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N_2O and CO_2 Emissions From Arable and Grassland Soils Under Various Moisture Regimes: A Microcosm Study

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ABSTRACT

Greenhouse gas emissions have increased during the last century due to human activities such as agricultural practices, fossil fuel burning and industrial practices. However, the formation of greenhouse gases, in particular N_2O or CO_2 is strongly controlled by both soil temperature and soil moisture. A laboratory experiment was conducted to assess the response of grassland and arable soils with regard to N_2O and CO_2 flow and mineral nitrogen concentration; soils were exposed to various drying- rewetting cycles at different gravimetric water contents (θwt) under controlled conditions for a duration of 60 days. In total, four treatments were conducted: soils under continuously moist conditions (control) at 32% θwt; soils received short drying-rewetting cycles (SDWC) of between 32 to 21% θwt; soils exposed to medium drying rewetting cycles (MDWC) of between 32 to 18% θwt and a treatment with long drying-rewetting cycles (LDWC) of between 32 to 5% θwt. Short, medium and long drying-rewetting cycle treatments went through 6, 4 and 2 drying-rewetting cycles (DWC) (0.1, 0.07 and 0.03 drying-rewetting frequencies). Soil samples of arable and grassland soils were analyzed for NH_4^+ and NO_3- at the different stages of incubation in order to compare changes over time. The results indicated that arable and grassland soils reduced N_2O-N flow in the long drying-rewetting treatments. For the grass soil, the short drying-rewetting cycle treatment yielded the highest cumulative N_2O-N flow (325 μg kg^{-1}). In arable soil, however, the long drying-rewetting cycles receiving treatment released 69% less N_2O-N flow as compared to the other treatments. For the CO_2-C flow, soils showed differing patterns, with the shortly dried-rewetted cycle treatment of grassland soils yielding the highest (130 μg kg^{-1}) cumulative flow that was 25% higher than LDWC. Drying-rewetting cycles (DWC) on grass soils had no effect. The stressed treatments emitted only 19% higher CO_2-C flow than the control. The treatment with 5% (θwt) successfully reduced N_2O-N flow in grassland and arable soils. Soil net nitrogen mineralization (NNM) and nitrification (NNN) rates of arable soils were significantly higher than in grassland soils.

Keywords: Grassland soils, arable soils, N_2O, CO_2, moisture regimes.

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INTRODUCTION

Soils are one of the major sources of atmospheric greenhouse gases, in particular CO_2 (Raich *et al*., 2002) and 70 % of the total N_2O emissions (Wei *et al.*, 2010; Conrad 1996). N_2O and CO_2 are the consequences of microbial mediated processes, enhanced by physico-chemical characteristics of soil (Batjes and Bridges 1992) and land management practices (Ugalde *et al.*, 2007). Nitrous oxide is very stable and persists in the atmosphere for approximately 120 years. It has a large global warming potential that is 296 times greater than CO_2 in a 100-year period and is related to the catalytic destruction of the stratospheric ozone (Diz-Muñoz *et al*., 2010). Atmospheric CO_2 concentration has increased by almost 100µL L^{-1} since pre-industrial levels, reaching as high as 379µL L^{-1} in 2005. The mean annual growth rate during 2000-2005 was higher than in the 1990s and will continue to rise in Europe, Caucasus and Central Asia by more than 40% until 2030 (IPCC, 2007).

Fierer *et al.,* (2003) predicted that mineral soils are expected to receive long drying periods during summers in this century because of climate change (Muhr *et al*., 2008). Surface soils get more exposure to drying-rewetting events (Fierer and Schimel, 2002) and this have a significant impact on the microbial community (Smith *et al*., 2003) by providing physiological stress (Fierer *et al.*, 2003).

Few studies have underlined how the frequency of stress events (drying-rewetting) control soil biochemical processes related to C and N cycles. Wang *et al.,* (2010) indicated that the C mineralisation rate was not significantly affected by moisture. However, several reports suggest that repeated drying-rewetting has an effect on nitrogen and carbon turnover in the soil (Kruse *et al*., 2004; Butterly, 2008) and on the microbial community (Fierer and Schimel, 2002; Smith *et al.*, 2003). Nitrifier activity may generally be sensitive to low moisture (Fierer and Schimel, 2002). Maximum N_2O was emitted when soil was rewetted (Ruser *et al.*, 2005), yet no differences between constantly moist (Beare *et al.*, 1999) and frequently dried soils (Kruse *et al*., 2004) were found. Shortage of water can retard microbial activity by lowering intracellular water potential and in solid matrices by restricting substrate supply, leading to a decline in nitrification rates (Stark and Firestone, 1995). However, nitrification rates were found to increase in the soils that were exposed to soil drying for short periods (Fierer and Schimel, 2002; Kessavalou *et al.*, 1998).

Nitrous oxide emissions are significantly affected by soil moisture during the wheat growing season (Liu *et al*., 2011). Normally, wheat crops require adequate irrigation and fertilisers during the entire growth period. High N fertilisation stimulates N_2O emission by providing substrate as NH_4^+ and NO_3^- for the microbes, enhancing nitrification and denitrification (Duxbury, 1994). In winter wheat, nitrogen fertiliser application (Mancino and Torello, 1986) and soil organic carbon (Huang *et al*., 2002a) did not affect the denitrifier population and N_2O emission. Chen *et al*., (2007) even postulated that N input is not the parameter that can predict seasonal N_2O emission from the soil. The release of CO_2 through aerobic respiration becomes a function of water content when the soil dries out

(Smith *et al*., 2003). Variability in moisture content can also affect respiration rates (Fierer and Schimel 2002). Thomson *et al.* (2010) detected significantly higher respiration rates in dried and rewetted microcosms.

Global circulation models indicate that an increase in global warming is due to C cycle feedbacks (Smith *et al*., 2003) because it is more sensitive to rewetting frequency than N (Miller *et al.*, 2005). Its uptake and storage by plants can be increased through improved agricultural management practices (Haney and Haney, 2010). However, the influence of autotrophic or heterotrophic activity to changes in CO_2 evolution is not verified yet (Kim *et al*., 2011); especially in grass soils which contain more labile carbon than annually cropped soils regardless of tillage regimes (Carpenter-Boggs *et al*., 2003).

However, the net N mineralization is considerably dominated by nitrification in grassland soils (Zhang *et al*., 1998) as seen in the higher N_2O emission due to increased nitrification rates and organic C availability that is used as an energy source for heterogenous microorganisms. The influence of drying-rewetting frequencies on overall ecosystem nutrient budgets is still unclear. In this connection, an effort was made to quantify the impact of various drying-rewetting cycles (DWC) on grassland and arable soils, specifically in relation to CO_2 and N_2O emissions, NH_4^+ and NO_3- contents at different stages by means of a microcosm experiment under controlled conditions.

MATERIALS AND METHODS

Soil Sampling

Two soils under different management practices were chosen for incubation, that is, grassland and arable soil from Heidfeldhof Research Station at the University of Hohenheim, 13 km south of Stuttgart, Germany (48° 43' 00" N; 9° 11' 40" E) where annual average temperature and total rainfall are 8.7°C and 685 mm, respectively. The soil is classified as Alfisols (USDA, 2010). Soil samples were taken from a depth of 0-15 cm by removing upper vegetation and then well integrated to ensure homogeneity. After sampling, soil was immediately transported to the laboratory and sieved through a 4 mm sieve (Thomson *et al*., 2010).

Experimental Setup

Soil weighing 130 g was packed into columns (100 cm^3) resulting in a bulk density of. 1.3 g cm^{-3}. The soils were artificially saturated and adjusted to pF 1.8 i.e. 32% gravimetric water content (θ_{wt}) by weight through pressure plates (Loveday, 1974). After pF adjustment, soil cores were placed into microcosms (0.85l) and sealed with plastic lids containing rubber septa. In total, 80 microcosms were prepared. The microcosms were then transferred to a climate chamber, set at a constant temperature of 20°C in darkness for 60 days.

Adding deionised water with a graduate pipette compensated evaporation losses. The experimental setup included four treatments with ten replicates each. During the experiment, soils were incubated for a period of 60 days and exposed

to multiple drying-rewetting cycles with target moisture content (Figures 2c, 4c, 5c and 6c). The control soil remained at constant moisture of 32% θ_{wt}. Treatments receiving short drying-rewetting cycles (SDWC) were exposed to six evenly distributed DWC; the soil was rewetted to 32% θ_{wt} after reaching a water content of 21% θ_{wt}; soils with medium drying-rewetting cycles (MDWC) were exposed to 15% θ_{wt} and brought back to 32% θ_{wt}, while soils with long drying-rewetting cycles (LDWS) were exposed to drying until 5% θwt and were rewetted back to their previous moisture state.

SDWC, MDWC and LDWC went through 6, 4 and 2 DWC i.e. 0.1, 0.07 and 0.03 drying-rewetting frequencies (drying-rewetting frequencies means the number of cycles in 60 days. Six drying-rewetting cycles are divided by 60 resulting in 0.1 drying-rewetting frequencies and so on).

All of the treatments received the final drying-rewetting cycles for a 2-month period. Soil drying was accomplished by removing the microcosm lids to allow for evaporation. Rapid rewetting was performed by dripping deionised water cautiously onto the soil surface with the use of a graduated syringe.

N_2O and CO_2 Flow Measurements

For measuring N_2O and CO_2 flows, the microcosms were tightly closed and a rubber septum was fixed in the lid with a 2-way Luer-Lock valve. Gas sampling was carried out at 0-, 30- and 60-min time intervals by connecting the microcosm atmosphere to the vacutainer with a mounted septum, using a surgical syringe (Smith et al., 1995) and then stored in the evacuated vacutainers of 0.25 L volume.

To ensure the absence of N_2O prior to gas sampling, all vacutainers were evacuated and rinsed with N_2 thrice shortly before sampling to avoid contamination. Nitrous oxide and CO_2 concentrations were analysed by N^{63} electron capture detector (ECD) and flame ionisation detector (FID) respectively, using a gas chromatograph (AutoSystem XL Perkin Elmer) coupled with an auto-sampler. The instrumental conditions were as follows: oven temperature 65°C, ECD operation temperature 100-450°C, carrier gas for ECD and FID CH_4/Ar (10%/90) and He (95%) respectively. Calibration was done with three external standards (0.0003, 0.0015 and 0.003 µl L^{-1} for N_2O and 400, 1500 and 3000 µl L^{-1} for CO_2). Gas flow rates were calculated by measuring the change of gas concentration in the headspace of the microcosm using linear regression. Cumulative flow rates were calculated by linear interpolation. To estimate cumulative N_2O and CO_2 flows throughout measuring period, sum curves were created by multiplying mean flow rates of two sequential gas flow rates with the consistent time period and summing up these time-weighted means afterwards as described by Goldberg *et al*., (2009).

Soil Analysis

Soil cores were harvested at the end of the pre-incubation period and thereafter every two weeks in order to compare changes over time. Total carbon (TC) was detected by a LECO 2000 CN analyser. The particle size distribution was determined by the pipette method (Gee and Bauder, 1986). Soil pH was measured

in 1: 2.5 (soil:0.01 M $CaCl_2$) using glass electrode pH meter. Soil mineral N (NH_4^+ and NO_3^-) was extracted in a 1 M KCl solution (soil/liquid ratio 1: 5 w/w) as referred to by Keeney and Nelson (1982). The filtrates were then analysed on an automated flow injection analysis (Brann en LuebbeTrAAcs 800 Auto analyzer).

Net nitrogen nitrification (NNN) mg kg^{-1} was calculated as final concentration of NO_3^--N minus initial concentration of NO_3^-. Likewise, net nitrogen mineralisation (NNM) mg kg^{-1} was assumed as final concentration of NO_3^- plus NH_4^+, minus initial concentration of NO_3^- plus NH_4^+.

Physico-Chemical Properties of Soil

The arable soil was cultivated with spring wheat (*Triticum aestivum L. cv. Triso*) and fertilised with 140 kg N, 60 kg K and 30 kg P ha^{-1}. Arable soil contained 1.2% total carbon (TC) and pH value of 6.5 ($CaCl_2$). Grassland soil exhibited 2% TC and pH value of 6.0 ($CaCl_2$), respectively.

Particle size distribution of the arable soil was 12.6% sand, 58% silt and 29.4% clay, while the grassland soil was 17.3% sand, 61.7% silt and 21% clay. Ammonium and NO_3^- contents of the soil before incubation were 5.3 and 6.1 mg kg^{-1} for arable and 4.3 and 2.4 mg kg^{-1} for grassland soils, respectively.

Statistical Analysis

The experimental results were statistically evaluated by one way analyses of variance (ANOVA) using the software IBM SPSS Statistics Version 19. The least significant difference (LSD) test (α=0.05) was used to identify significant differences among treatments.

RESULTS

N_2O Cumulative Flow

On a cumulative basis, the response of the grassland soils to frequent stress (SDWC) with regard to N_2O flow was significantly (α=0.05) higher than those of control, MDWC and LDWC treatments (Figure 1). Arable soil behaved differently to DWC, where the control (245 µg kg^{-1}), SDWC (242 µg kg^{-1}) and MDWC(220.7 µg kg^{-1}) treatments produced significantly higher cumulative flows compared to the LDRW (75 µg kg^{-1}).

Temporal Dynamics of N_2O over the 2-Month Incubation

Temporal N_2O evolution patterns of both soils by different DWC are depicted in Figure 2. With regard to arable and grassland soils against different θ_{wt}, the flows started rising after the 38th day of incubation. Such an increase was negligible in the control (0-10 µg kg^{-1} hr^{-1}) treatments of arable soils, but continued to rise to 24.09 µg $kg^{-1}hr^{-1}$ in grassland soils. During periods of background emission, SDWC treatment induced a N_2O-N peak of 30.78 µg kg^{-1} hr^{-1} and 24.81 µg kg^{-1} hr^{-1} grassland and arable soils, respectively, and only appeared on the 50th day of incubation when the treatment returned to the actual moisture content of 32% θ_{wt} (Figure 2).

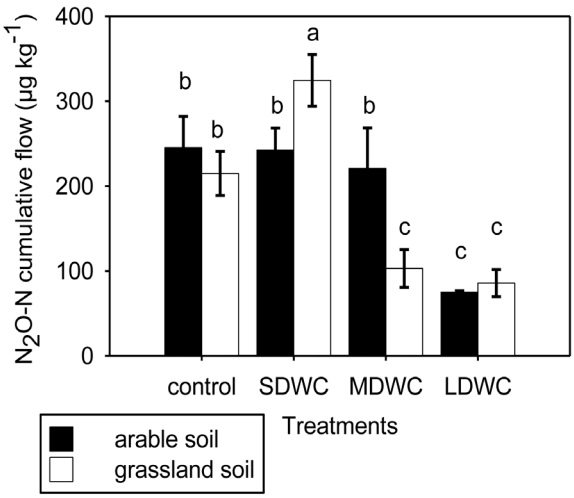

Figure 1: Cumulative flow of N_2O-N (µg kg^{-1}) in arable and grassland soils during the two months' incubation, when drying-rewetting frequencies were manipulated. Means of three replicates per treatment with standard error.

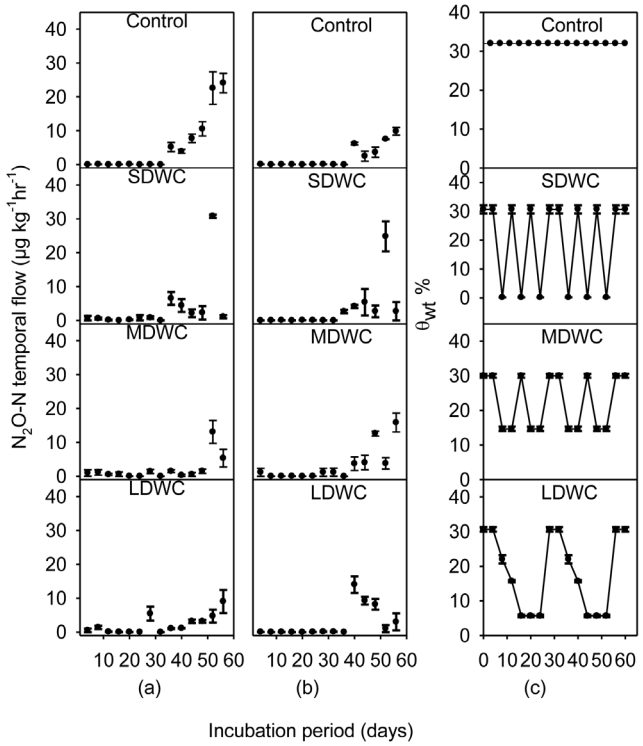

Figure 2: Temporal dynamics of N_2O-N (µg kg^{-1} hr^{-1}) in grassland (a) and arable (b) soils against different moisture regimes (c). Data points represent means of three replicates per treatment with standard error.

The flows were within the range of 0.4-1.8 µg kg^{-1} hr^{-1} during the first month of all treatments (Figure 2). MDWC and LDWC yielded two higher peaks (16. and 14.11 µg $kg^{-1}hr^{-1}$, respectively) in arable soils within the 2nd month of incubation (Figure 2). In MDWC of grassland soils, the flow also rose to 13.08 µg kg^{-1} hr^{-1} when brought back to 15% θ_{wt}.

CO_2 Cumulative Flow

Based on the cumulative flow illustrated in Figure 3, after a 2-month incubation period, statistically significant (α=0.05) differences were found between the cumulative flows of CO_2 by the grass soil receiving LDWC (97.2 mg kg^{-1}) and SDWC (130.50 mg kg^{-1}), where SDWC was 25.38% higher than LDWC. Furthermore, the arable soil (Figure 3) showed no statistically significant difference in response to the frequency of stress events compared to the control while the stressed treatments emitted CO_2 flows that were only 19.85% higher than the control.

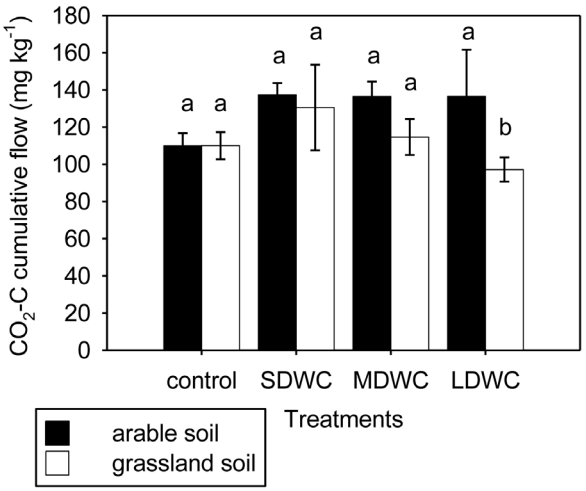

Figure 3

Figure 3: Cumulative flow of CO_2-C (mg kg^{-1}) in arable and grassland soils during the two months' incubation, when drying-rewetting frequencies were manipulated. Means of three replicates per treatment with standard error.

CO_2 Temporal Dynamics over the 2- Month Incubation Period

Evolution of CO_2 was initially higher in all arable soil treatments (Figure 4). SDWC behaved similarly to the control during the entire period of incubation. Flows dropped from 2 to 0 mg kg^{-1} $hr^{-1}$when exposed to a second drying cycle in MDWC. The flows of LDWC treatments reduced to nearly 1 from 3.5 mg kg^{-1} hr^{-1} when exposed to the first drying cycle and then remained low. With regard to the grassland soils, a significant increase was detected between 30 and 40 days, about half way in the incubation period. Flows significantly reduced to 0.5 mg kg^{-1} hr^{-1} from 2.5mg kg^{-1} hr-1 when the SDWC soils were brought back (Figure 4) to their

initial θ_{wt} (32%). An immediate response in the MDWC treatment occurred when exposed to the third drying cycle. Long drying-rewetting events significantly suppressed CO_2 flows during the entire incubation period.

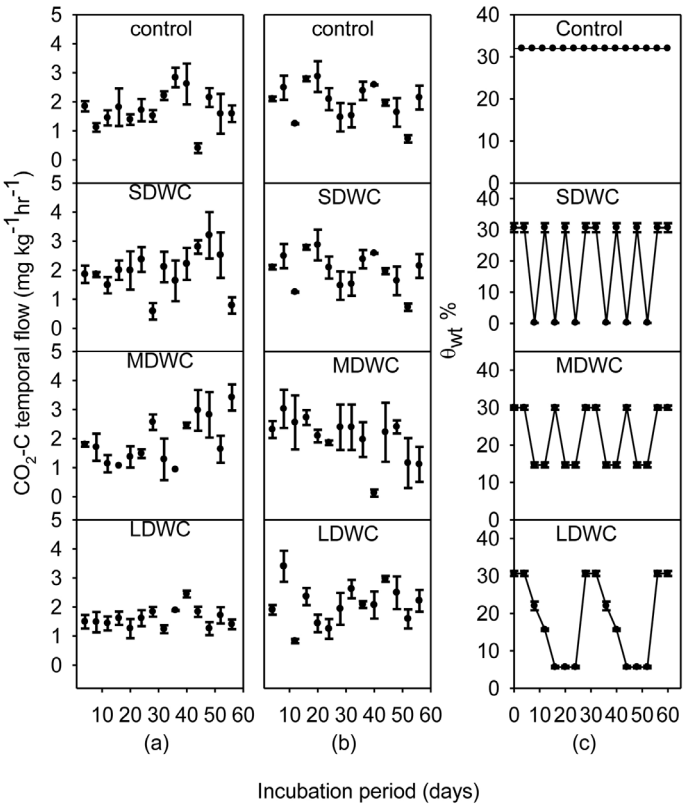

Figure 4: Temporal dynamics of CO_2-C (mg kg^{-1} hr^{-1}) in grassland (a) and arable (b) soils against different moisture regimes (c). Data points represent means of three replicates per treatment with standard error.

Nitrogen Concentration

Nitrogen concentration was affected in all treatments regardless of stress events. Ammonification increased significantly in MDWC and LDWC treatments in both soils gradually with time in the control treatment of arable soils (Figures 5 and 6). Ammonium content in the SDWC treatment of arable soils steadily declined (Figure 5), followed by a rapid increase in nitrate content (4.75-36.51 mg kg^{-1}). In contrast, in the grassland soils (Figure 6) NH_4^+ content decreased thereby increasing NO_3^-, but only minutely.

With regard to MDWC treatments of grass and arable soils, NH_4^+ increased slightly and decreased sharply at the end, but NO_3^- continued to rise in arable soils (Figure 5) yet remained constant in grassland soils (Figure 6). In grass soils, a significant increase in NH_4^+-N content took place in MDWC (2.32-4.01 mg kg^{-1})

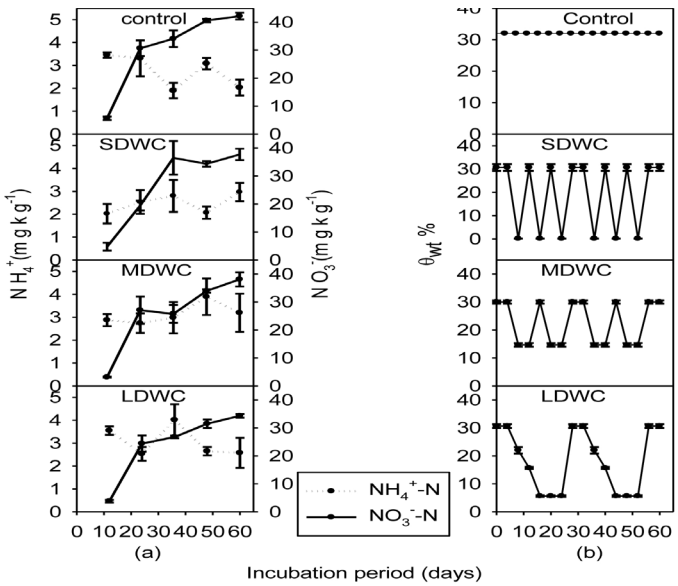

Figure 5: Figure 5: NH_4^+ and NO_3-(mg kg^{-1}) contents of different arable soil (a) treatments against different moisture regimes (b). Data points represent means of three replicates per treatment with standard error.

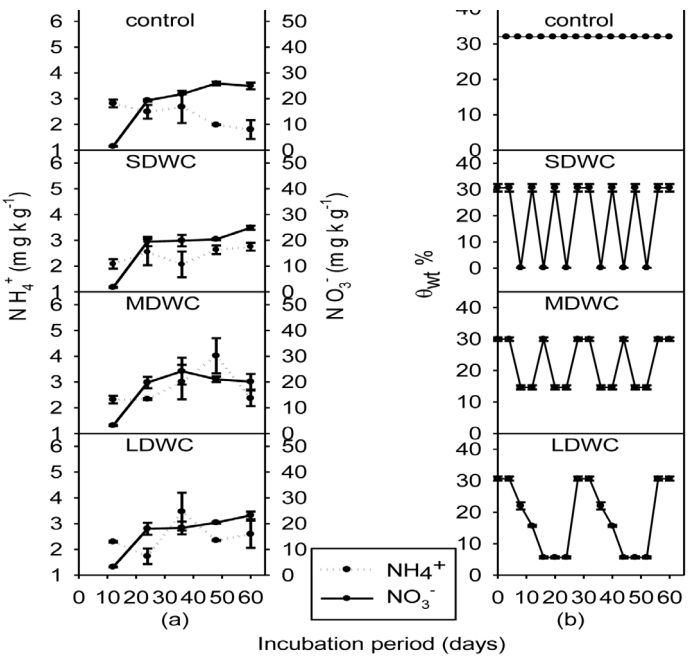

Figure 6: Figure 6: NH_4^+ and NO_3- (mg kg^{-1}) contents of different grassland soil (a) treatments against different moisture regimes (b). Data points represent means of three replicates per treatment with standard error.

and LDWC (1.47-3.46 mg kg^{-1}) and in the LDWC treatment of arable soil as well (2.5-4.0 mg kg^{-1}). However, NO_3^- contents of arable soils were significantly higher than in grassland soils in all cases (Figures 5 and 6).

DISCUSSION

N_2O Flow During a Two-Month Incubation Period and N concentration

Distinct temporal patterns of N_2O flows from control and SDWC treatments of grass soils, as well as the results obtained for N mineralisation, when using different moisture conditions, reveal that grass soil induced N_2O flows were weakly related to the NO_3^- content that might have been denitrified. Nevertheless, the presence of only NO_3^- does not ensure denitrification (Kunickis *et al.*, 2010). Thus, it can be postulated that N_2O flows were not only due to microbial nitrification, but also due to the limited availability of total organic carbon(McCarty and Bremner, 1992). On the other hand, such short and temporary drying-rewetting frequency enhanced denitrifier activity by availing physically protected organic matter (Fierer and Schimel, 2002). The behaviour of both soils (Figures 5 and 6) under a constant moisture regime (32% θ_{wt}) is different in the second half of the incubation period, where significantly higher N_2O emission was observed.

Bateman and Baggs (2005) and Ciarlo *et al*., (2008) pointed out the predominance of nitrification between 18-21% volumetric water content in the soil and that continuous moisture treatments influenced release of N_2O. It can be assumed that in arable soils, most of the organic carbon was lost as CO_2 at the beginning of the incubation. However, NO_3^--N content of arable soils was significantly higher, but organic carbon was not available for the denitrifiers. The activity of denitrifiers might have accelerated when the MDWC finished its first and second drying cycle.

Long drying significantly reduced N_2O temporal and cumulative flows in both soils indicating that the activity of nitrifying and denitrifying microorganisms was disrupted (Bottner 1985). Significantly lower N_2O production from nitrification at low water content (below 40% WFPS) has been reported previously (Dalal *et al.*, 2003). Likewise, Smith and Parsons (1985) postulated that drying results in a large decrease in the number of denitrifiers and their membrane bound denitrifying enzyme system.

Mineral Nitrogen Concentration Affected by Soil Moisture and Temperature

Ammonium content decreased due to a continuous moist state, but not in the stressed treatments of the grassland soils (Figure 6). The other possibility could be that NH_4^+ might have been promptly converted to NO_3^-. The favourable temperature (20°C) had a measurable effect on the oxidation of NH_4^+ to NO_3^- (Parker and Larson, 1962). Moisture manipulation enhanced the ammonification process in arable and grassland soils and was significantly higher in MDWC and LDWC (Figure 5). It can be concluded that ammonification in the LDWC and MDWC treatments responded significantly to drying-rewetting events in the

grass soils. The considerable increase in NH_4^+ content in MDWC and LDWC is likely due to the mineralisation of the amount of organic N because of soil drying (Appel, 1998). The NH_4^+ content of arable soil was initially higher than in grass soil, which might be due to fertiliser application to the crop in the field. Nitrate concentration shot up significantly between days 12-24 in all treatments regardless of stress events; either the nitrifiers were in a more active state (Abera *et al.*, 2012) or they were stress resistant (Fierer and Schimel, 2002). In arable soils, the NNM and NNN were significantly higher than in the grassland soils in all treatments revealing the internal cycling of nitrogenous compounds into biologically available forms (Strauss, 2000). Higher NH_4^+ contents indicate the slow mineralisation or reduced availability of indigenous N in grassland soils rather than arable soils. On the contrary, Fierer and Schimel (2002) found no significant differences between stressed and unstressed oak and grassland soils with regard to NO_3^- concentration. They proposed that nitrifier population might be able to survive during the drying periods. With regard to NNN, the NO_3^- has been denitrified. However, under natural grassland conditions, the quantification of available N is difficult as NH_4^+ is rapidly converted to NO_3^- and both are taken up by developed grass root systems.

The gradual increase in NO_3^- with time (Figures 5 and 6) in manipulated and control soils can be justified in both cases by explaining that NH_4^+ has been transformed to NO_3. The most likely explanation is that nitrifiers were stress resistant and survived (Fierer and Scimel, 2002) in arable soils.

Temporal Dynamics of CO_2.

Carbon mineralisation trends observed in arable and grassland soils in relation to CO_2-C flow are opposite. The manipulations affected grassland soils with different VWC during the first month of incubation, while arable soils proved more responsive with different θ_{wt} during the second month of incubation. The flows associated with arable soils were initially higher and afterwards decreased (Figure 4) under all treatments. When brought back to the actual moisture content (32% θ_{wt}), LDWC was quite efficient in its evolution of CO_2-C flows. Later, an increase in CO_2 flows in the SDWC and MDWC of grass soils (Figure 4) were identical to the control. Microbes managed to survive at 21% θwt and 15 % θ_{wt}.

The lower temporal and cumulative flow related to the treatment with LDWC in grassland soils may be ascribed to the reduction in microbial activity at a moisture regime of 0.05% θ_{wt} due to moisture deficiency (Stark and Firestone, 1995; De Nobili *et al*., 2006) or even death of microbes (Chen and Alexander 1973). But it is noted that the flows were initially higher as seen in the other treatments.

The findings related to the grass soils are supported by the results published by Thomson *et al*. (2010), who detected significantly higher CO_2 emission from shortly dried and rewetted microcosms than those of longer dried. Significantly higher CO_2 flows in arable soils as compared to grassland soils show the availability of carbon as a substrate (Brant *et al*., 2006) due to the decomposition of organic

matter, likely because of higher microbial activity due to N fertiliser application at sowing time and possibly its re-mineralisation afterwards.

A late appearance of peaks in the control (32 %), SDWC (21 %), MDWC (18 %) and LDWC (5 %) after one month of incubation was a result of the decomposition of very minute roots (mixed with soil), which might have been a major source of organic C (Herman *et al.*, 1977). Furthermore, no statistically significant differences were found between the cumulative flow of the control and the stressed soils (Figure 3). The results are in agreement with Muhr *et al*. (2008), who found no differences among CO_2 flows of constantly moist soil and drying-rewetting treatments.

CONCLUSION

The factors that influence carbon and nitrogen mineralisation leading to N_2O and CO_2 emissions are influenced by a range of factors: temperature, fertiliser application and organic carbon availability. Moreover, for CO_2 and N_2O production, we can conclude that the variation between soils at different periods of emission was accounted for by differences in organic carbon availability. Gravimetric water content (5%) appeared to be effective in reducing CO_2 and N_2O emissions in both soils. However, NO_3^- content was significantly higher in arable soils than in grass soils. Thus, it is concluded that long drying and rewetting can increase NH_4^+ but not NO_3^-.

High doses of nitrogen fertiliser result in low N utilisation by denitrifiers and a high risk of water contamination by nitrates leading to further research on the judicious use of N on wheat crops. Grassland soils can be N retaining if not frequently moistened. As far as the control treatment is concerned, it can be argued that the soils under continuous moist conditions, or frequently rewetted, could undergo nitrification thereby increasing N losses as N_2O or as ground water leaching losses.

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