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Carbon and nitrogen emissions from stored manure and cropped fields in irrigated mountain oases of Oman

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Abstract

Little is known about gaseous carbon (C) and nitrogen (N) emissions from traditional terrace agriculture in irrigated high mountain agroecosystems of the subtropics. In an effort towards filling this knowledge gap measurements of carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3) and dinitrous oxide (N_2O) were taken with a mobile photo-acoustic infrared multi-gas monitor on manure-filled PE-fibre storage bags and on flood-irrigated untilled and tilled fields in three mountain oases of the northen Omani Al Jabal al Akhdar mountains. During typical 9-11 day irrigation cycles of March, August and September 2006 soil volumetric moisture contents of fields dominated by fodder wheat, barley, oats and pomegranate ranged from 46-23%. While manure incorporation after application effectively reduced gaseous N losses, prolonged storage of manure in heaps or in PE-fibre bags caused large losses of C and N. Given the large irrigation-related turnover of organic C, sustainable agricultural productivity of oasis agriculture in Oman seems to require the integration of livestock which allows for several applications of manure per year at individual rates of 20 t dry matter ha^{-1}.

Keywords: CO_2, CH_4, NH_3, N_2O, carbon dioxide, methane, ammonia, dinitrous oxide, irrigation agriculture

1 Introduction

Little is known about N and C fluxes in flood-irrigated agro-ecosystems of the arid subtropics. To quantify the effects of temperature, irrigation, manure application and soil tillage on daily and seasonal C and N fluxes, the often many centuries-old fields in the Al Jabal al Akhdar mountain range in Oman provide an interesting agro-environmental setting for case studies. Large positive partial balances determined from measurements of horizontal nutrient fluxes in fields of these oases sparked interest to investigate the fate of apparent nutrient surpluses, which for N were reported to reach on average 131 kg ha^{-1} annually (Buerkert *et al.*, 2005). The high fertility of the terraced irragric Anthrosols with pH 8.3, reflected in C contents of 3% and a C/N ratio of 10 in the upper 0.45 m of the soils (Wichern *et al.*, 2004b; Luedeling *et al.*, 2005), results from centuries of surface application of animal dung to the man-made terraces filled with silt-rich, mineral soil. From field studies of these soils Wichern *et al.* (2004a) estimated annual turnover rates of 2,400-8,500 kg C ha^{-1}, indicating the need for a continuous large-scale recycling of organic carbon (C_{org}) by manure applications, straw incorporation and root debris to compensate for such losses.

It is well known that many factors influence gaseous emissions from agricultural soils, but their relative importance and interrelatedness vary widely. A particular field's C and N status, its biological activity and soil and water management practices appear to be decisive factors governing C and N emissions whereby excessive application of N certainly increases N_2O and NH_3 emissions (Bouwman *et al.*, 1997; Velthof *et al.*, 2003).

For CH_4 emissions the relative rate of methanogenic and methanotrophic activity determines whether a soil is a net source or sink for CH_4 with, however, large site-specific variations. Topp & Pattey (1997) estimated that about 10% of the global CH_4 sink is caused by oxidation in well-drained soils, whereas Crutzen (1995) estimated only 5% of the global CH_4-oxidation to occur in soils as the major part is oxidized by photochemical reactions in the atmosphere. Duxbury (1994) stated that without

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the soils' microbial CH_4 oxidation global emission rates would increase by factor 1.5 thus attributing to microbial activity a more important role in CH_4 oxidation than claimed by other authors.

A major drawback of the most commonly used gaschromatographic and chemoluminescence-based approaches to measure gaseous emissions in field environments is that they do not allow direct readings. Instead gas samples from the field have to be stored in containers and taken to the laboratory for analysis. This is cumbersome and may lead to errors of often unknown magnitude given losses during transport and possible gas adhesion to the container surfaces. Closed (static) chambers directly connected to analytical devices and providing automatic readings (Butterbach-Bahl *et al.*, 1997) overcome this disadvantage, but are very expensive, hard to move and therefore unsuitable for most on-farm measurements. To address these weaknesses, mobile photo-acoustic infrared multi-gas monitors, originally developed to analyze concentrations of poison gas in post-war settings and of N_2O during medical operations, have recently been used to monitor C and N emissions (Kretschmann *et al.*, 2005; Reth *et al.*, 2005a,b).

In view of the scarcity of data on gaseous C and N emissions from fields in irrigated subtropical environments and to elucidate the fate of the apparent N surpluses in Omani mountain oases, the purpose of this study was to use a simple closed chamber system in an effort to estimate the effects of air and soil temperature, irrigation, soil tillage and manure application on fluxes of CO_2, CH_4, N_2O and NH_3 in these oasis agroecosystems.

2 Methodology

2.1 Description of the study sites

The Al Jabal al Akhdar mountain range in northern Oman is situated within the Great Arabian Desert and receives 100-340 mm of annual rainfall (Gebauer *et al.*, 2007). It comprises about 75 flood-irrigated mountain oases (Luedeling & Buerkert, 2008) of which some may have existed for thousands of years (Nagieb *et al.*, 2004). Due to their apparent sustainability and unique agro-environmental settings these oases systems of which many have been abandoned during the last decades given rapid modernization processes in the largely oil-based economy have recently received attention by scientists and policy makers alike.

The typical oases in which our study was conducted were Al 'Ayn (57°39'48"E, 23°04'21"N, 1900 m) and Al Qasha' (57°39'46"E, 23°04'02"N, 1640 m) in the upper part of the wadi Muaydin watershed of the central Al Hajar mountain range. Al Qasha' comprises about 2.1 ha of terraced fields and obtains its water from the same spring of Al 'Ayn, from where the water flows through a steep channel down to the oasis.

Typically the terraces of both oases are covered by perennial crops such as roses (*Rosa damascena*), pomegranate (*Punica granatum* L.), walnut (*Junglans regia* L.), apricot (*Prunus armeniaca* L.) peach (*Prunus persica* L.), and alfalfa (*Medicago sativa* L.), and annual crops such as garlic (*Allium sativum*), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and wheat (*Triticum* spp.), mostly used as fodder crops.

In both oases partly composted cattle and goat manure is typically surface applied 2-3 times per year to the bunded irrigation basins (Arabic: 'jalba') of 12 m^2 at a height of 1-3 cm, equivalent to annual application rates up to 60 t ha^{-1} (Buerkert *et al.*, 2005). At both oases the C-rich surface soils of the irragric Anthrosols resembled those described by Luedeling *et al.* (2005). Typically irrigation intervals last from 9-18 days depending on actual evapotranspiration with up to 70 mm water per event (Siebert *et al.*, 2007). In this study irrigation intervals varied from 9-11 days. This lead to volumetric water contents of 40-46% in the topsoil just after irrigation, which decreased to 25-29% on shaded plots such as fodder wheat under pomegranate which were used for our measurements.

2.2 Setup to measure C and N-fluxes

Field-based emissions of CO_2, CH_4, NH_3 and N_2O were determined with a mobile photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark). Before and after the measurement series the multi-gas monitor was calibrated with pure gases and gas mixtures yielding errors <4% compared to the true concentrations of the standards. Pre-tests showed that to obtain stable readings, optimal sample integration times were 5 s for CO_2 and NH_3, 20 s for CH_4, and 50 s for N_2O. Lower detection limits were 3.4 mg CO_2 kg^{-1}, 20 µg N_2O kg^{-1}, 200 µg NH_3 kg^{-1} and 400 µg CH_4 kg^{-1}. The device was operated by a 12V-40Ah car battery to which a 300 W pure sine wave inverter WAECO-Mobitronic Pocket Power 740-012PP (Conrad Electronics, Hirschau, Germany) was connected providing a constant output voltage of 220 V.

The multi-gas monitor was connected by two standard Teflon® tubes of 0.8 m length and 2 mm diameter each serving as inlet and outlet, respectively, to the measurement cuvette. The recycling of the gas flow allowed monitoring the gas accumulations without outside air being sucked into the system. The cuvette consisted of a 0.3 m wide and 0.11 m high PVC cylinder weighing about 500 g, coated inside by a self-adhering Teflon® film (Chemfab Germany GmbH, Cologne, Germany) which - as shown by pre-tests with rapid concentration changes of gases - effectively reduced adherence of the emitted gases at the cuvette surface to the detection limit (unpublished data). Inside the cuvette a small ventilator was mounted to facilitate continuous mixing of the gas mixture. During all measurements care was taken to minimize the formation of condensation water in the cuvette, as NH_3 and CO_2 molecules are likely to dissolve in it leading to erroneous readings. Inside the cuvette the sensor of a thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany) was installed to record the humidity and temperature of the gas mixture during measurements. Volumetric soil moisture in the upper 0.06 m of the soil was determined with a TDR/FDR soil humidity meter (Theta Probe Sensor attached to an Infield7b datalogger, UMS, Munich, Germany).

To avoid penetration of gas emissions from outside the measured soil, a 0.3 m wide and 0.06 m high fitting ring made of PVC and sharpened at its lower end was pushed 0.03 m into the ground allowing a tight connection with the cuvette and creating a closed static chamber during measurement intervals in which gas concentrations increased over time.

For longer intervals, particularly the increase of CO_2 and NH_3 but also increasing temperature and moisture may lead to an unwanted feedback on gas emissions (Hutchinson & Mosier, 1981; Fowler *et al.*, 2001). To minimize these effects, after a minimum interval of gas accumulation and subsequent measurements, the cuvette was lifted, allowing fresh air to enter.

To compare measured gaseous emissions with concentrations in the manure applied to the respective experimental fields, samples from all manures used for the experiments were frozen and analysed in Germany for total N and C with a N-analyzer (FP-328) and a C-analyzer (RC-412; both LECO, Monchengladbach, Germany) on a dry weight basis (105°C).

Trace gas emission rates from the soil surface were calculated by subtracting gas concentrations measured at the onset of the accumulation time (t_0) from the concentrations after accumulation (t_1) divided by the time of accumulation ($\Delta t = t_1 - t_0$) for which the increase in the gases of interest was linear. To ease interpretation of results in the context of nutrient balance calculations, these values, based on the cuvette surface of 0.07 m^2 and the different measurement periods, were extrapolated to g ha^{-1} h^{-1} or kg ha^{-1} yr^{-1}. For conversion to mg m^{-2} h^{-1}, the former values should be divided by 10.

2.3 Experiments conducted and measurements of C and N emissions taken

2.3.1 Effects of manure storage

To measure C and N emissions of goat manure during their typical field-storage in closed PE-fibre cloth bags, in March 2006 the cuvette was firmly pressed on three randomly chosen locations of a representative bag filled with 28 kg of manure whereby accumulation times of 3.5-5 minutes were used. Care was taken to obtain an air-tight sealing of the cuvette by placing the bags on a flat soil but this may not have been completely successful in all cases. For each measurement location on the bag, the local volumetric moisture content of the manure was measured by inserting the Theta-Probe through the PE-fibre.

2.3.2 Cold season tillage effects

To measure tillage effects on C and N emissions from farmers' fields in March 2006 day courses of C and N emissions from an untilled plot in Al Qasha' and a tilled plot in Al 'Ayn which both had been manured at an estimated rate of 60 t dry matter ha^{-1} with 47.7% C and 2.4% N four months ago and irrigated recently (soil moisture content ∼40%) were recorded. In Al Qasha' prior to the measurements the fodder wheat field had been hand weeded twice while in Al 'Ayn the fodder wheat had just been harvested and the soil tilled with a cultivator. At each site measurements occurred in five replicates with accumulation times of 3.5 min for CO_2 and NH_3 and 2 h for CH_4 and N_2O.

2.3.3 Manure application effects

To estimate C and N emissions from a typical unmanured and a neighbouring manured field of the same cropping history without tillage, measurements were conducted in two separate intervals (replications over time) in August-September 2006 at Al 'Ayn. Before manure application, C and N emissions of the unmanured soil were determined. Subsequently, partly composted goat dung containing 47.7% C and 2.4% N was evenly spread in a 3 cm layer on the soil surface within five fitting rings serving as replicates whereby three unmanured rings were used as control treatments. Emissions were recorded during the first irrigation cycle after manure application with accumulation times lasting for 3.5-5 min.

2.4 Data analysis

All data were processed with SPSS 11.5 (Backhaus *et al.*, 2003) and Sigma Plot 7.0 (Backhaus *et al.*, 2003) to test for treatment differences and time trends after examination for normal distribution of residuals and homogeneity of variances.

3 Results

3.1 Effects of manure storage

The volumetric moisture contents of the 10-day old manure at the three measured locations in the PE-bag were 10%, 20% and 30% with respective concentrations of 47% C and 3% N, 47% C and 2.6% N, and 44% C and 2.5% N. The emission measurements at the three spots revealed large daytime-related differences in

C- (Figure 1a-d) and N-fluxes (Figure 1e-h) which were substantially higher at mid-day (31.6°C ± one standard error of 1.3) than during early morning hours (21.5°C ± 0.9). The data also suggest a doubling of day-time CO_2 emissions with a temperature increase of 10 K. There also were large moisture effects on CO_2 emissions from the bag. Bag locations with 20 and 30% moisture tended to have slightly higher emissions than that of 10% moisture (Figure 1a-b). From morning to mid-day CH_4 emissions increased two- to three-fold (Figure 1c-d).

In the morning NH_3 emissions tended to be highest at 30% moisture, whereas at mid-day they were lowest at this moisture which may be related to adsorption of emissions in condensation water inside of the cuvette, even if we tried to avoid such circumstances (Figure 1e-f). Emissions of N_2O tended to be highest at 20% moisture in the morning and at mid-day, but these differences were not significant (Figure 1g-h).

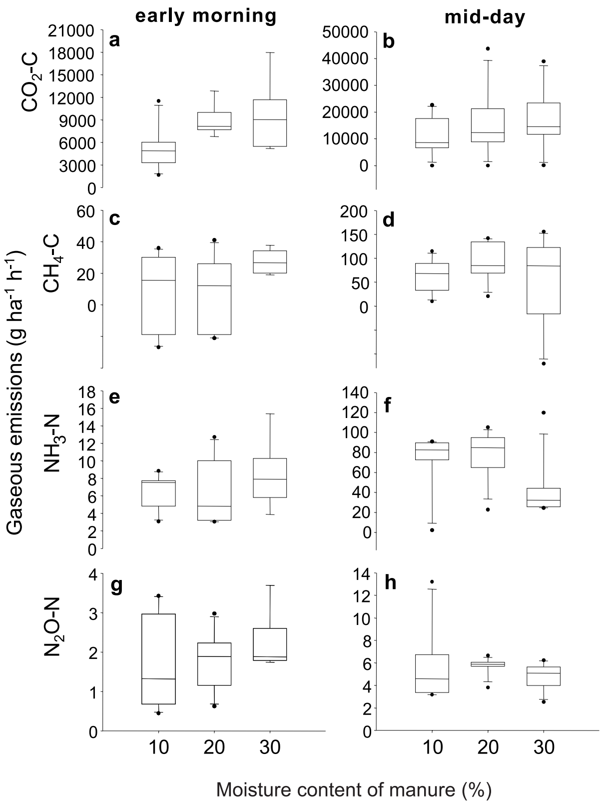

Fig. 1: *Gaseous emissions from manure in a closed PE- fibre bag in the mountain oasis of Al' Ayn (Oman) in August 2006. Measurements were measured on the top of the bag. The boxplots show the median, the 10th, 25th, 75th and 90th percentiles as well as the outliers of 10 measured gas concentrations at sample integration times of 5 s for* CO_2 *and* NH_3*, 20 s for* CH_4*, and 50 s for* N_2O.

3.2 Cold season tillage effects

Regardless of tillage the CO_2 emissions from fodder wheat under pomegranate reflected the air rather than the soil temperature whereas the flux rates of the other gases varied widely throughout the day irrespective of temperature (Figure 2a-f). Rates of CO_2 emission were much higher with than without tillage even though this operation had occurred two weeks prior to the measurements.

Methane emissions did not differ significantly between the tilled and untilled plot and in both measurements average flux rates were negative showing the role of the studied fields as CH_4 sinks.

The measured NH_3 emissions did not differ significantly between tilled and untilled plots and were overall negligible. Fluxes of N_2O were negligible on the untilled plots, while the tilled plot showed very low but constant emission rates suggesting a tillage-related increase in denitrification.

3.3 Manure application effects

On both manured and unmanured plots in August soil moisture content after irrigation was similar with initially 45%, decreasing to 29 and 25%, respectively until the next irrigation event. Soil temperature decreased in the first three days after irrigation and then increased again until the next irrigation (Figure 3). Unmanured plots showed a higher variation in moisture content and temperature reflecting the well-known buffering effect of manure application on soil physical properties.

Irrespective of the measurement period in August and September, during the first ten days after irrigation CO_2 emissions from the manured soil (Figure 4e-h) were about twice as high as those from the unmanured field (Figure 4a-d). Only in September, CO_2 emissions from the manured field after the second irrigation event reached emission levels similar to those measured after the first irrigation (Figure 4g-h). Differences between CO_2 emissions from the unmanured field between August and September were large, even though temperatures and soil moistures did not differ much. This may reflect differences in soil microbial activity possibly due to still poorly understood soil microbial changes and management effects.

Methane emissions from the unmanured plot during the cool morning hours in August and on most days also in September were consistently lower than those measured at mid-day (Figure 5a-d). Mid-day CH_4 emissions from the unmanured plot in August and to a smaller degree also in September were higher than those from the manured plot (Figure 5b, d and 5d, h). On a dry matter basis the C content of the applied manure declined from 49.8 to 46.2% during the 11 days of measurement.

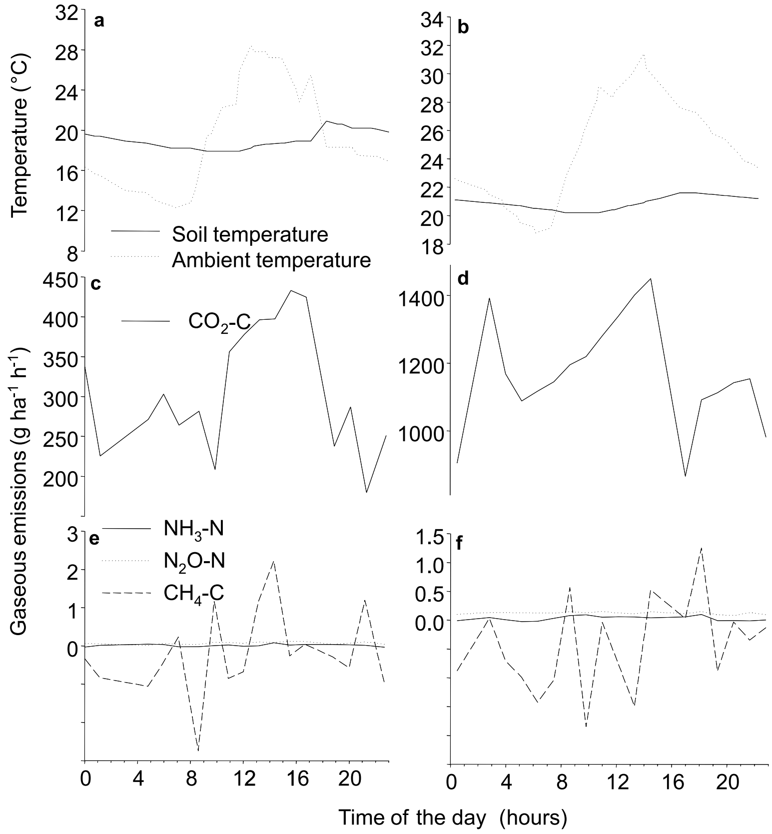

Fig. 2: *Day course of soil and ambient temperature and gaseous emissions in fodder wheat from an untilled plot in mountain oases of Al Qasha' and a tilled plot in Al' Ayn (Oman), both under pomegranate in March 2006.*

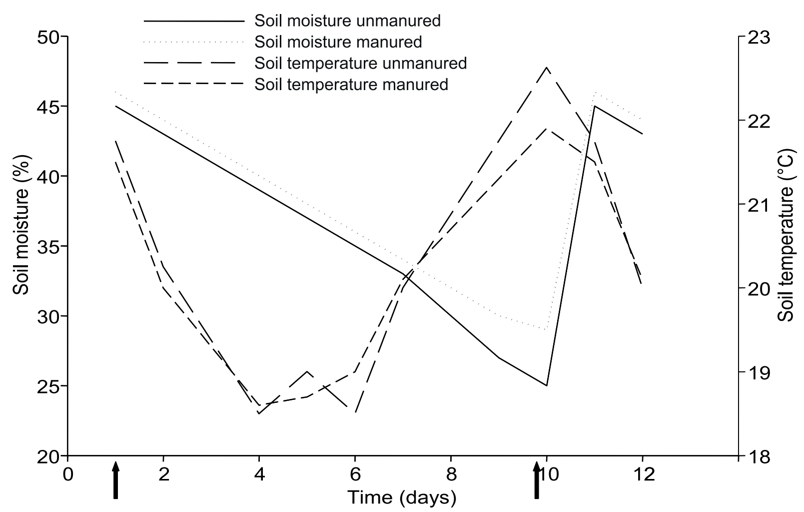

Fig. 3: *Time course of average soil moisture and temperature of manured and unmanured plots without tillage in Al 'Ayn (Oman) in August 2006. Irrigation occurred on day 1 and 10 as indicated by the arrows.*

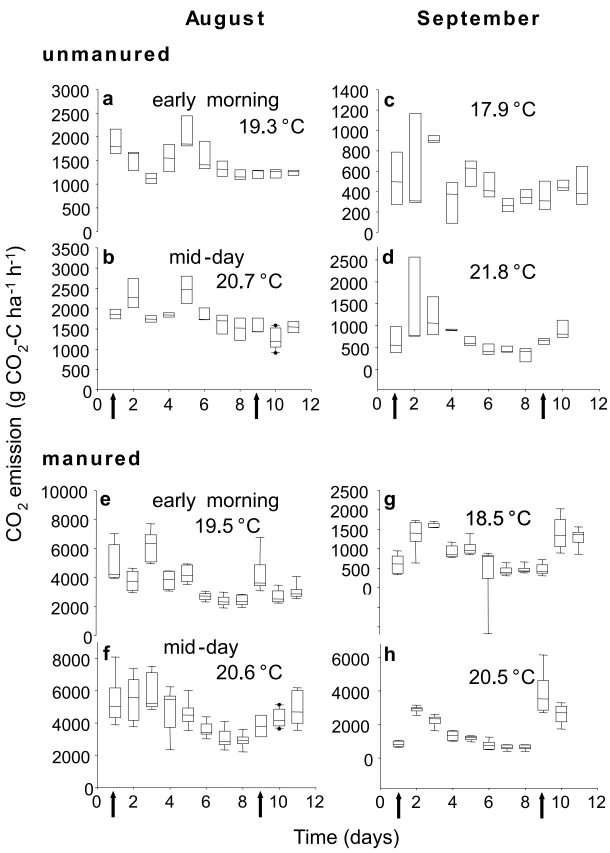

Fig. 4: *Time course of* CO_2 *emissions from plots without and with manure application in the mountain oasis of Al' Ayn (Oman) in August and September 2006. Irrigation occurred at day 1 and 9 as indicated by the arrows. Average soil temperatures are indicated. The boxplots show the median, the 10th, 25th, 75th and 90th percentiles as well as the outliers of five measured gas concentrations at sample integration times of 5 s for* CO_2 *and* NH_3*, 20 s for* CH_4*, and 50 s for* N_2O*. The boxplot-like figures (a-d) in the unmanured treatments show the three measured values.*

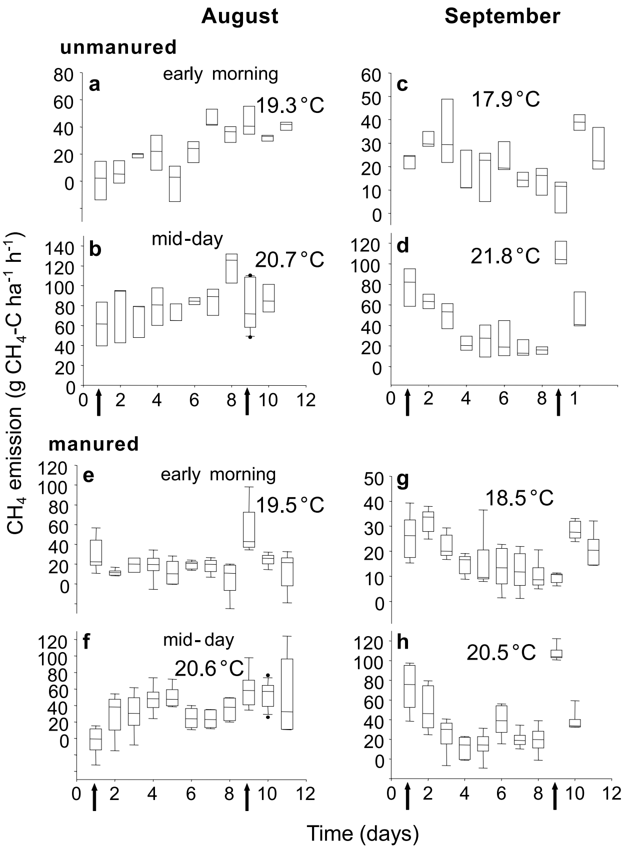

Fig. 5: *Time course of* CH_4 *emissions from plots without and with manure application in the mountain oasis of Al' Ayn (Oman) in August and September 2006. Irrigation occured at day 1 and 9 as indicated by the arrows. Average soil temperatures are indicated. The boxplots show the median, the 10th, 25th, 75th and 90th percentiles as well as the outliers of five measured gas concentrations at sample integration times of 5 s for* CO_2 *and* NH_3*, 20 s for* CH_4*, and 50 s for* N_2O*. The boxplot-like figures in the unmanured treatments show the three measured values.*

In August the field with manure application showed a significant decline of NH_3 emissions after two days, particularly during early morning hours (Figure 6e-f), while in September NH_3 emissions from the more mature manure used decreased slower, starting from much lower initial values than those measured in August (Figure 6g-h). In both August and September from three days after irrigation onwards, the emissions from manured plots were not significantly different from those of unmanured plots (Figure 6). The second irrigation lead to significantly higher NH_3 emissions only for the September mid-day measurements regardless of manure application (Figure 6d, h) suggesting that this increase was soil- and not manure-driven.

Regardless of daytime and for both measurement periods, N_2O emissions were higher with than without manure (Figure 7a-d) and tended to decrease with soil moisture, even if the latter was not always consistent. Emissions on unmanured plots (Figure 7) were significantly lower in the morning than at mid-day. In September the second irrigation increased N_2O emissions from manure plots more than it did in August. The analysis of the total N concentration in the applied manure revealed a decline from 2.9 to 2.6% within the first 11 days of the August experiment.

4 Discussion

For manure storage, the increase in mid-day emissions irrespective of substrate moisture (Figure 1) may not only result from a temperature-related increased microbial activity as mentioned by Dalias *et al.* (2001), but also from increased gas diffusion (Granli & Bøckman, 1994) leading to higher flux rates through the loose fibres of the bag.

For tillage our results (Figure 2) confirm those of Paustian *et al.* (2000) who reported that such operations lead to large, persistent increases in CO_2 emissions.

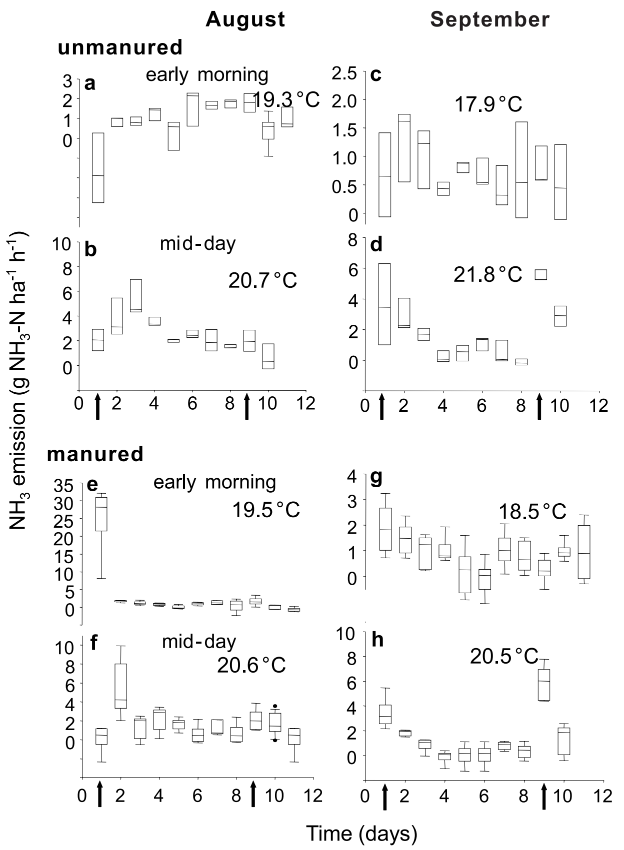

Fig. 6: *Time course of* NH_3 *emissions from plots without and with manure application in the mountain oasis of Al' Ayn (Oman) in August and September 2006. Irrigation occurred at day 1 and 9 as indicated by the arrows. Average soil temperatures are indicated. The boxplots show the median, the 10th, 25th, 75th and 90th percentiles as well as the outliers of five measured gas concentrations at sample integration times of 5 s for* CO_2 *and* NH_3*, 20 s for* CH_4*, and 50 s for* N_2O*. The boxplot-like figures in the unmanured treatments show the three measured values.*

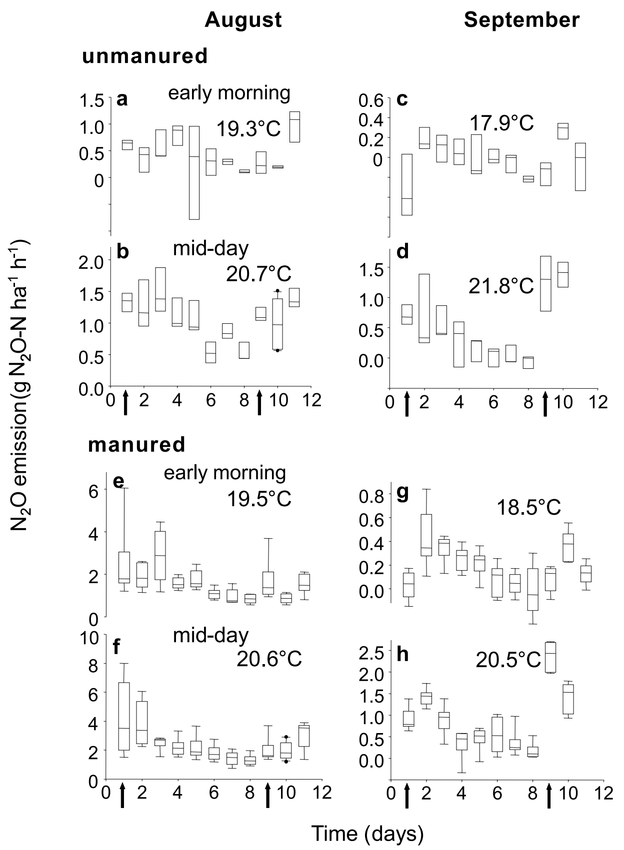

Fig. 7: *Time course of* N_2O *emissions from plots without and with manure application in the mountain oasis of Al' Ayn (Oman) in August and September 2006. Irrigation occurred at day 1 and 9 as indicated by the arrows. Average soil temperatures are indicated. The boxplots show the median as well as the 10th, 25th, 75th and 90th percentiles The boxplots show the median, the 10th, 25th, 75th and 90th percentiles as well as the outliers of five measured gas concentrations at sample integration times of 5 s for* CO_2 *and* NH_3*, 20 s for* CH_4*, and 50 s for* N_2O*. The boxplot-like figures in the unmanured treatments show the three measured values.*

The negative CH_4 flux rates support the statements of Crutzen (1995) and Duxbury (1994) about the important role of methanotrophic bacteria in soils. The assumption of Borken & Beese (2006), that methanotrophic microbes have slow reproduction and metabolism rates, may thus not be always true.

Our measurements of higher CH_4 emissions at warmer mid-day temperatures in manured and unmanured fields compared to those on early morning hours (Figure 5) confirm similar results obtained in earlier work by Hans *et al.* (2005) at Balad Seet and findings of Zeeman (1994) and Johnson *et al.* (1996) whose measurements also provided evidence of a clear increase of CH_4 emissions with higher substrate temperatures. The fact that mid-day CH_4 emissions from the unmanured plot in August were higher than those from the manured plot (Figure 5b, d and 5d, h) was also observed by Hans *et al.* (2005) but only for the first three days after the application of manure. These results may reflect the effects of methanotrophic microbes which according to Crutzen (1995) and Duxbury (1994) are able to prevent CH_4 emissions at high manure rates particularly as their activity increases with temperature. This is also supported by data from Hütsch (1998) who reported a high CH_4 oxidation after the application of straw compost.

The C losses calculated for our study were higher than those reported earlier from the Omani mountain oasis of Balad Seet (Wichern *et al.*, 2004a) which was likely related to more mature manure compost used by the latter authors.

The finding that N_2O emissions were higher with than without manure (Figure 7) and tended to decrease with soil moisture confirms similar results by Davidson *et al.* (1993). The observed temperature effects, particularly on unmanured plots (Figure 7a-d), possibly reflected the effects of increased denitrification processes at higher temperatures also shown by Granli & Bøckman (1994) but contradicting Holtan-Hartwig *et al.* (2002) who reported higher N_2O emissions at lower temperatures. This conflicting evidence underlines the complex nature of N_2O emissions from manure which may vary as much as 100-fold in response to differences in environmental conditions (Velthof *et al.*, 2002).

In view of recent findings about low annual leaching losses from such mountain oases soils (Luedeling *et al.*, 2005), the relatively small rates of NH_3- and N_2O-N emissions shown in this study suggest that the major proportion of the large N surpluses from horizontal balance calculations in these oases (Buerkert *et al.*, 2005) may either be emitted as NO and N_2 or used for the continued built-up of soil C_{org}.

Overall the results of this study show that the intensive turnover processes in the continuously irrigated oases soils require the application of large manure quantities to balance C and N losses. The bio-physical sustainability of these systems thus depends on the continuation of the millennia-old integration of livestock husbandry into oasis agriculture.

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