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Legume-based forage production systems reduce nitrous oxide emissions

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ABSTRACT

Nitrous oxide (N_2O) emissions from agriculture demand attention because they are the main source of total global anthropogenic N_2O-emissions. High N-fertilization and soil compaction are important factors that increase N_2O-emissions. On intensively managed grassland sites both factors occur. Knowledge of the interaction of high N-fertilization and simultaneous soil compaction on N_2O-emissions is therefore essential, but previous studies about this scenario are rare. In the presented study, N-fertilized grass swards (G) and unfertilized lucerne–grass mixtures (LG) were compared over a three-year period (2006–2008): N_2O-emissions and dry matter yield were measured as a function of N-fertilization (0 (LG), 360 kg N ha^{-1} yr^{-1} (G) as CAN) and soil compaction (0 (C0), 321 kPa (C321)) on a loamy stagnic Luvisol derived from glacial till in northern Germany. CO_2-equivalents (CO_2eq) per hectare and per unit metabolizable energy (GJ ME) were calculated.

N_2O-emissions were significantly influenced by the interaction N-fertilization × soil compaction; emissions increased significantly when both factors were induced simultaneously (G/C0: 8.74, LG/C0: 2.46, G/C321: 13.31 and LG/C321: 2.22 kg N_2O-N ha^{-1}, respectively). Concerning the specific CO_2-emissions, expressed in CO_2eq $(GJ\ ME)^{-1}$, the N-fertilized G swards emitted 67% more CO_2eq than LG swards assuming that 50% of the field plots were compacted due to heavy wheel traffic, which are reliable figures from agricultural practice. Neither dry matter (DM) yield nor forage quality (MJ ME (kg $DM)^{-1}$) differed significantly between fertilized G and unfertilized LG swards. Hence, legume-based instead of fertilizer-based forage production is a promising mitigation option without significant reduction of DM yields. In addition, results regarding soil compaction effects on GHG-emissions emphasize the urgent need to implement controlled traffic systems on intensively managed grassland in order to reduce the area affected by heavy wheel traffic.

1. Introduction

Nitrous oxide (N_2O) is among the most potent greenhouse gases (GHG) that contribute to global warming and to the reduction in stratospheric ozone. N_2O has a 298 times (100-yr time horizon) greater global warming potential than CO_2 on a molecule for molecule basis and an atmospheric lifetime of 114 years (Forster et al., 2007).

Recently, a number of nations have approved individual targets in addition to the Kyoto Protocol (UNFCCC, 2010), with legally binding measures aiming at a reduction in GHG-emissions. The EU, for example, implemented a commitment to reduce GHG-emissions from 2008 to 2012 by 8% below the level of 1990 (UNFCCC, 2010). Thus, countries that have signed the Kyoto Protocol need to quantify their emissions of N_2O and to develop mitigation options.

Since 1750, the tropospheric concentration of N_2O has increased from 270 ppb to 320 ppb (IPCC, 2007). Enhanced microbial production due to an expanded area of fertilized agricultural land has been identified as the primary driver for the increase in N_2O in the industrial era (Thompson et al., 2004). In

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the USA, for example, N_2O-emissions originating from agriculture accounted for 80% of the total N_2O-emissions in 2005 (Snyder et al., 2009). In Germany, 31 Mio Mg CO_2-equivalents N_2O were emitted in 2009 as a result of agricultural activities (UBA, 2010).

N_2O is produced in soils by microbial nitrification (the oxidation of ammonium NH_4^+ to nitrate NO_3^-) and denitrification (reduction of NO_3^- to dinitrogen gas N_2) (Stevens et al., 1997) as an intermediate product of each process. Consequently, the magnitude of emissions depends on soil conditions, including the soil water content, concentrations of NH_4^+ and NO_3^- and soil temperature (Davidson, 1991; Dobbie and Smith, 2001; Keeney et al., 1979; Wolf and Russow, 2000). In situations when aerobic and anaerobic microsites can develop within the same soil aggregate, nitrification and denitrification can also occur simultaneously (Azam et al., 2002). In compacted soils, aerobic and anaerobic zones can occur in close proximity in the upper few centimeters of the soil. Thus, nitrification and denitrification could occur concurrently and adjacently (Davies et al., 1989). It is frequently reported that no-tillage enhance N_2O-emissions due to greater levels of protease activity and organic matter content (Ball et al., 2008). Rochette (2008) summarized in a review that increased N_2O-emissions associated with no-tillage are mostly dependent on soil texture and occur mainly in poorly drained soils. Grassland soils in particular have a high potential for mineralization and subsequent nitrification and denitrification (Clayton et al., 1997). Additionally, Kester et al. (1997) observed in grassland soils that nitrification dominates N_2O production in spring, whereas denitrification was the main source of N_2O in autumn.

Several studies have shown the significance of soil moisture in affecting N_2O production (Clayton et al., 1997; Pihlatie et al., 2004). Davidson (1991) detected the highest N_2O production was at 60% water-filled pore space (WFPS), which, according to his judgment, can be attributed to soil moisture conditions that favor both nitrification and denitrification.

Soil compaction changes soil structure and affects the key variables controlling N_2O-emissions. More precisely, soil compaction reduces apart from the total pore volume and changes the pore-size distribution toward a higher percentage of small pores especially the pore functions like hydraulic conductivity and air permeability and their three-dimensional arrangements (Trükmann, 2010). The formation of a platy structure e.g. due to wheeling and plow pan layer formation enhances the N_2O formation and emission manifold (Ruser et al., 1998) As a consequence of impaired aeration, a reduction in pore volume induced by compaction also increases the likelihood of anaerobic conditions. Hence, soil compaction can increase N_2O-emissions by inducing anoxic conditions favorable to denitrification (Ball et al., 1999; Bessou et al., 2010; Davies et al., 1989; Hansen et al., 1993; Oenema et al., 1997; Sitaula et al., 2000). Furthermore, shearing due to wheel slip and restricted stress application result in a complete deterioration of the continuous pore systems and end up with the formation of often intense anoxic soil conditions which coincides with a complete consumption of oxygen and the formation of N_2O or even CH_4 (Weisskopf et al., 2010). In a field experiment on grassland, Yamulki and Jarvis (2002) reported a 3.5-fold increase in N_2O-emissions induced by soil compaction compared with non-compacted plots.

Higher N_2O-emissions from fertilized soils, compared with unfertilized soils, have been widely reported (Abbasi and Adams, 2000; Breitenbeck et al., 1980; Dittert et al., 2005; Flessa et al., 1996; Lampe et al., 2006; Wachendorf et al., 2008). Azam et al. (2002) found that the increase in N_2O-emissions from soils treated with mineral N was substantially higher when both NH_4^+ and NO_3^- were applied. Christensen (1983) observed the N_2O-flux after applications of NH_4NO_3 was up to 5 times higher. Furthermore, Hansen et al. (1993) calculated that fertilizer-derived emissions of N_2O increased from 3.9% to 5.3% due to soil compaction. The lack of differentiated default values for N_2O-emissions in the IPCC guidelines to take account of the interactions of fertilized or manured and/or compacted soils has also been criticized (van Groenigen et al., 2005).

Although interactions of nitrogen fertilization and soil compaction on N_2O emissions have been reported (Hansen et al., 1993; Ruser et al., 1998) the effect has received insufficient attention, particularly in the context of grassland that is commonly subjected to heavy machinery traffic and high N-fertilization. It furthermore gets more important, because the simple soil compaction process defined as increase in bulk density but also and more pronounced the shear induced changes in pore continuity even at the identical bulk density but altered pore functionality gains more importance due to heavier and more powerful agricultural machinery.

Therefore the objective of this study was to quantify the effects of N-fertilization and simultaneous soil compaction on nitrous oxide emissions. We tested the following hypotheses:

I) Simultaneous treatments of high N-fertilization and soil compaction enhance N_2O-emissions on grassland sites,
II) The N-source (biologically N_2-fixation versus mineral N-fertilization) has a decisive impact on N_2O-emissions, indicating that legume-based grassland/ley systems receiving a similar supply of nitrogen due to biological nitrogen fixation will provide a reduced load of greenhouse gas emissions per unit of forage produced (and thereby, a reduced carbon footprint).

2. Material and methods

2.1. Experimental site

A three-year field experiment was conducted at the experimental station 'Hohenschulen' (9°58′ E; 54°19′ N; 30 m a.s.l.) of the Christian Albrechts University, Kiel in the north-west of Germany close to Kiel. The relief at the experimental station was formed in the last glacial period (Weichselian) approximately 12,000 years ago, and the presence of end moraine characterizes a hilly landscape (Ziogas, 1995). The climate is oceanic with moderately cool summers and, in the context of northern Europe, comparatively warm winters. The mean annual temperature is 8.3 °C and the mean annual precipitation 777 mm. Due to the geological genesis, the soils vary between Luvisol, stagnic Luvisol and humic Gleysols with sandy loam texture (Table 1). The dominant soil type at the experimental site was a stagnic Luvisol (Trükmann, 2010). The organic carbon content in the topsoil ranged between 1 and 1.5% that is equivalent to 2.5–3.2% humus. The pH values range between 5.3 and 6.8, and are irrespective of the fertilizer applied always lowest in the top 5 cm (pH = 5.3). In 2004 swards were established by using a uniform seed mixture representing the following species: perennial ryegrass (*Lolium perenne*), meadow fescue (*Festuca pratensis*), smooth-stalked meadow grass (*Poa pratensis*), timothy grass (*Phleum pratense*), orchard grass (*Dactylis glomerata*), white clover (*Trifolium repens*) and lucerne (*Medicago*

Table 1
Soil properties on the stagnic Luvisol derived from glacial till (experimental station Hohenschulen, Germany).

Depth (cm)	Soil zone	Texture (%)			Soil type
		Sand	Silt	Clay	
0–25	rAp	54	30	16	Sl4
25–45	SwBtv1	50	31	19	Ls3
45–70	SwBtv2	49	33	18	Ls3
70	Bv	55	31	14	Sl4

Trükmann (2010).