, F., Emmenegger, L., and Zeyer, K.: Experimental assessment of N₂O background fluxes in grassland systems, *Tellus B*, 59, 470–482, 2007.

10 Neftel, A., Ammann, C., Fischer, C., Spirig, C., Conen, F., Emmenegger, L., Tuzson, B., and Wahlen, S.: N₂O exchange over managed grassland: Application of a quantum cascade laser spectrometer for micrometeorological flux measurements, *Agric. Forest Meteorol.*, 150, 775–785, 2010.

15 Pilegaard, K., Skiba, U., Ambus, P., Beier, C., Brüggemann, N., Butterbach-Bahl, K., Dick, J., Dorsey, J., Duyzer, J., Gallagher, M., Gasche, R., Horvath, L., Kitzler, B., Leip, A., Pihlatie, M. K., Rosenkranz, P., Seufert, G., Vesala, T., Westrate, H., and Zechmeister-Boltenstern, S.: Factors controlling regional differences in forest soil emission of nitrogen oxides (NO and N₂O), *Biogeosciences*, 3, 651–661, doi:10.5194/bg-3-651-2006, 2006.

Rappoldt, C. and Crawford, J. W.: The distribution of anoxic volume in a fractal model of soil, *Geoderma*, 88, 329–347, 1999.

20 Rolston, D. E., Sharpley, A. N., Toy, D. W., and Broadbent, F. E.: Field Measurement of denitrification: III. Rates during irrigation cycles, *Soil Sci. Soc. Am. J.*, 46, 289–296, 1982.

Ruser, R., Flessa, H., Russow, R., Schmidt, G., Buegger, F., and Munch, J. C.: Emission of N₂O, N₂ and CO₂ from soil fertilized with nitrate: effect of compaction, soil water content and rewetting, *Soil Biol. Biochem.*, 38, 263–274, 2006.

25 Schaufler, G., Kitzler, B., Schindlbacher, A., Skiba, U., Sutton, M. A., and Zechmeister-Boltenstern, S.: Greenhouse gas emissions from European soils under different land use: effects of soil water content and temperature, *Eur. J. Soil Sci.*, 61, 683–696, doi:10.1111/j.1365-2389.2010.01277.x, 2010.

30 Schindlbacher, A., Zechmeister-Boltenstern, S., and Butterbach-Bahl, K.: Effects of soil water content and temperature on NO, NO₂, and N₂O emissions from European forest soils, *J. Geophys. Res.*, 109, D17302, doi:10.1029/2004JD004590, 2004.

Sexstone, A. J., Parkin, T. B., and Tiedje, J. M.: Temporal response of soil denitrification rates to rainfall and irrigation, *Soil Sci. Soc. Am. J.*, 49, 99–103, 1985.

- Skiba, U., Smith, K. A., and Fowler, D.: Nitrification and denitrification as sources of nitric oxide and nitrous oxide in a sandy loam soil, *Soil Biol. Biochem.*, 25, 1527–1536, 1993.
- Smith, C. J. and Patrick Jr., W. H.: Nitrous oxide emission as affected by alternate anaerobic and aerobic conditions from soil suspensions enriched with ammonium sulfate, *Soil Biol. Biochem.*, 15, 693–697, 1983.
- Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J., and Ray, A.: Exchange of greenhouse gases between soil and atmosphere: Interactions of soil physical factors and biological processes, *European J. Soil Sci.*, 54, 779–791, 2003.
- Swinbank, W. C.: The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere, *J. Meteorol.*, 72, 135–132, 1951.
- Tiedje, J. M., Sexstone, A. J., Parkin, T. B., Revsbech, N. P., and Shelton, D. R.: Anaerobic processes in soil, *Plant Soil*, 76, 197–212, 1984.
- van Groenigen, J. W., Zwart, K. B., Harris, D., and van Kessel, C.: Vertical gradients of $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ in soil atmospheric N_2O – temporal dynamics in a sandy soil, *Rapid Commun. Mass Sp.*, 19, 1289–1295, 2005.
- Verchot, L. V., Davidson, E. A., Cattânio, J. H., Ackerman, I. L., Erickson, H. E., and Keller, M.: Land-use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia, *Global Biogeochem. Cy.*, 13, 31–46, 1999.
- Vicca, S., Janssens, I. A., Flessa, H., Fiedler, S., and Jungkunst, H. F.: Temperature dependence of greenhouse gas emissions from three hydromorphic soils at different groundwater levels, *Geobiology*, 7, 465–476, 2009.
- Vinther, F. P.: Measured and simulated denitrification activity in a cropped sandy and loamy soil, *Biol. Fert. Soils*, 14, 43–48, 1992.
- Wagner-Riddle, C., Thurtell, G. W., King, K. M., Kidd, G. E., and Beauchamp, E. G.: Nitrous oxide and carbon dioxide fluxes from a bare soil using a micrometeorological approach, *J. Environ. Qual.*, 25, 898–907, 1996.
- Wagner-Riddle, C., Furon, A., McLaughlin, N., Lee, I., Barbeau, J., Jayasundara, S., Parkin, G., Von Bertoldi, P., and Warland, J.: Intensive measurements of nitrous oxide emissions from a corn-soybean-wheat rotation under two contrasting management systems over 5 years, *Glob. Chang Biol.*, 13, 1722–1736, 2007.
- Webb, E. K., Pearman, G. I., and Leuning, R.: Correction of flux measurements for density effects due to heat and water-vapor transfer, *Q. J. Roy. Meteor. Soc.*, 106, 85–100, 1980.
- Wu, X., Brüggemann, N., Gasche, R., Shen, Z., Wolf, B., and Butterbach-Bahl, K.: Environ-

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mental controls over soil-atmosphere exchange of N₂O, NO, and CO₂ in a temperate Norway spruce forest, *Global Biogeochem. Cy.*, 24, GB2012, doi:10.1029/2009GB003616, 2010.
Zumft, W. G.: Cell biology and molecular basis of denitrification, *Microbiology and Molecular Biology Review*, 61, 533–616, 1997.

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Table 1. Single variable model (GLM) for the N₂O fluxes (19–25 August 2010), displayed are R^2 , F-ratio and p-values; in bold the single environmental variable with the highest explanatory power of the N₂O fluxes. Notice that during this period surface temperature explains most of the N₂O fluxes.

	variable	R^2	F-ratio	p-value
N ₂ O fluxes	surface T	0.48	178	< 0.001
	soil T (0–8 cm)	0.37	127	< 0.001
	soil T (20 cm)	0.27	76	< 0.001
	soil T (30 cm)	0.06	14	< 0.001
	soil T (40 cm)	0	1	0.395
	soil T (60 cm)	0.025	6	0.019
	WFPS (0–10 cm)	0	0.58	0.45
	WFPS (20 cm)	0	0	0.96
	WFPS (30 cm)	0	0.02	0.88
	WFPS (40 cm)	0	1	0.31
	WFPS (60 cm)	0.27	83	< 0.001
	water table	0	0.023	0.88
	wind speed	0	0.3	0.62
	u^*	0	0.7	0.42

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Table 2. Single variable model (GLM) for the N₂O fluxes (19–22 August 2010), displayed are R^2 , F-ratio and p-values; in bold the single environmental variable with the highest explanatory power of the N₂O fluxes. Notice that during this period surface temperature explains most of the N₂O fluxes.

	variable	R^2	F-ratio	p-value
N ₂ O fluxes	surface T	0.56	113	< 0.001
	soil T (0–8 cm)	0.54	113	< 0.001
	soil T (20 cm)	0.45	80	< 0.001
	soil T (30 cm)	0.26	33	< 0.001
	soil T (40 cm)	0.17	19	< 0.001
	soil T (60 cm)	0.11	12	< 0.001
	WFPS (0–10 cm)	0.31	42	< 0.001
	WFPS (20 cm)	0.31	45	< 0.001
	WFPS (30 cm)	0.3	41	< 0.001
	WFPS (40 cm)	0.21	18	< 0.001
	WFPS (60 cm)	0.14	15	< 0.001
	water table	0.29	41	< 0.001
	wind speed	0.29	40	< 0.001
	u^*	0.33	48	< 0.001

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Table 3. Single variable model (GLM) for the N₂O fluxes (23–25 August 2010), displayed are R^2 , F-ratio and p-values; in bold the single environmental variable with the highest explanatory power of the N₂O fluxes. Notice * during this period u^* explains most of the N₂O fluxes.

	variable	R^2	F-ratio	p-value
N ₂ O fluxes	surface T	0	0	0.93
	soil T (0–8 cm)	0.02	2	0.13
	soil T (20 cm)	0	1	0.3
	soil T (30 cm)	0.02	3	0.086
	soil T (40 cm)	0	2	0.16
	soil T (60 cm)	0.035	4	0.039
	WFPS (0–10 cm)	0	0	0.81
	WFPS (20 cm)	0.054	7	0.011
	WFPS (30 cm)	0.026	3	0.078
	WFPS (40 cm)	0	0	0.89
	WFPS (60 cm)	0.12	16	< 0.001
	water table	0	2	0.21
	wind speed	0.38	73	< 0.001
	u^*	0.42	86	< 0.001

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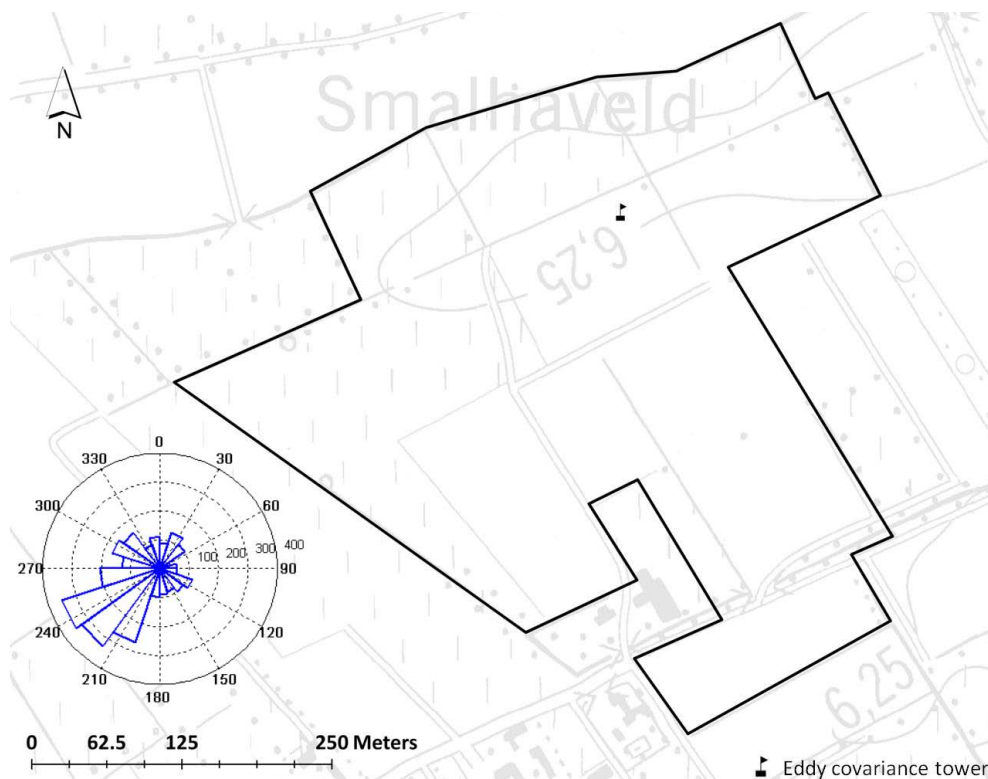


Fig. 1. Topographic map of the study site (Lochristi, East of Flanders, Belgium) and wind rose for the entire period of measurements (4 August–30 September 2010). The position of the eddy covariance mast is also indicated.

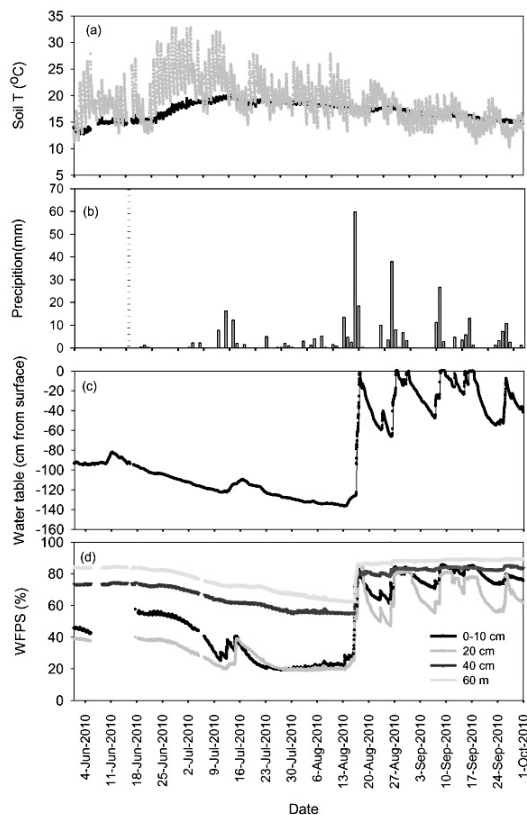


Fig. 2. Soil temperature at 1 m and 0–8 cm depth **(a)**, total daily precipitation **(b)**, water table **(c)**, water-filled pore space (WFPS) at 0–10 cm, 20 cm, 40 cm, and 60 cm depth in the soil during the period 1 June to 1 October 2010. Precipitation data were only available from 18 June 2010 onward (notice dashed line in panel **(b)**).

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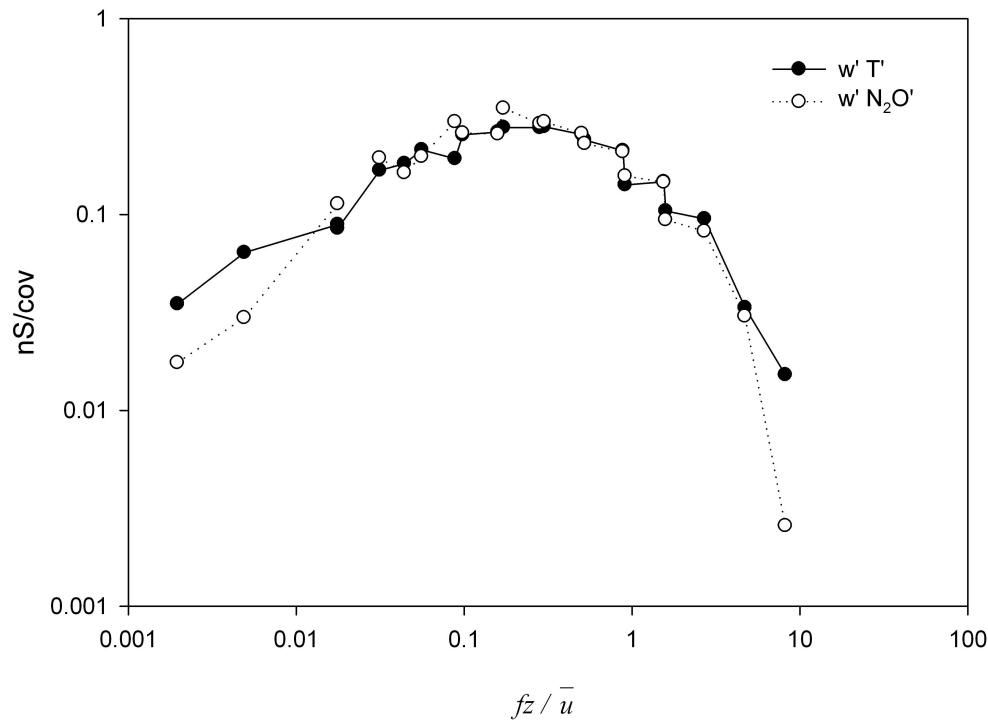


Fig. 3. Cospectra normalized by frequency (n) and covariance (cov) of the fluctuation in vertical wind velocity and the fluctuation in sonic temperature ($w'T's'$) and N₂O ($w'N_2O'$) averaged for 19–25 August 2010 (in logarithmic scale); f is the frequency in Hz, z is the measurement height (5.8 m) and \bar{u} is the mean wind speed in each corresponding half hour ($m\ s^{-1}$).

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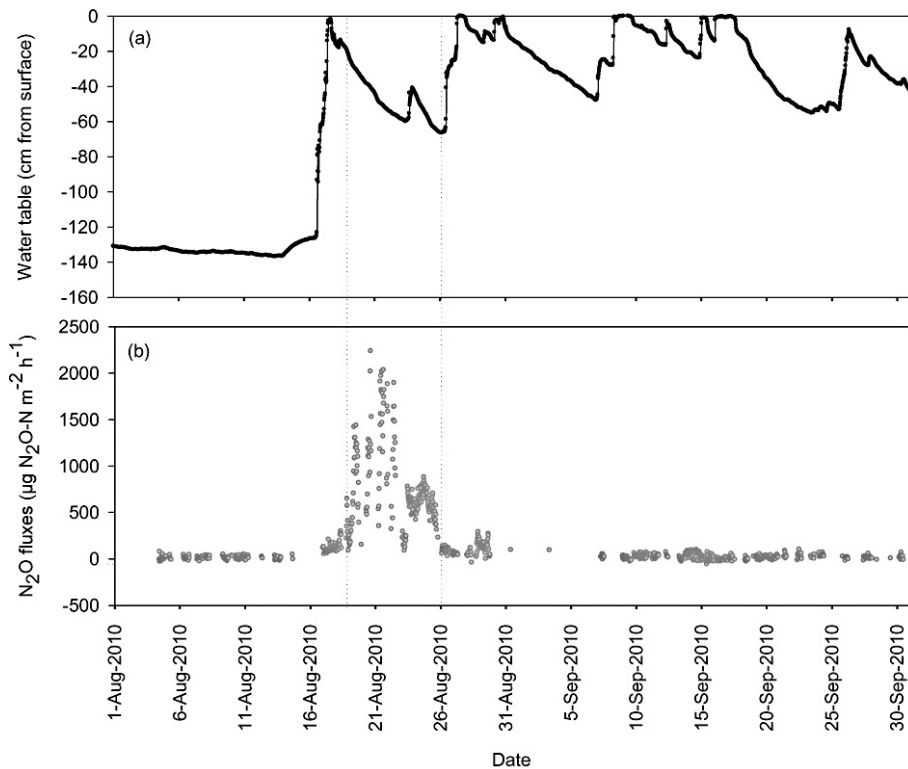


Fig. 4. Height of the water table **(a)** and N₂O fluxes **(b)** for the entire measurement period. Notice the large N₂O emission from 19 to 25 August 2010 after the water table increased to the surface and then decreased below 20 cm.

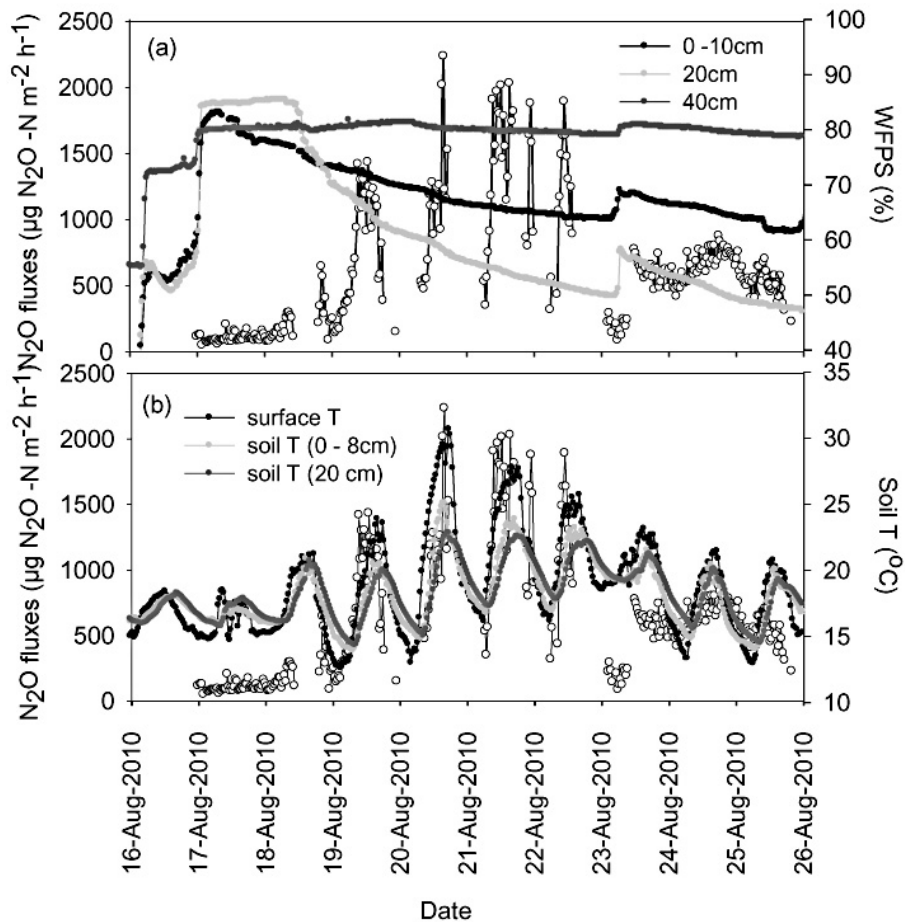


Fig. 5. N_2O fluxes superimposed to WFPS (at 0–10 cm, 20 cm, and 60 cm) **(a)**, and to soil temperature (0–8 cm and 60 cm) **(b)**, right before and during the peak emission period (16–25 August 2010).

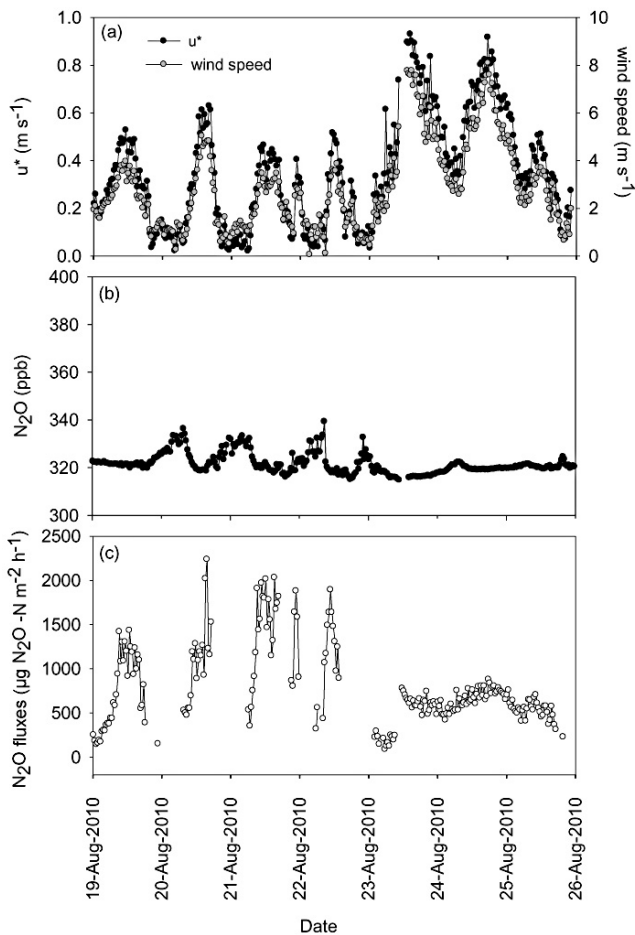


Fig. 6. Wind speed and u^* (a), N_2O concentration (b), and N_2O fluxes (c), during the peak emission days (19–25 August 2010).

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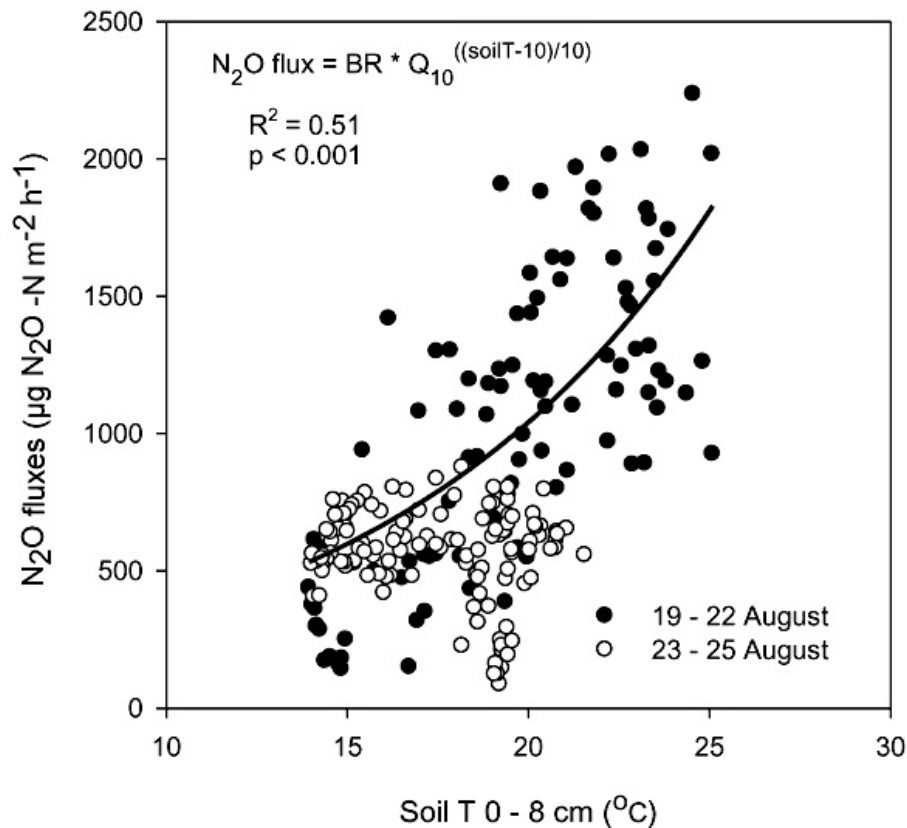


Fig. 7. Q_{10} dependence of N_2O fluxes for the different peak emission periods (19–22 August and 23–25 August 2010). The fitted curve, R^2 and p-value displayed refer to the period 19–22 August, as N_2O fluxes from 23–25 August 2010 were not correlated with soil temperature. BR indicates basal respiration.