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Nitrous oxide emissions from winter oilseed rape cultivation

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ABSTRACT

Winter oilseed rape (*Brassica napus* L., WOSR) is the major oil crop cultivated in Europe. Rapeseed oil is predominantly used for production of biodiesel. The framework of the European Renewable Energy Directive requires that use of biofuels achieves GHG savings of at least 50% compared to use of fossil fuel starting in 2018. However, N_2O field emissions are estimated using emission factors that are not specific for the crop and associated with strong uncertainty. N_2O field emissions are controlled by N fertilization and dominate the GHG balance of WOSR cropping due to the high global warming potential of N_2O. Thus, field experiments were conducted to increase the data basis and subsequently derive a new WOSR-specific emission factor.

N_2O emissions and crop yields were monitored for three years over a range of N fertilization intensities at five study sites representative of German WOSR production. N_2O fluxes exhibited the typical high spatial and temporal variability in dependence on soil texture, weather and nitrogen availability. The annual N_2O emissions ranged between 0.24 kg and 5.48 kg N_2O-N ha^{-1} a^{-1}. N fertilization increased N_2O emissions, particularly with the highest N treatment (240 kg N ha^{-1}). Oil yield increased up to a fertilizer amount of 120 kg N ha^{-1}, higher N-doses increased grain yield but decreased oil concentrations in the seeds. Consequently oil yield remained constant at higher N fertilization. Since, yield-related emission also increased exponentially with N surpluses, there is potential for reduction of the N fertilizer rate, which offers perspectives for the mitigation of GHG emissions.

Our measurements double the published data basis of annual N_2O flux measurements in WOSR. Based on this extended dataset we modeled the relationship between N_2O emissions and fertilizer N input using an exponential model. The corresponding new N_2O emission factor was 0.6% of applied fertilizer N for a common N fertilizer amount under best management practice in WOSR production (200 kg N ha^{-1} a^{-1}). This factor is substantially lower than the linear IPCC Tier 1 factor (EF1) of 1.0% and other models that have been proposed.

1. Introduction

In the context of biofuel production especially nitrous oxide (N_2O) contributes to high GHG emissions during the step of biomass production (Dufossé et al., 2013; Hong, 2012). N_2O is a climate relevant trace gas that absorbs light in the IR spectrum and therefore reduces the atmospheric transparency to thermal radiation from the earth's surface (Granli and Bøckman, 1994). The atmospheric N_2O concentration in the last decade increased by 0.73 ppb a^{-1} and with a mean concentration of 328 ppb in 2015 it exceeded the pre-industrial level by about 21%

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(WMO, 2016). N_2O contributes 7.4% (0.17 W m^{-2}) of the total anthropogenic radiative forcing (IPCC, 2013); it has a high heat adsorption capacity, a long atmospheric lifetime of more than 100 years and has a 296 fold higher global warming potential (IPCC, 2001; RED, 2009) compared to the same mass of carbon dioxide (CO_2). Besides its contribution to the greenhouse effect, N_2O also contributes to stratospheric ozone depletion (Crutzen, 1981; Ravishankara et al., 2009).

Approximately 60% of anthropogenic N_2O emissions are released by agricultural soils (Clais et al., 2013). There is general agreement that nitrification and biological denitrification are the main sources for N_2O production in soils (Bremner, 1997), whereas the contribution of other processes such as nitrifier-denitrification is currently under discussion (Wrage et al., 2001; Shaw et al., 2006; Butterbach-Bahl et al., 2013).

All processes of N_2O production in soils rely on mineral N (i.e. Ruser et al., 2001; Zebarth et al., 2008). Therefore, N_2O emissions from agricultural soils generally increase with increasing N fertilization as it provides the substrates (NO_3^-, NH_4^+) for N_2O production (i.e. Stehfest and Bouwman, 2006). Furthermore, N_2O emission is correlated with N surpluses (N fertilization – N removal) in arable systems (Kaiser and Ruser, 2001; Van Groenigen et al., 2004) as well as in horticultural systems (Pfab et al., 2011).

Oilseed rape (*Brassica napus* L.) is the major oil crop in Europe, accounting for more than 70% of the European oilseed volume in 2012 (Carré and Pouzet, 2014). In 2014, oilseed rape covered 9.1×10^6 ha or approximately 8.5% of the total European arable land (FAO, 2016). The corresponding mean grain yield was 3.17 Mg ha^{-1}. In the same year, the mean grain yield in Germany was 4.48 Mg ha^{-1} on 1.4×10^6 ha (German Federal Statistical Office, 2017), showing both the high potential for winter oilseed rape (WOSR) cultivation as well as the reason for Germany's leading position (together with France) regarding WOSR production in the EU.

The acreage of WOSR in the European Union more than doubled between 2003 and 2014 (FAO, 2016), which went along with the increase of biodiesel contributing more than 75% of the transport biofuels in Europe (Hamelinck et al., 2013). This increased production is also a result of the Renewable Energy Directive (RED, 2009), in which the European Union mandates a share of 10% from renewables in the transport energy sector by 2020. The RED also defined sustainability criteria for biofuels, which were updated in 2015 (EU, 2015). According to these criteria, biofuels can only be considered and consequently subsidized as such if they contribute to a total reduction of greenhouse gas emissions (GHG) of 35% (current reduction value) and, starting from 2018, of 50% (for production plants that became operational before October 2015) and by 60% (for new production plants) in comparison to the use of fossil fuel.

WOSR is a crop demanding high amounts of N fertilizer to build up efficient photosynthetic leaf tissue (Hegewald et al., 2016). Maximum yields are often achieved with N rates exceeding 200 kg N ha^{-1} whereas N removal with the seeds as well as the N harvest index are low, thereby resulting in high N surpluses of up to 90 kg N ha^{-1} a^{-1} (Henke et al., 2007; Sieling and Kage, 2010). It has also been reported that large amounts of crop residues (petals and leaves), which can be mineralized easily, are returned to the soil after flowering (Sieling and Kage, 2010). Furthermore, N uptake by WOSR plants ends early and increases in N content in seeds during pod filling is more the result of N translocation from vegetative plant parts than from N uptake from soil (Malagoli et al., 2005); both will result in enhanced soil mineral N contents during or shortly after the harvest period. Winter wheat (*Triticum aestivum* L.) is the predominant succeeding crop for WOSR in German crop rotations. The N uptake of winter wheat before winter is approximately 20 kg N ha^{-1} and as such markedly below the N release after WOSR cultivation (Sieling and Kage, 2010). Both, the N surpluses as well as the high soil nitrate contents have the potential of fueling N_2O production in soils.

Due to the high global warming potential of N_2O, the assessment of N_2O emissions with a reliable emission factor is of vital importance for the calculation of GHG balances of biofuels, such as biodiesel produced from WOSR. Results from life cycle analysis (LCA) suggest that direct and indirect N_2O emissions account for between 20 and 40% of the total GHG emission associated with the production and consumption of biodiesel (Hong, 2012; Dufossé et al., 2013). For a bioethanol production system, the choice of different available N_2O emission factors in LCAs might result in completely contrasting results and conclusions, as Smith and Searchinger (2012) remarkably demonstrated. Following IPCC guidance, they set the emission factor to 1.5% (including direct and indirect emissions) and the corresponding emission reached the 35% GHG reduction goal. Using the distinct higher emission factor of 4%, as suggested by Crutzen et al. (2008), based on their so called "top-down" approach, the reduction potential for wheat-based bioethanol was completely eliminated.

In order to assess fertilizer-induced N_2O emissions, different N_2O emission factors have been proposed. The IPCC (2006) guidelines suggest a constant direct N_2O-N loss of 1% of N applied and N in crop residues. This default emission factor was modified from a global data set for wheat and grassland sites originally provided by Bouwman (1996) and, as mentioned by Bouwman, does not consider crop type or site-specific effects. A further drawback of this emission factor is that N_2O emissions do not necessarily correlate linearly with N fertilizer amounts and that N_2O emissions increase over-proportionally when high N fertilizer doses exceed plant demand (McSwiney and Robertson, 2005; Hoben et al., 2011; Kim et al., 2013).

The Joint Research Centre (JRC) of the EU provides an online tool (the so-called Global Nitrous Oxide Calculator, GNOC) to assess GHG emissions from biofuels in EU legislation (Edwards et al., 2013). This tool calculates N_2O emissions based on the approach of Stehfest and Bouwman (2006). It uses an exponential algorithm that considers site and management specific characteristics such as soil texture, climate, soil organic matter, pH and vegetation. In this model, WOSR was originally in the vegetation class "other" but the JRC recently moved it into the same class as "cereals" without refitting the model (Edwards et al., 2016). This resulted in a calculative reduction of the N_2O emissions from WOSR.

The decision to move WOSR to the cereals group in the GNOC tool is supported by Walter et al. (2015) who used data sets on N_2O emissions from WOSR fields to run a meta-analysis. They also used an exponential model for fertilizer-derived N_2O emission from WOSR, which resulted in even lower N_2O emissions than the GNOC tool.

In regions with strong frost-thaw cycles, high N_2O fluxes can occur during thawing periods (Flessa et al., 1995; Röver et al., 1998). These high thaw pulses can account for more than 50% of the annual N_2O budget from agricultural soils (Kaiser and Ruser, 2001; Jungkunst et al., 2006). Due to these high N_2O winter fluxes, annual measurements are a prerequisite for the reliable quantification of N_2O emissions. Consequently, the duration of the period of trace gas measurements was a criterion for the inclusion (measurements covering > 300 days) or exclusion of data sets in the review by Walter et al. (2015), and only 12 studies with 18 annual datasets (43 data points in total) fulfilled this criterion. Additionally, the small dataset showed a high variability of the N_2O emissions among study sites and also among experimental years.

The main aims of our investigations were therefore: (i) to determine direct annual N_2O emission from WOSR fields over a broad range of production sites, representing areas with a high proportion of WOSR within the crop rotations, thereby extending the currently available data substantially, (ii) to quantify the effect of N fertilization on N_2O fluxes and on yield-related N_2O emission, and (iii) to deduce a fertilizer-related emission factor (FRE) specific for the production of winter WOSR.

2. Materials and methods

2.1. Study sites, experimental design and management

Trace gas measurements were conducted at five study sites located