European Journal of Agronomy 89 (2017) 88–96

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Efficacy of agronomic strategies for mitigation of after-harvest N_2O emissions of winter oilseed rape

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ARTICLE INFO

Keywords:
Rapeseed
N_2O emission
Residue management
Crop rotation
Nitrogen
Tillage management

ABSTRACT

Winter rapeseed is one of the most important field crops in Germany. In comparison to other crops, nitrogen (N) surplus of rapeseed is usually high and increased values of mineral nitrogen are observed in soil after harvest. N losses via nitrate leaching or emissions of nitrous oxide (N_2O) have a negative impact on the greenhouse gas (GHG) balance of biodiesel produced from rapeseed. So far, the effects of different post-harvest management options on these losses after rapeseed cultivation have not been assessed. The aim of this study was to investigate agronomic measures, such as different following main crops (wheat and barley) as well as different catch crops (mustard respectively ryegrass) and varied tillage intensity for their effectiveness in reducing high soil nitrate contents and the associated N_2O emissions after rapeseed harvest. A field trial was conducted in Southern Germany at a site characterized by a silty loam soil, temperate climate and high precipitation. N_2O fluxes were measured twice a week with the closed chamber method. In 2013/14 and 2014/15 the calculated N-balance (N input – N output) showed a surplus after rapeseed harvest of 61 kg N ha^{-1} and 117 kg N ha^{-1}, respectively. N_2O-N emissions were relatively low from August to March in both years, remaining within a range of 0.3 and 2.0 kg ha^{-1}. The biomass N uptake of the succeeding crops increased significantly in both years and all treatments over winter with the exception of the mustard treatment which lost N due to freezing off. No clear relationship between N_2O emissions and the course of soil mineral nitrogen (SMN) dynamics was observed. In both years, there were no significant differences in N_2O emissions between all treatments. Our results indicate that as far as N_2O emissions under well-managed soils in southern Germany are concerned, there is no need to change the established crop sequence of rapeseed – winter wheat.

1. Introduction

Winter rapeseed is the most important oil crop in Germany. Due to its economic attractiveness, it is grown on 11% of the arable land in Germany; currently, rapeseed is grown on approximately 1.3 million hectares (Statistisches Bundesamt, 2015). The area used for rapeseed cultivation has increased in the last two decades, which can be attributed to political measures aiming at increasing biofuel production (Bmelv, 2009; Bmelv, 2009; Eu Red, 2009) and to advances in plant breeding which have resulted in higher yields (Friedt et al., 2003). Rapeseed is processed to cooking oil or to rapeseed oil methyl esters (RME), which are used for biodiesel production. The coproduct rapeseed cake is mostly used for animal feeding.

There are several positive effects of the inclusion of rapeseed in cereal crop rotations. It interrupts infection cycles of plant pathogens (Kirkegaard et al., 2008), thereby reducing pesticide demand. Rapeseed also improves soil structure due to its strong root formation and provides good soil cover for long periods (Kirkegaard et al., 2008). Mineralization of rapeseed crop residues provides significant amounts of nitrogen to the following crop (Malagoli et al., 2005), which is of particular advantage for cultivation of winter wheat for bread-quality flour. Compared to preceding crops like sugar beet or maize, winter wheat cultivation also benefits from the early harvest of rapeseed, which allows a timely sowing of winter wheat. As a result, inclusion of rapeseed in crop rotations results in significant increase of yield from winter wheat in comparison to less-optimal preceding crops such as maize or other cereals (Rieger et al., 2008; Sieling et al., 2005).

In comparison to other crops, the nitrogen (N) surplus of rapeseed cultivation is usually high, and high values of mineral nitrogen are observed in soil after harvest (Lickfett, 2000; Aufhammer et al., 1994). N demand of winter rapeseed is high and N uptakes of more than 250 kg ha^{-1} can occur (Spicker, 2016). Despite notable advances in yield potential over the years, harvest index (0.25–0.3 for rapeseed and 0.5 for wheat) as well as N-harvest index (0.6–0.7 for rapeseed and 0.8

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http://dx.doi.org/10.1016/j.eja.2017.06.009
Received 21 February 2017; Received in revised form 23 June 2017; Accepted 26 June 2017
1161-0301/

for wheat) of oilseed rape are still lower compared to cereals like wheat (Sieling and Kage, 2010; Hege et al., 2002; Diepenbrock, 2000). Often only a proportion of the biomass N is exported with the harvested rape seeds (Rathke et al., 2006; Aufhammer et al., 1994). Thus, high amounts of N can remain in crop residues after harvest (Lickfett, 2000; Hocking et al., 1997). Rapeseed crop residues are characterized by a C/N ratio of 50–70 and can therefore be mineralized quicker than residues of wheat or rye (Kaul, 2004; Justes et al., 1999; Kaiser et al., 1998). Nevertheless even rapeseed crop residues can show N immobilizing effects during certain periods (Rahn et al., 2003; Baggs et al., 2000). Depending on tillage intensity, weather, mineralization conditions and N uptake of the following crop, high N losses due to nitrate leaching or emissions of nitrous oxide (N_2O) and dinitrogen (N_2) can occur after harvest (Walter et al., 2014).

High N_2O emissions have a negative impact on the GHG and ecological balance of RME (Leopoldina, 2012; Crutzen et al., 2008; Gaertner and Reinhardt, 2003). Thus, N_2O emissions should be minimized through suitable agronomic measures. The European Union (EU) has defined sustainability criteria for biofuels in its Renewable Energy Directive (RED), which demands that GHG emissions from biofuels must be at least 35% lower than those of fossil fuels. In 2018, this threshold increases to 50% and will increase to 60% for new production plants in 2018 (Eu Red, 2015). During crop production, direct N_2O field emissions are the largest share of GHG emissions. They are commonly estimated according to IPCC Tier 1 methodology (Biograce, 2017; Ipcc, 2006); i.e., an emission factor of 1% of fertilizer nitrogen and harvest residues is assumed. Sustainability and acceptance of RME as a biofuel face the challenge of mitigating high N_2O emissions during cultivation and utilizing the high N surplus after harvest without negatively impacting rapeseed yields. Several recent research projects have therefore investigated strategies for reducing N-losses during rapeseed cultivation. Examples of these strategies include site-specific fertilization (precision farming) (Spicker, 2016) and the cultivation of semi dwarf hybrids (Miersch, 2014), although the results concerning the sustainability potential of these genotypes is ambiguous (Sieling and Kage, 2008). There are also several older scientific studies about N_2O emissions during rapeseed cultivation in Germany, but these were conducted in obsolete low N-input systems, such as sites with very low yield or low N_2O emission potential (Hellebrand et al., 2008; Kaiser et al., 1998; Schmaedeke, 1998).

In particular, N_2O emissions after rapeseed harvest have not been studied extensively. Currently it is not possible to accurately estimate N_2O emissions that are caused by rapeseed cultivation but occur during cultivation of the following crop. This lack of knowledge hinders a sufficient evaluation of potential mitigation strategies. However, it is commonly accepted that high soil nitrate contents in the autumn and winter after rapeseed cultivation need to be avoided in order to reduce N_2O emissions. To achieve that, the nitrogen surplus of rapeseed needs to be taken up quickly by following plants, a task which can be achieved with N-conserving crop sequences and adapted tillage (Sieling and Kage, 2010) or with catch crops (Henke et al., 2008; Justes et al., 1999).

The objective of this study was to investigate the effectiveness of agronomic measures in reducing high soil nitrate contents and associated N_2O emissions after rapeseed harvest. A field trial in southern Germany was set up to study the following research questions:

1. Impact of following crop: How do the differing dates of sowing winter barley (*Hordeum vulgare* L.) and winter wheat (*Triticum aestivum* L.) influence their pre-winter development as well as their N uptake and the resulting nitrogen dynamics and N_2O emissions after rapeseed cultivation?
2. Impact of tillage: Does reduction of tillage by direct seeding of winter wheat impact nitrogen dynamics and reduce N_2O emissions?
3. Impact of catch crops: Can fast growing catch crops such as mustard (*Sinapis alba* L.) and annual ryegrass (*Lolium multiflorum* Lam.) contribute to a mitigation of N_2O emissions after rapeseed cultivation?

Table 1
Soil properties at 0–30 cm depth, experimental station Roggenstein[a].

parameter	unit	2013/14	2014/15
soil type		calcaric cambic Phaeozem	calcaric endoskeletic Phaeozem
clay	$g\ kg^{-1}$	330	350
silt	$g\ kg^{-1}$	470	460
sand	$g\ kg^{-1}$	200	190
SOC	$g\ kg^{-1}$	12.4	31.1
SON	$g\ kg^{-1}$	1.0	2.2
C/N ratio		12.4	14.1
$CaCO_3$	$g\ kg^{-1}$	3.3	22.0
pH		6.2	7.2
soil depth until gravel	m	0.8	0.6

[a] Soil taxonomy according to FAO world reference base for soil resources (Fao, 2006).

2. Material and methods

2.1. Site conditions

A field trial was established at the Roggenstein experimental station, which is situated 20 km west of Munich (48°10′47”N 11°19′11“E). Mean annual temperature at the site is 8.5 °C (1995–2010), and the mean annual precipitation is 930 mm (Agrarmeteorologie Bayern, 2016). The soil of the field trials is characterised in Table 1. Both fields are normally managed with conventional tillage (mouldboard ploughing). The depth of the Ap horizon is 25 cm. Below the Ap horizon is a 60–70 cm Bv horizon above calcareous terrace gravel. Due to excellent natural drainage, the soils are not influenced by groundwater and drain quickly even after strong precipitation events. Although soil organic carbon (SOC) content of the soil in 2014/15 is three times as high as in the preceding year, the site is cultivated as cropland for more than 100 years and therefore does not show typical characteristics of organic soils anymore.

2.2. Field trial

Prior to the field trial, winter rapeseed was cultivated on the fields. Concerning the N input it was fertilized with 200 $kg\ ha^{-1}$ (2013) and 230 $kg\ ha^{-1}$ (2014) given as mineral fertilizer and yielded seed harvests of 4.3 $Mg\ ha^{-1}$ and 3.8 $Mg\ ha^{-1}$, respectively. The difference between applied fertilizer N and harvested N indicates an N surplus of 61 $kg\ ha^{-1}$ and 117 $kg\ ha^{-1}$, respectively. No mineral or organic fertilizer was applied on the field after rapeseed harvest. The field trial was a randomized block design with five treatments in four replicates. The size of the plots was 3 m × 10 m. They were placed outside the areas impacted by traffic during rapeseed cultivation. Treatments were wheat with conventional tillage (W_t), wheat with reduced till (W_{rt}), barley (B), ryegrass (R), and mustard (M). Details regarding field management are given in Table 2. Wheat (variety: Kerubino) was sown in both treatments with a density of 320 kernels m^{-2}, barley (variety: Sandra) with 335 kernels m^{-2} and the catch crops mustard (variety: King) respectively ryegrass (variety: Fabio) with 200 and 1200 kernels m^{-2}. Row spacing was 12 cm except wheat sown after reduced tillage in 12 cm broad bands with a row spacing of 25 cm.

2.3. Weather conditions

Both measurement periods were characterized by long growing seasons, mild and very dry winters resulting in an early vegetation start (Table 3). Most months were approximately 1–3 °C warmer than the long-term average. This trend was especially pronounced in 2013/14