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Modelling of nitrous oxide emissions from clover grass ley – wheat crop rotations in central eastern Germany

An application of DNDC

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Scientific Summary

Nitrous oxide (N_2O) is one of the three primary anthropogenic greenhouse gases. The agricultural sector accounts for 75.7 % of all anthropogenic N_2O emissions in Germany (Umweltbundesamt, 2012). Thus, accurately estimating N_2O emissions as well as mitigation strategies for N_2O are crucial.

This study optimizes the process-based model DNDC to simulate N_2O emissions by conventional winter wheat and three different organic clover grass ley – wheat rotations at a site in central eastern Germany (Bad Lauchstädt: 51°24' N, 11°53' E). The model simulates the soil environment (temperature, moisture, oxygen content etc.), plant growth and decomposition to determine nitrification, denitrification as well as fermentation. The central focus of this study is to assess the ability of DNDC to simulate N_2O emissions in Bad Lauchstädt, followed by a comparison of the different crop rotations with respect to their N_2O emissions based on weekly measurements and DNDC simulations. The study concludes with an investigation of emissions under future climate conditions.

DNDC is able to reproduce monthly patterns of emissions in Bad Lauchstädt. Underlying processes such as plant growth and soil moisture are not represented with sufficient precision. The mean modelling efficiency (Nash Sutcliff Efficiency) of the validation runs for the monthly N_2O fluxes is 0.136 and ranges from -0.526 to 0.446. Predicted daily and annual fluxes show a great offset compared to measured values. Emissions in Bad Lauchstädt are very low if compared to other observations in Germany and are primarily constrained by soil moisture and not by nitrogen availability. Neither the measurements nor the modelling results are able to resolve significant differences between the four crop rotations. According to the measurements, conventional winter wheat emits 836 g N ha^{-1} a^{-1}, while the organic treatments release between 645 g N ha^{-1} a^{-1} and 1044 g N ha^{-1} a^{-1}. DNDC simulates no significant change of N_2O emissions under future climate conditions; this finding is not robust due to the abovementioned drawbacks of DNDC in this study.

Improved estimates could be obtained by adjusting the ability of DNDC to capture the situation in Germany and in Bad Lauchstädt. Special attention should be given to the implementation of plant growth and evapotranspiration. Better comparison of treatments requires a longer measurement period and a higher temporal resolution, so that duration and height of peak emission events can be captured.

Keywords: Physical Geography and Ecosystem analysis, DNDC, N_2O, Bad Lauchstädt, clover grass ley, winter wheat, spring wheat, climate change, emission factors

Wissenschaftliche Zusammenfassung

Lachgas (N_2O) zählt neben Kohlenstoffdioxid (CO_2) und Methan (CH_4) zu den drei bedeutendsten anthropogenen Treibhausgasen. Als größte durch den Menschen verursachte Quelle ist hier die Landwirtschaft anzuführen, welche in Deutschland einen Anteil von 75.7 % ausmacht (Umweltbundesamt, 2012). Eine genaue Quantifizierung der N_2O – Emissionen und eine Entwicklung möglicher Vermeidungsstrategien ist somit vonnöten.

Diese Studie parametrisiert das prozessbasierte Model DNDC, um Lachgasemissionen von konventionellen Weizen und drei verschiedenen Kleegrass – Weizenfruchtfolgen in Bad Lauchstädt (51°24' N, 11°53' E) abzubilden. Beruhend auf simulierten biogeochemischen Bodenverhältnissen, Pflanzenwachstum und mikrobiellen Abbau, bestimmt DNDC Denitrifikation, Nitrifikation und Fermentation. Ziel dieser Arbeit ist es, die Modelgüte am Standort Bad Lauchstädt zu evaluieren und verschiedene Fruchtfolgen hinsichtlich ihrer Emissionen zu bewerten. Darüber hinaus wird der Einfluss des Klimawandels auf die Freisetzung von Lachgas beleuchtet.

DNDC ermöglicht die Modellierung der monatlichen N_2O-Emissionen, ist jedoch nicht geeignet, um tägliche und jährliche Emissionsdynamiken abzubilden. Die mittlere Modeleffizienz (Nash Sutcliff Effizienz) für monatliche N_2O-Flüsse für die verschiedenen Parzellen, welche für die Validierung herangezogen wurden, beträgt 0.136. Darüber hinaus weichen die DNDC Ergebnisse stark von dem gemessenen Bodenwassergehalt und den jährlichen Ernteerträgen ab. Die hohe Trockenheit und somit geringe Bodenfeuchte ist der wesentliche limitierende Faktor für Lachgasemissionen in Bad Lauchstädt. Die Stickstoffverfügbarkeit nimmt hier nur eine untergeordnete Rolle ein. Somit können weder die Messungen noch die Modellergebnisse signifikante Unterschiede zwischen den verschiedenen Fruchtfolgen feststellen. Konventioneller Winterweizen emittiert jährlich 836 g N ha^{-1}. Die Lachgasflüsse der biologischen Fruchtfolgen variieren zwischen 645 g N ha^{-1} a^{-1} und 1044 g N ha^{-1} a^{-1}. Der Klimawandel wird laut DNDC nicht zur Veränderung der Stickstoffverluste in Form von Lachgas führen. Da wesentliche Einflussgrößen der Lachgasproduktion von DNDC nicht angemessen wiedergegeben werden, ist dieses Ergebnis mit großen Unsicherheiten behaftet.

Genauere Modelresultate benötigen eine Anpassung von DNDC auf die Gegebenheiten in Deutschland, im speziellen Bad Lauchstädt. Dabei ist eine Weiterentwicklung der pflanzenphysiologischen Simulation und der Bestimmung der Evapotranspiration von großer

Bedeutung. Längere Lachgasflussmessungen mit zugleich höherer zeitlicher Auflösung können einen besseren Vergleich der Fruchtfolgen ermöglichen.

Schlüsselwörter: Physische Geographie und Ökosystemanalyse, DNDC, N_2O, Bad Lauchstädt, Kleegras, Winterweizen, Sommerweizen, Klimawandel, Emissionsfaktoren

Table of contents

Glossary

CGL	Clover grass ley
cWW – cWW	Treatment where conventional winter wheat is grown in two subsequent years
DNDC	Denitrification – Decomposition, a process-based model to simulate agricultural trace gas emissions
hCGL – oSW	Treatment where clover grass ley is tilled in spring and the cut is harvested followed by spring wheat (plot 312, 412 and 512)
hCGL – oWW	Treatment where clover grass ley is tilled in fall and the cut is harvested followed by winter wheat (plot 311, 411 and 511)
mCGL – oWW	Treatment where clover grass ley is tilled in fall and the cut is mulched followed by winter wheat (plot 321, 421 and 521)
NSE	Nash Sutcliffe Modelling Efficiency, A dimensionless parameter to describe model accuracy. One equals a perfect fit, while zero indicates that the model is as accurate as the average observed value.
RMSE	Root mean square error
SOC	Soil organic carbon
SOM	Soil organic matter
SON	Soil organic nitrogen
SW	Spring wheat
WW	Winter wheat

1 Introduction

This report is part of a larger study headed by the von Thünen Insitute in Brunswick/Germany, which investigated the effect of different clover grass ley – wheat crop rotations on nitrous oxide (N_2O) emissions between 2010 and 2012. This portion of the study focuses on modelling emissions and yield of different crop rotations with a process-based biogeochemical model using observations on site.

N_2O is, after carbon dioxide and methane, the main anthropogenic greenhouse gas (GHG) (Forster et al., 2007; WMO, 2012). Its global warming potential over a 100 year time frame is 298 higher compared to carbon dioxide (Forster et al., 2007). In 2011 the atmospheric concentration of N_2O was 324 ppb and it is increasing by 0.78 ppb a^{-1} (WMO, 2012). The growth over the last century causes a radiative forcing of 0.16 W m^{-2} (Forster et al., 2007).

The natural and anthropogenic sources of atmospheric N_2O are manifold. About 64 % of all N_2O emissions are caused by natural processes (Ussiri and Lal, 2012). The greatest source within this group are upland soils below natural vegetation (Ussiri and Lal, 2012). The other contributors are linked to sources within aquatic and marine ecosystems such as rivers, estuaries and coastal waters (Ussiri and Lal, 2012). The natural N_2O production and atmospheric N_2O break down were in balance before the industrial revolution in the early 20th century (Forster et al., 2007; Smith, 2012). Intensification of agriculture as well as industrial pollution led to a tremendous increase of atmospheric N_2O concentration from a pre-industrial level of 270 ppb to 324 ppb in 2011 (IPCC, 2007; WMO, 2012). The agricultural sector accounts for 67 % to 80 % of global anthropogenic N_2O emissions (Ussiri and Lal, 2012). In Germany, the agricultural sector is responsible for 75.7 % of all anthropogenic N_2O emissions (Umweltbundesamt, 2012). The total global agricultural emissions are subject to debate. Mosier et al. (1998) give a range of direct N_2O emissions by agricultural soils of 0.4 Tg N a^{-1} to 3.8 Tg N_2O-N a^{-1} globally. A more narrow range is given by Berdanier and Conant (2012), who attribute 1.6 Tg N a^{-1} to 3.2 Tg N a^{-1} to farming.

One significant source of uncertainty stems from the fact that many countries, including Germany, use Tier 1 IPCC default emission factors. This emission factor assumes that 1 % of the N input to the soil is emitted as N_2O (Bouwman, 1996; Eggleston et al., 2006; Penman et al., 2000). Process-based models could serve as a tool for improving national emission reporting of N_2O to the United Nations Framework Convention on Climate Change (UNFCC). DNDC (denitrification – decomposition) is one process-based model that has, in many studies, proven its ability to simulate N_2O emissions from arable land (Beheydt et al., 2007; Li et al., 1994, 1992b; Ludwig et al., 2011; Smith et al., 2004, 2002).

This study evaluates if DNDC can be successfully applied to predict N_2O emissions from organic cropland at a site in central eastern Germany characterised by very low annual emissions (<1kg N ha^{-1} a^{-1}).

The study also compares four different treatments regarding their total N_2O emissions. All four treatments are typical crop rotations in conventional and organic farming in Germany. Comparison is based on interpolation of discrete weekly measurements and on modelling results. Because N_2O production and emissions fluctuate, both spatially and temporally, interpolation of measurements is prone to errors (Dobbie et al., 1999; Freibauer and Kaltschmitt, 2003; Kaiser et al., 1998; Venterea et al., 2009). A model may help understand emission dynamics and confirm measured results. Many studies have addressed emissions from legumes such as soy beans or alfalfa (Ciampitti et al., 2008; Rochette and Janzen, 2005; Yang and Cai, 2005; Zhong et al., 2009). Currently, however, there is a lack of measurements and literature on N_2O emissions of entire clover grass ley rotations. Knowing this information is critical because current farming practices have the greatest potential for mitigating anthropogenic N_2O emissions (Forster et al., 2007; Smith, 2012).

Investigating entire rotations rather than the individual crop is crucial, due to the hysteresis effect on soil properties such as moisture, nutrients, soil organic carbon. This is in particular true for legumes, because of their effect on soil nitrogen. A study in the Czech Republic by Šimek et al. (2004) measured emissions by clover grass over one growing season (224 days) to be 0.9 kg N ha^{-1}, but did not observe the N_2O fluxes for the subsequent crop. Misselbrook et al. (1998) and Williams et al. (1999) detected much higher emissions at sites where clover grass was fertilized (3.2 kg N ha^{-1} over 365 days) or manure was applied (0.684 kg N ha^{-1} and 0.945 kg N ha^{-1} over 60 days) (Rochette and Janzen, 2005). Ball et al. (2007) looked at emissions by winter barley undersown with clover grass ley and gave an emission range of 2.5 kg N ha^{-1} a^{-1} to 4 kg N ha^{-1} a^{-1}. Nadeem et al. (2012) considered a subsequent growth of clover grass ley and barley. They have found significant differences between different green manure management practices at clover grass ley – barley crop rotation in Norway (Nadeem et al., 2012). According to the Nadeem et al. (2012) study, mulching enhanced N_2O emissions by 0.37 kg N ha^{-1}.

This study is based on new measurements over a period of two years and thus will help to close this gap in the understanding of N_2O emissions by different clover grass ley crop rotations.

Besides improving the precision of estimates of current emissions and comparing different crop rotations, this study also looks into potential emissions under future climate conditions. The IPCC expects an increase of N_2O emissions by arable land of 35 % to 60 % by 2030 relative to 1990 (Smith et al., 2007). The advantage that process-based models have over empirical models is in their ability to work even though some boundary conditions change. Future N_2O behaviour is investigated by changing precipitation and temperature individually as well as computing different climate scenarios. Dobbie et al. (1999) detected an increase in N_2O fluxes with higher temperature and higher soil moisture. Hsieh et al. (2005) used a process-based model to simulate emissions by grassland under future climate conditions in Ireland. According to their study, emissions will be 45 % higher by the end of the century. N input into the atmosphere by clover grass ley rotations under future climate conditions is not well understood and is further investigated in this report.

To summarize, this study addresses three questions regarding N_2O emissions and their modelling:

a) Are process-based models, in particular DNDC, capable of simulating sites with low N_2O emissions and therefore able to serve as a method to determine emission factors?
b) Are there differences between varying management practices when growing clover grass ley – wheat crop rotations?
c) How is climate change affecting N_2O emissions by clover grass ley – wheat crop rotations?

2 The nitrogen cycle and the production and emission of nitrous oxide

This chapter briefly describes the nitrogen (N) cycle (Fig. 1) and specifies factors that influence the production and emission of N_2O.

2.1 The natural nitrogen cycle

Dinitrogen (elemental nitrogen, N_2) makes up 78 % vol. of the atmosphere and is thus by far the most abundant chemical component in the atmosphere (Brady and Weil, 2007). The strong triple bond between both nitrogen atoms makes it unavailable for direct plant uptake (Brady and Weil, 2007). Thus, dinitrogen must be transformed into reactive nitrogen, which is defined as all forms of nitrogen that are chemically and biologically active such as nitrous oxide (N_2O), ammonium (NH_4^+), ammonia (NH_3) nitrate (NO_3^-) and nitrite (NO_2^-) (Hill, 2007). The nitrogen cycle is the sum of mainly biologically driven transformations of nitrogen between the different forms of reactive nitrogen and dinitrogen. The cycle is driven by at least five major processes: nitrogen fixation, nitrogen immobilization, nitrogen mineralization, nitrification and denitrification (Allaby, 2002; Blume et al., 2009; Brady and Weil, 2007; Hill, 2007).

Nitrogen fixation

Nitrogen fixation is the process that transforms dinitrogen into reactive nitrogen. Every year 139 million Mg N_2 is fixed through non-anthropogenic pathways (Brady and Weil, 2007). Biological N fixation by different soil bacteria is mediated by the enzyme Nitrogenase.

$$N_2 + 8H^+ + 6e^- \xrightarrow{Nitrogenase} 2NH_3 + H_2 \qquad (1)$$

The most common pathway is symbiotic N fixation by Rhizobia bacteria that live in root nodules connected to legumes. Another path is fixation by autotrophic Cyanobacteria utilizing the energy of light (Allaby, 2002). These bacteria are abundant in rice paddies (Allaby, 2002). In addition, some free-living bacteria are able to fix nitrogen; the bacterial fixation pathway is widespread in tropical regions (Allaby, 2002).

Nitrogen fixation by lightning is another significant source of reactive nitrogen, although it is minor compared to bacterial fixation (Allaby, 2002). Lightning supplies enough energy to cause a reaction of oxygen and dinitrogen producing oxides of nitrogen that are washed out of the atmosphere by precipitation (Allaby, 2002).

Nitrogen immobilization

Nitrogen immobilization describes all processes that transform inorganic forms of nitrogen into organic forms (Brady and Weil, 2007). Nitrogen bound in organic compounds is protected from nitrification and denitrification. Nitrogen immobilization is also called nitrogen assimilation. Nitrogen can also exit the nitrogen cycle for a period of time by ammonium fixation to clay minerals (Brady and Weil, 2007).

Nitrogen mineralization

Nitrogen mineralization is the reverse process of nitrogen immobilization. Around 95 % to 99 % of soil nitrogen is part of organic compounds, hence it cannot be utilized by plants (Brady and Weil, 2007). Therefore, mineralization is a crucial step of the nitrogen cycle. The entire process is governed by the enzymes of microorganisms (Brady and Weil, 2007). The central process of mineralization is hydrolysis of simple amino compounds to ammonium ions, which are then available for nitrification (Brady and Weil, 2007).

Nitrification

Nitrification describes the enzymatic oxidation of ammonium ions (NH_4^+) to nitrate ions (NO_3^-) by autotrophic bacteria (Blume et al., 2009). The process is mediated by different bacteria that benefit by withdrawing energy from the oxidation process (Brady and Weil, 2007).

$$NH_4{}^+ + \frac{3}{2}O_2 \xrightarrow{Nitrosomonas} NO_2{}^- + 2H^+ + H_2O + 275kJ \tag{2}$$

$$NO_2{}^- + \frac{1}{2}O_2 \xrightarrow{Nitrobacter} NO_3{}^- + 76kJ \tag{3}$$

Both reactions occur in immediate sequence, which is crucial because $NO_2{}^-$ is toxic to most plants (Brady and Weil, 2007). Nitrate is very soluble and is easily leached into the ground water.

Denitrification

Denitrification is the reduction of nitrate to dinitrogen. This occurs under oxygen limitation in the soil matrix, mostly when water filled pore space (wfps) exceeds 70 % to 80 % (Blume et al., 2009). Reduction occurs via the following pathway.

$$NO_3{}^- \rightarrow NO_2{}^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \tag{4}$$

The different chemical reactions are mediated by various microorganisms that use oxygen nitrogen connections as electron acceptors. Slightly different soil conditions are required for the different reactions. NO, N_2O and N_2 can leave the soil matrix and enter the atmosphere.

The above is a brief description of some of the main processes of the nitrogen cycle. More information is available in Brady and Weil (2007), Blume et al. (2009) as well as in other books on biogeochemistry in soils.

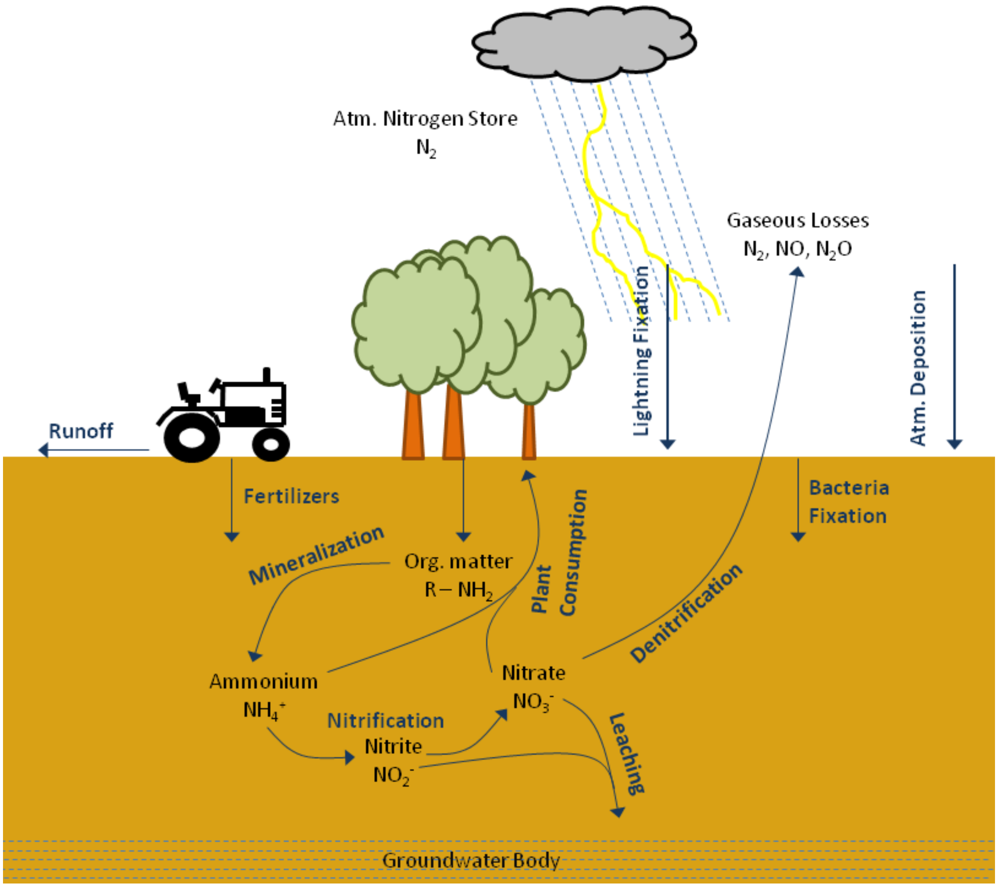

Fig. 1. Nitrogen cycle (adapted from Pidwirny (2009)).

2.2 Production of nitrous oxide and its environmental controls

The following section describes the major pathways of N_2O production in agricultural soils and their controlling environmental factors. Denitrification and nitrification account for 90 % of all agricultural emissions (Ussiri and Lal, 2012). However, there are also other production pathways that are beyond the scope of this chapter. Further information is available in Ussiri and Lal (2012) as well as in Smith (2012).

As described in section 2.1, N_2O is an intermediate product of denitrification. Thus, it occurs if soil conditions favour denitrification but do not to allow a full reduction to N_2. Nitrification produces N_2O as well, but it is not an intermediate product, thus is not as productive.

Approximately 2 % to 4 % of nitrified nitrogen turns into N_2O (Duxbury and McConnaughey, 1986; Ussiri and Lal, 2012).

Nitrification and denitrification require different environmental conditions, but can occur in the same soil at different microsites. Both processes are governed by several environmental drivers including substrate availability (e.g. soil organic carbon), soil temperature, soil moisture, texture, bulk density, pH and vegetation (Ussiri and Lal, 2012). Denitrification needs nitrogen oxides such as nitrate, nitrite and nitric oxide while nitrification requires ammonium. Soil temperature directly influences microbial activity as well as enzymatic reactions, hence metabolic turnover. The optimal temperature for the production and emission of N_2O is 30 °C to 35 °C (Ussiri and Lal, 2012). In addition, freeze and thaw cycles in winter months enhance N_2O production and may contribute greatly to annual emissions (Dobbie et al., 1999; Flessa et al., 1995). Soil moisture affects the concentration and transport of oxygen through the soil matrix and therefore determines if a soil is anaerobic or aerobic. Anaerobic conditions benefit denitrification which has much higher production rates of N_2O (Ussiri and Lal, 2012). Texture and bulk density also control aeration of the soil matrix, besides controlling substrate availability by determining surface area of the soil matrix. Low bulk density increases porosity thereby raising the availability and diffusion of oxygen. Soil texture determines water holding capacity and drainage. Optimal soil moisture content for N_2O production is 60 % wfps to 65 % wfps (Ussiri and Lal, 2012). However different studies mention different optimal soil moisture ranges. Blume et al. (2009) give an optimal range of 60 % to 70 % wfps. Furthermore the temporal dynamics of soil moisture influence N_2O emissions as well. A strong rain event after an extended dry period triggers high fluxes of N_2O (Cabrera, 1993; Ruser et al., 2006; Skiba and Smith, 2000). Higher soil carbon content amplifies emissions, because it supplies microbes with substrates. This is important for both production processes, but in particular for denitrification (Ussiri and Lal, 2012). Denitrification is mostly accomplished by heterotrophic microbes that require organic carbon as electron donor. N_2O production is at its minimum when soil pH is above 7.3, and emissions increase when soil pH decreases (Stehfest and Bouwman, 2006; Ussiri and Lal, 2012). Finally, vegetation affects N_2O emissions. High plant diversity has been reported to reduce emissions (Niklaus et al., 2006; Ussiri and Lal, 2012). Furthermore N_2O emissions are enhanced by nitrogen fixing legumes. However these control emissions on a different spatial scale.

In sum, N_2O production and emissions are driven by many interlinking factors, hence predicting and modelling them is difficult.

3 Research project “regional greenhouse gas emissions by clover grass ley – wheat cropping systems”

The study is part of a research project initiated by the Department of Climate Smart Agriculture at the Johann Heinrich von Thünen Institute in collaboration with the Technical University Munich, the Helmholtz Zentrum Munich, the Rheinische Friedrich-Wilhelms- University Bonn and the Martin-Luther-University Halle-Wittenberg. Funding was provided by the Federal Ministry of Food, Agriculture and Consumer Protection from 2010 to 2012.

The overall goal of the project was to establish regional emission factors for N_2O for four different wheat crop rotations (Freibauer et al., 2009). The studied cropping systems were: (i) organic clover grass ley, harvested and tilled in fall, followed by winter wheat; (ii) organic clover grass ley, harvested and tilled in spring, followed by spring wheat; (iii) organic clover grass ley, mulched and tilled in fall, followed by winter wheat and (iv) conventional winter wheat grown in two subsequent years. The primary difference between treatment (i) and (iii) is that mulching adds additional organic carbon and nitrogen to the soil. Treatment (ii) reduces soil organic nitrogen and carbon availability during winter months. This may result in lower emissions in the absence of frost and thaw cycles due to temperature dependency of nitrification and denitrification (Dörsch et al., 2004; Röver et al., 1998).

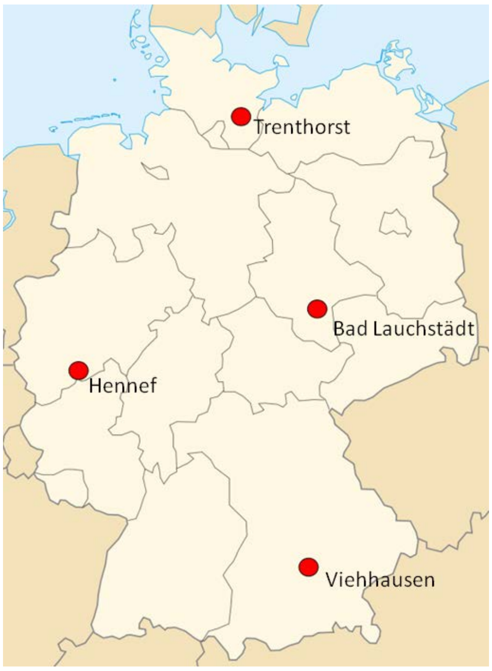

Fig. 2. Nitrous oxide fluxes were measured at four locations in Germany that represent different climatic regions (adapted from Fuß et al., 2013).

Measurements of N_2O emissions were taken at four different sites, each representing a geographic and climatic region in Germany. In addition, soil moisture and weather data were determined at all sites over the entire period. The experimental locations are displayed in Fig. 2 and characterised in Tab. 1.

Tab. 1. Location, mean annual temperature and average annual precipitation of all four sites that have been investigated during the research project (Freibauer et al., 2009).

	North	**West**	**South**	**East**
Location	Trenthorst	Hennef	Viehhausen	Bad Lauchstädt
Average temperature [°C]	8.7	10.3	7.8	8.7
Precipitation [mm]	740	840	786	484

Initial results were presented at the European Geosciences Union (EGU) General Assembly 2013 in Vienna by Fuß et al. (2013). However, most of the data analysis and publishing is still in progress.

Fuß et al. (2013) confirmed that emissions fluctuate greatly from year to year and between regions. They could not identify any systematic differences between emissions below clover grass ley and wheat (Fuß et al., 2013). All clover grass treatments showed similar results. Mulching does not increase emissions and tilling in spring does not reduce fluxes (Fuß et al., 2013). However, these findings were based on annual sums and need further investigation and testing of hypotheses.

This study aims to contribute to improved greenhouse gas emission reporting to the UNFCCC and to explore options for reducing emissions by clover grass ley – organic wheat crop rotations. Based on previous studies and measurements, the project partners to the research project "regional greenhouse gas emissions by clover grass ley – wheat cropping systems" proposed five working hypotheses (Freibauer et al., 2009):

1. N_2O emissions after incorporation of clover grass residues vary strongly between regions.
2. N_2O emissions do not occur during clover grass ley, but under the subsequent crop.
3. Mulching increases N_2O emissions.
4. The inter-annual variability of emissions is governed by frost and thaw cycles as well as by precipitation distribution.
5. Incorporation of clover grass residues in spring decreases N_2O emissions.

4 Material and Methods

This chapter introduces the study site and the experiments. DNDC is also generally described and the model parameterisation procedure is explained.

4.1 Study site

Bad Lauchstädt is a long-term experimental site maintained by the Helmholtz Center for Environmental Research (UFZ). It is located in the central eastern part of Germany (51°24' N, 11°53' E). Since 1902 the site has been used to investigate the effects of different management practices on soil organic matter (Blair et al., 2006). The cool temperate climate in Bad Lauchstädt is characterised by an average annual precipitation of 484 mm and an average annual temperature of 8.7 °C (Freibauer et al., 2009). The soil is a Haplic Chernozem with a loam texture and a clay content of 21 % (Altermann et al., 2005). The soil organic carbon content is 2.07 %, including a black carbon share of 13.16 % (Brodowski et al., 2007). The soil pH is 6.6 (Christen, pers. comm.).

4.2 Experimental set up and data measurements

This study compares the N_2O emissions of four different crop rotations. The list below identifies the rotations as well as the plot numbers on which they have been grown in Bad Lauchstädt.

i. organic harvested and fall tilled clover grass ley – organic winter wheat (311, 411, 511) (clover grass ley yield is **not left on field** and residues are incorporated **before winter**)
→ abbreviated as: hCGL – oWW

ii. organic harvested and spring tilled clover grass ley – organic spring wheat (312, 412, 512) (clover grass ley yield is **not left on field** and residues are incorporated **after winter**)
→ abbreviated as: hCGL – oSW

iii. organic mulched and fall tilled clover grass ley – organic winter wheat (321, 421, 521) (clover grass ley yield **is left on field** and residues are incorporated **before winter**)
→ abbreviated as: mCGL – oWW

iv. conventional winter wheat – conventional winter wheat (221, 621)
→ abbreviated as: cWW – cWW

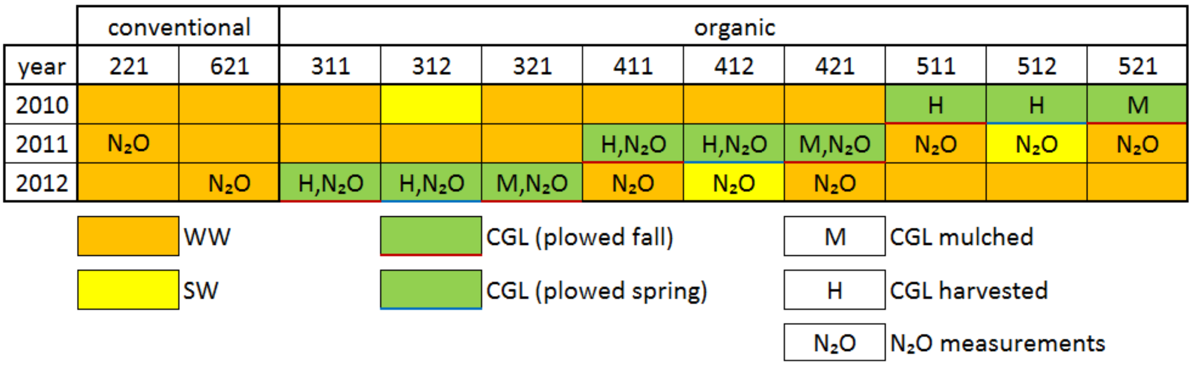

Fig. 3. Cropping schedule for all plots in Bad Lauchstädt. The chart shows the year the crop was harvested. In most cases the crop was planted the previous year. The above numbers refer to the plot and help to identify the treatment (compare to the list above). Each plot number occurs four times on the experimental site.

The crop rotations were grown on 11 m by 6 m rectangular plots. Every plot number occurred four times on the experimental site, ensuring that each treatment run has four replicates. Plot 411, 412 and 421 have been measured for two consecutive growing seasons, while the others only represent one year of an entire crop rotation. The cropping schedule is depicted in Fig. 3. Parameters characterising meteorology, soil properties, management and nitrogen concentration and fluxes were measured between October 2010 and August 2012.

Meteorological data

Air temperature, relative humidity, global radiation and precipitation were observed at one meteorological station on-site with a time resolution of 10 minutes. Weather data for the model spin up before January 2011 were derived from the closest German National Meteorological Service (DWD) stations in Halle – Kroellwitz (distance approx. 14.4 km) and Freyburg (distance approx. 18.1 km).

Soil data

The physical parameters of the soil such as bulk density, porosity and the soil moisture retention curve (pF – curve) at different depth, were determined once at the beginning of the experiment. Soil moisture and soil temperature were measured below organic winter wheat (411) and clover grass ley (311) at 10 cm, 20 cm and 30 cm of depth from 10.10.2011 until 15.10.2012 in 5 to 15 minutes time intervals.

Soil nitrate and ammonium concentrations in the first 10 cm of soil were measured weekly. Both concentrations were also measured between 10 cm and 30 cm on a monthly basis.

Crop data

The entire workflow was recorded on all plots. For all crops and plots, the sowing, harvesting, tilling, cutting, and fertilizing dates are known. Yields from all crops were determined as wet and dry matter. In addition, the C:N ratio of the clover and grass fraction was determined. For all spin up years prior to 2011, the grown crop, the annual yield, the annual applied fertilizer amount and annual applied manure amount are given.

N_2O data

N_2O flux measurements were conducted on a weekly basis, when NO_3^- and NH_4^+ concentrations were measured as well. The closed chamber method was used to observe N_2O movement (Hutchinson and A. R. Mosier, 1981; Ussiri and Lal, 2012). Four samples were taken from the chamber over the course of one hour and analysed in the lab with a gas chromatograph.

4.3 DNDC model description

DNDC is an acronym for denitrification – decomposition. The model was first developed and published in 1992 for predicting N_2O, N_2 and CO_2 emissions from agricultural soils in the USA (Li et al., 1992b). Over the last 20 years it has been expanded to also simulate methane fluxes as well as to model biogeochemical dynamics at various locations around the globe (Giltrap et al., 2010). This study applies model version DNDC 9.4 (UNH EOS, n.d.).

The model is divided into two thematic and functional components, which themselves contain several sub-models. The first part of the model determines the characteristics of the soil environment and is driven by climate, vegetation, soil properties and anthropogenic activities (Li, 2000). It is composed of the thermal-hydraulic, the plant growth and the decomposition sub-models (Li, 2000).

The second part of the model employs the outcomes of the first part to simulate the biogeochemical trace gas production using a denitrification, nitrification and fermentation sub-model (Li, 2000). The chart below provides a brief visual summary of the parts that are most relevant for this study and the discussion that follows. The informational content of this section is entirly derived from Brown et al. (2002), Giltrap et al. (2010), Li (2007, 2000), Li et al. (2006, 2004, 1994, 1992b), Pathak et al. (2006) and UNH EOS (2012).

4.3.1 First model component: soil environment

Soil thermo-hydraulic sub-model

The first 50 cm of the soil is represented as a set of uniform horizontal layers (Li et al., 1992b). The water and heat flow in between layers are governed by the hydraulic head and heat gradient, respectively, and their soil specific conductivities (Li et al., 1992b).

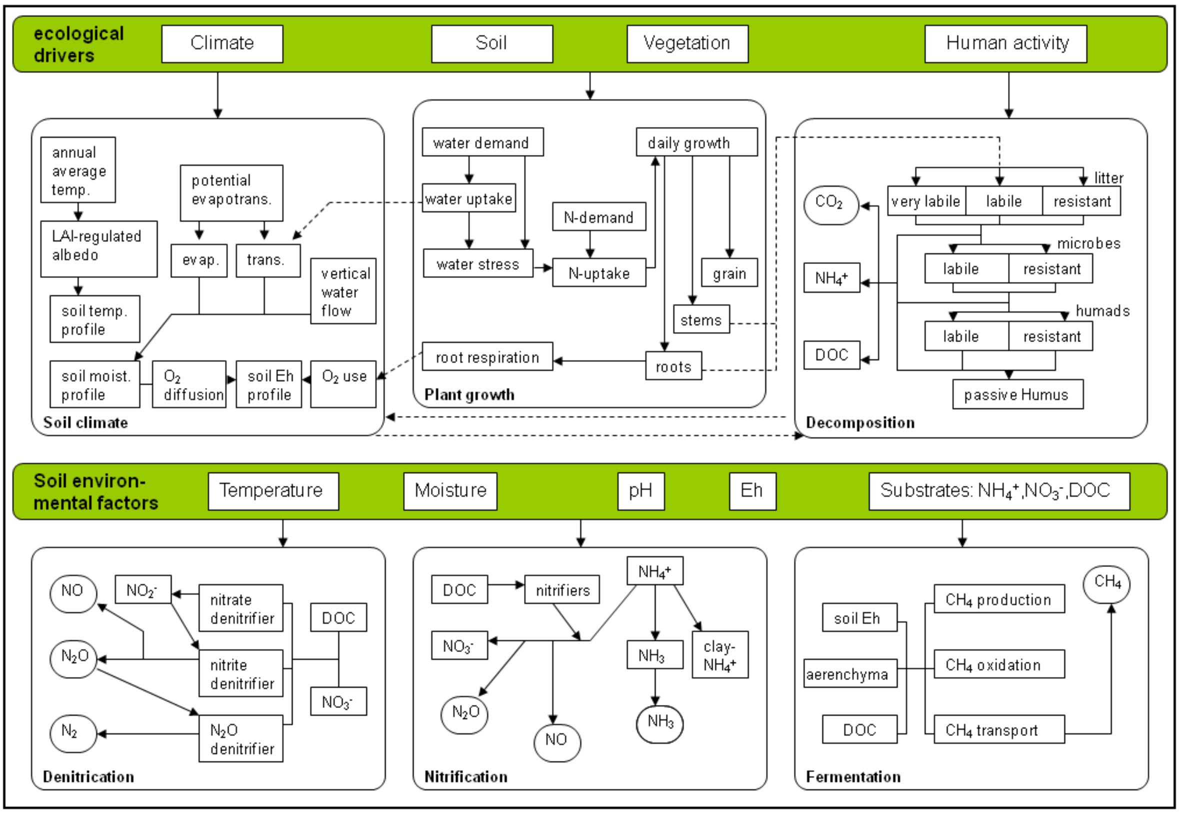

Fig. 4. Model structure adapted from Li (2000) and UNH EOS (2012). The model consists of two parts: the soil environment (soil hydraulic, plant growth and decomposition sub-model) and the biogeochemical trace gas production (nitrification, denitrification and fermentation sub-model). Eh is the soil reduction potential and pH is the soil acidity (Springer Copyright, reprint license number: 3240300528117).

The heat flux is based on an average conductivity of the solid phase and water, weighted by fraction (Li et al., 1992b). The heat exchange at the bottom of the soil profile is based on the average annual air temperature, which is then used to estimate the heat flux in and out of the bottom layer (Li et al., 1992b).

Water availability in the soil profile is determined by precipitation, snowfall, drainage and actual evapotranspiration (Pathak et al., 2006). Every rain event starts at midnight and has a constant intensity (Li et al., 1992b). Drainage at 50 cm of depth of the soil profile is based on gravity (Li et al., 1992b). Potential evapotranspiration is estimated based on solar radiation and temperature using the Priestly and Taylor approach (Pathak et al., 2006). The leaf area index is utilized to divide potential evapotranspiration into potential evaporation and potential transpiration. Actual transpiration is determined by the daily crop growth and the plant specific water demand. Water for evaporation is only withdrawn from the first 20 cm of the soil profile thus is limited only by water availability (Li et al., 2006, 1992b).

Plant growth sub-model

The plant growth sub-model estimates root respiration, plant growth as well as N and water uptake (Pathak et al., 2006). The plant partitioning into shaft, leafs, grain and roots is based on constant fractions. A temperature driven empirical crop growth curve is used to simulate plant growth (Li et al., 1994; Watts and Hanks, 1978). DNDC only considers water and nitrogen stress, and neglects all other nutrient limitations (Li et al., 1994).

DNDC also accounts for N fixation by crops. Maximum atmospheric N fixation is equal to maximum soil N fixation (Li et al., 1994). Therefore, legume crops can also be affected by N scarcity if the soil is not able to provide half of the required N (Li et al., 1994).

Root dynamics are represented in DNDC by three processes: root growth, root maintenance and ion uptake and transport.

Decomposition sub-model

Present substrate concentrations of DOC, nitrate and ammonium are calculated by the decomposition sub-model (Li, 2000). This part of the model is controlled by four factors: climate, farming practices, soil properties and plant effect (Li, 2000). Soil organic carbon is divided into an active phase and the passive phase (Li et al., 1992b). The active phase is split into decomposable residues (i.e. litter), microbial biomass and humads (i.e. active humus), consisting of two or three sub-pools each (Li et al., 1992b; Pathak et al., 2006; UNH EOS, 2012). The passive phase only consists of passive humus (UNH EOS, 2012). Each pool and sub-pool is defined by its C:N ratio and decomposition rate.

Decomposition is governed by precipitation events. The sub-model becomes inactive as soon as a rain event occurs and halts as long as the water filled pore space in the top 20 cm of the soil profile is above 40 % wfps or for a maximum of ten days (Li et al., 1992b). The decomposition rates of SOC in the active phase are based on first order kinetics and reduced by nitrogen limitation and clay adsorption of SOC (Li et al., 1992b). In addition, the breakdown of organic carbon is affected by temperature and soil moisture. The optimum temperature for decomposition is between 30 °C and 40 °C and the optimum soil moisture is 60 % wfps (Li et al., 1992b).

The exact pathway of decomposition is dependent on the specific SOC pool. Like carbon dioxide, nitrogen compounds are a product of the decomposition of organic matter. All decomposed nitrogen is immediately transformed into ammonium in DNDC (Li et al., 1992b).

4.3.2 Second model component: biogeochemical trace gas production

This section describes the implementation of the biogeochemical processes in DNDC that result in trace gas emissions. This report describes only the nitrification and denitrification sub-model, because fermentation is not linked to the research question. This part of the DNDC model uses substrate concentrations, temperature, soil moisture and pH that have been determined by the first model component (Li, 2000).

Denitrification and nitrification require different oxygen concentrations in the soil matrix, but occur in the same soil profile at different microsites. Li (2000) separates the soil matrix into aerobic and anaerobic microsites and attributes substrates (e.g. DOC, NH_4^+,NO_3^-) to the different sites according to their fractions (Giltrap et al., 2010). This can be visualised as an anaerobic balloon, that swells and shrinks based on the Eh of the soil liquid phase (Giltrap et al., 2010; Li et al., 2004). The balloon has its maximum size (1) when the soil is fully anaerobic. After the size of the anaerobic balloon has been determined and the substrates have been allocated to the different compartments, DNDC computes the reaction rates for the different substrates and establishes the new substrate concentrations (Li, 2007).

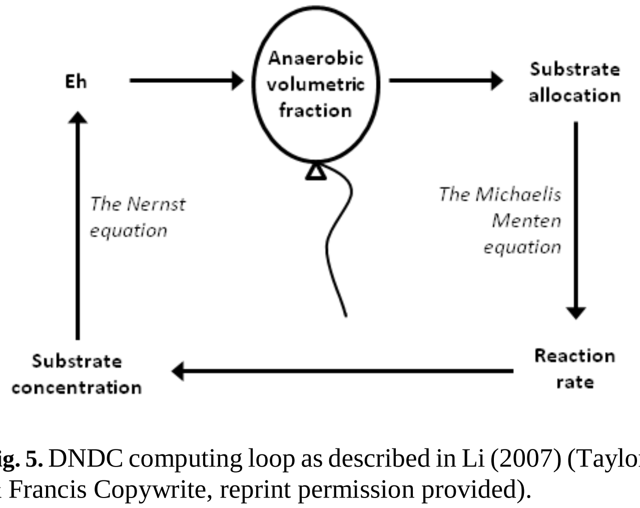

Fig. 5. DNDC computing loop as described in Li (2007) (Taylor & Francis Copywrite, reprint permission provided).

This loop is regulated by two equations: the Nernst equation and the Michaelis-Menten equation (Fig. 5) (Li, 2000). The thermodynamic Nernst equation determines Eh using the concentrations of oxidants and reductants in the soil liquid phase and thus establishes the size of the anaerobic balloon (Li et al., 2004). The Michaelis-Menten equation is used to compute reaction rates and hence the fraction of the oxidant that is being reduced (Li et al., 2004). This equation determines reduction rates and increase of microbial biomass based on substrate availability, in particular DOC and oxidant concentration (Li et al., 2004).

Nitrification sub-model

Nitrification rate is simulated empirically based on nitrifier population dynamics, NH_4^+ concentration and pH (Pathak et al., 2006). Nitrifier population is computed by estimating relative growth rate and relative mortality, taking into account DOC concentration, temperature and soil moisture (Li, 2000; Li et al., 1992b; Pathak et al., 2006). DNDC models N_2O and NO production as a temperature dependent fraction of the nitrification rate (Li, 2000).

Denitrification sub-model

The modelling scheme for denitrification is more complex because different groups of denitrifiers are involved. Population dynamics of denitrifiers is controlled by temperature, pH as well as by the concentration of DOC, NO_3^-, NO_2^-, NO and N_2O, therefore by the size of the anaerobic balloon (Li, 2000; Li et al., 1992b; Pathak et al., 2006). Growth rate is determined using the Michaelis-Menten equation (Li et al., 2004). Denitrifiers that use different N compounds compete via the common carbon pool (Li et al., 1992b). DNDC describes the mortality of denitrifiers as stable fraction of their total biomass (Li, 2000). The diffusion of NO and N_2O in the soil matrix is defined by the soil porosity, moisture and clay content (Li, 2000; Li et al., 1992b).

Equations and parameters for all model components can be obtained from Li (2007, 2000) and Li et al. (2004, 1992b)

4.4 Model optimization and parameter settings

DNDC was parameterized using five different plots: two hCGL – oWW (311, 411), one mCGL – oWW (421), one hCGL – oSW (412) and one cWW – cWW (621). Plots were selected so that every treatment is represented in parameterization and validation.

DNDC has been used to simulate a variety of different crops, climates and soils. Some studies used the default version of DNDC and merely replaced the parameters that were measured on site (Beheydt et al., 2007). Others saw the need for calibration (Ludwig et al., 2011; Tonitto et al., 2007). Most publications do not mention their model fitting procedure, which makes discussion and comparison of modelling results difficult. This omission was criticised by Ludwig et al. (2011). Beheydt et al. (2007) altered soil thermo-hydraulic input parameters, initial SOC distribution and crop parameters. However, all these changes were subsequently disregarded because they did not lead to a better estimation of N_2O emissions (Beheydt et al., 2007). In contrast, Ludwig et al. (2011) and Tonitto et al. (2007) implemented several significant changes to the model. Tonitto et al. (2007) focused on soil physical parameters and discovered that DNDC performs much better if the default parameters are changed drastically.

This shows that there is no straightforward approach to parameterize DNDC. In this study we used the general workflow of Ludwig et al. (2011) who suggested a step wise fitting of DNDC: "*(i) using default values, adjusting (ii) soil hydrology, (iii) crop yields, and (iv) cumulative N_2O emissions.*"

The main emphasis of the Bad Lauchstädt study was a proper simulation of all crucial processes. Process-based modelling is not merely the way in which a model is implemented. Links between different processes have to be considered when optimizing a process-based model to ensure a mechanistic simulation. SOC and soil moisture are the main drivers of N_2O emissions in DNDC (Li, 2007). These causal relationships are disregarded when DNDC is only calibrated to fit N_2O emissions and soil moisture and yield, thus residue inputs, are neglected. In accordance with this guidelines we started by optimizing the first model component (soil environment) before fitting the second model component (biogeochemical trace gas production).

A major drawback of the model version applied in this study is that batch runs only give annual means and no daily outputs. A batch run enables the user to do several subsequent model runs with different input parameters after each other without always starting DNDC manually. Therefore, all model runs were started individually.

4.4.1 Default run

The default run used the default settings of DNDC almost entirely. Changes we have made to the default settings are described in the text below and in Tab. 2.

Daily precipitation and daily minimum and maximum temperature where given as climate inputs. The atmospheric carbon dioxide concentration was set to match current atmospheric conditions (IPCC, 2007). DNDC only allows for an indirect simulation of dry nitrogen deposition, therefore all atmospheric input was assumed to be through precipitation. The nitrogen concentration in the rainfall was derived from total nitrogen input due to wet and dry deposition in the Bad Lauchstädt area (Gauger et al., 2001; Körschens et al., 1998; Russow and Böhme, 2005) and the long-term average precipitation (Freibauer et al., 2009).

The default runs used the values of field capacity and hydraulic conductivity that are linked to the loam soil type in DNDC. Porosity, wilting point, clay share, pH and bulk density were altered to match the measured values (Tab. 2). The soil organic carbon was determined to be 2.07 % (Christen, pers. comm.). According to Brodowski et al. (2007) the soil organic carbon at the Haplic Chernocem in Bad Lauchstädt consists of 13.16 % of black carbon. Black carbon is considered inert over intermediate timescales and slowly decomposable over decadal time spans (Brodowski et al., 2007; Hamer et al., 2004; Kuzyakov et al., 2009). Thus, soil organic carbon was set to 1.8 %.

Crop parameters were not changed in the default run, except for the C:N ratios for clover grass ley. Those are highly dependent on the fractioning of clover and grass (Laber, 2007). In accordance with own measurements and the report of Laber (2007), the C:N ratios of the leaf, stem and grain fractions were set to 24 and the C:N ratio for the roots to 27.5.

This study assumes that 15 % of above ground biomass was incorporated into the soil after harvest. All information about tillage, sowing and harvesting was taken from the recorded field data. The exact work steps for the years prior to 2011 are not known. Therefore, the general procedures for 2011 and 2012 and common sowing and harvesting dates for Germany were used to implement the spin up period.

Tab. 2. Parameter settings for the default run.

Default run				
Number of years:	6	*Plots:*	311, 411, 412, 421, 621	
Time period:	2008 – 2012			
Climate settings:				
Atmospheric CO_2 conc.:	380 ppm			
Wet N deposition:	10.35 mg l^{-1}			
Soil settings:				
Soil type:	loam			
Clay content:	21 %			
Bulk density:	1.37 g cm^{-3}			
Porosity:	49.14 %			
Permanent wilting point:	29.16 % wfps	*Field capacity:*	49 % wfps	
Water retention layer:	9.99 m	*Hydraulic conductivity:*	0.025 cm h^{-1}	
Crop settings:				
	winter wheat	*spring wheat*	*clover grass ley*	
water demand:	200 g H_20 g DM^{-1}	300 g H_20 g DM^{-1}	550 g H_20 g DM^{-1}	
maximum grain yield:	3200 kg C	3600 kg C	100 kg C	
C:N ratio grain:	40	50	24	
C:N ratio shoot:	95	80	24	
C:N ratio root:	95	80	27.5	

4.4.2 Optimizing the model – part one: soil environment

This study started by parameterizing the first model component, in particular soil moisture and plant growth.

To improve the model performance for soil moisture, the study evaluated the impact of field capacity, hydraulic conductivity, water retention layer and crop water demand. The water retention layer is either a layer of clay or compacted soil which prevents water from draining into deeper soil layers. This study did not look into the effect of using different pedo-transfer functions as performed by Ludwig et al. (2011) because the actual soil type was determined. Soil moisture was fitted based on the two measurements of water filled pore space at plots 311 and 411. Both sites grew harvested clover grass ley – winter wheat, but had a time lag of one year.

SOC concentration and dynamics in DNDC are primarily affected by initial soil organic carbon and by crop growth. Thus, as the initial SOC is given here, crop growth is the main process that tunes soil organic matter.

Yield was optimized for each crop individually using all five parameterization sites. To improve the growth simulation of spring wheat, winter wheat and clover grass ley the effect of altering water demand and the maximum grain yield of each crop type was tested.

Initially, the individual influence on soil moisture and yield of field capacity, hydraulic conductivity, water retention layer, crop water demand and maximum potential yield was evaluated. The accuracy of the model was determined by computing the relative error (RE), the root mean squared error (RMSE) and the Nash Sutcliff modelling efficiency (NSE) as defined by Chin (2012), Ludwig et al. (2011), Smith et al. (1997) and Tonitto et al. (2007). The RE gives the average deviation from the observed values in percent.

$$RE = \frac{100}{N}\sum_{t=1}^{N}\frac{O(t)-S(t)}{O(t)} \qquad (5)$$

The RMSE is a non dimensionless aggregate of the mean residual. It computes the square root of the average squared individual error.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{N}\left(S(t)-O(t)\right)^2}{N}} \qquad (6)$$

The NSE describes how much the total variation of the data can be explained by the model (Chin, 2012). The output can have any value between -∞ and one. A value above zero indicates that the model is a better predictor than the average observed value. If the NSE is one the model is in perfect agreement with observed data.

$$NSE = 1 - \frac{\sum_{t=1}^{N}\left(O(t)-S(t)\right)^2}{\sum_{t=1}^{N}(O(t)-\bar{O})^2} \qquad (7)$$

Parameters that had no or little effect on the model error were not optimized and the default value was used. If a single parameter led to a major decrease of the model error for soil moisture or yield, the value with the lowest root mean square error was used. If two or more parameters led to a great improvement of the model accuracy, the combined effect was investigated to determine the best parameter combination.

Special caution had to be taken when optimizing crop water demand because it affects both soil moisture and yield. Therefore, the goal was to always reduce the combined error of yield and soil moisture. This was done by averaging the mean NSE for water filled pore space at all three observed depths and the overall NSE for yield of the specific crop on all five plots. The procedure was performed for winter wheat at all sites and soil moisture on site 411 as well as clover grass ley on all sites and soil moisture on site 311. An equal weighting of the mean soil moisture NSE and the yield NSE was applied due to the fact that different publications identify both factors (SOC, soil moisture) as important (Abdalla et al. 2009, Blume et al. 2009, Brady and Weil 2007).

Spring wheat was optimized solely by reference to yield as no measurements of water filled pore space where available.

The ranges for the tested parameters were derived from the literature and from measurements on site (Tab. 3). Sources give a very diverse picture for maximum yields, which therefore were set to ±45 % of the default value.

Tab. 3. Parameters that have been tested in order to improve the performance of the first model part.

parameter	range	unit	source
field capacity	0.604 - 0.822	% wfps	observed pF curve between pF=1.8 - 2.5 (Fiedler, 2001)
hydraulic conductivity	0.025 - 0.085	cm min^{-1}	USDA NRCS (n.d.)
water retention layer	0.5 - 9.99	m	Full possible range, 0.5 is not plausible
maximum grain yield	SW: 1980 - 5220 WW: 1762 - 4645 CGL: 55 - 145	kg C ha^{-1}	Hartmann and Ewald Sticksel, (2010); Loges et al. (2002); Ludwig et al., (2011); Sieling et al. (2005); Thomas et al. (1993)
water demand	SW: 35.6 - 454.5 WW: 35.6 - 454.5 CGL: 217 - 599	g H_2O g DM^{-1}	Bolger (1988); Pietsch (2004); Quanqi et al. (2012)

4.4.3 Optimizing the model – part two: biogeochemical trace gas production

The second part of the model was parameterized by altering the microbial activity index between zero and one to amend N_2O flux simulations, as suggested by Babu et al. (2006). Microbial activity alters not only N_2O emissions but also soil organic carbon and oxygen content and thereby all other soil biogeochemical processes. The N_2O fluxes were optimized as monthly sums in order to reproduce seasonal patterns of emissions (Beheydt et al., 2007). Monthly values were determined by linear interpolation and integration of weekly measurements.

4.5 Statistical means for comparing treatments

This study employed two statistical tools for comparing data: The Wilcoxon-Mann-Whitney U test and boxplots.

The Wilcoxon-Mann-Whitney U test is a statistical test that allows the user to determine if two datasets are significantly different (Mann and Whitney, 1947; Wilcoxon, 1945). It is a non-parametric rang-sum test and does not require a certain data distribution. The Wilcoxon-Mann-Whitney U test is applicable if the following criteria are fulfilled (Sheskin, 2003):

a) Both samples are not dependent on one another.
b) Both samples have a similar data distribution.
c) The observed variable is continuous.

The boxplot is a tool that provides better visual comparison. It displays the median, the first and the third quartile of the dataset. It also visualizes the minimum and maximum measured value as whiskers as long as the distance between those values and the quartiles is not greater than 1.5 times the distance between the quartiles. If the distance is greater than 1.5, the whisker is cut off and the remaining points are visualized as outliers.

4.6 Investigation of climate sensitivity of DNDC and nitrous oxide

The last part of the study investigated the sensitivity of DNDC to precipitation and temperature change, thus evaluated the effect of future climate change in central eastern Germany on the nitrogen cycle. This part of the study was conducted in cooperation with the CC-LandStraD project funded by the Federal Ministry of Education and Research. This research project investigates sustainable land use strategies under consideration of future climate change (vTI, n.d.).

4.6.1 Sensitivity analysis

The model's sensitivity was investigated by altering temperature and precipitation independently. The objective was to better understand the model's behaviour and the causal connections within DNDC and the soil environment.

The sensitivity was analysed for the hCGL – oWW, mCGL – oWW and cWW – cWW crop rotation. The spring wheat rotation was not utilized due to the prior focus on different winter wheat management practises. Sensitivity was evaluated using the years 2010 and 2011 as one crop rotation grown until 2060.

Climate data was derived from the STAR model (STAtistical Regional model), which was developed at the Potsdam Institute for Climate Impact Research (CEC Potsdam GmbH, 2009;

Orlowsky et al., 2010; PIK e.V., 2012; Werner and Gerstengarbe, 1997). STAR uses a linear temperature trend and past meteorological data to create future weather scenarios (PIK e.V., 2012). The statistical approach allows many different realisations, which differ with respect to the total precipitation. The sensitivity analysis employed the median precipitation scenario at the closest available location to simulate future N_2O emissions. Average annual precipitation between 2011 and 2060 is 879 mm.

The sensitivity of DNDC to temperature was evaluated by block shifting the entire temperature input of the STAR model until 2060 by -2 °C, -1 °C, +1 °C and +2 °C as described by Hastings et al. (2010). Precipitation effect was evaluated using a similar method as for temperature. Rainfall was reduced and raised by 20 % and 10 %. Outputs of N_2O, SOC and yield from the different model runs were compared between 2051 and 2060.

4.6.2 Climate scenario analysis

The general procedure of analysing climate scenarios was closely linked to the investigation of the model's sensitivity. The same treatments were run till 2060 using STAR model climate scenarios. In addition to the median scenario, the 5^{th} and 95^{th} percentile precipitation scenarios with precipitation of 827 mm to 931 mm, respectively, were used to evaluate future uncertainty.

5 Results

This chapter reports the results of the model fitting, the treatment comparison, as well as the scenario analysis.

5.1 Model fitting and performance

This section displays the results of the default run and the parameter sensitivity before showing the results of the optimized model and the validation. It also visualizes the fitting procedure.

5.1.1 Default run

The default version of DNDC underestimates soil moisture at both plots, but with different magnitude. The offset is much larger for the clover grass lay (311), compared to winter wheat (411) (Fig. 6). The model performance decreases with depth. It represents the general patterns at 10 cm of depth and performs particularly well for the summer peaks at the winter wheat plot. Modelled soil moisture in 20 cm and 30 cm depth generally remains at the permanent wilting point of 29.16 % wfps and shows only a small amplitude in mid-February and end of July.

The modelling efficiency varies between -0.127 and -2.861 which provides evidence that the default settings of DNDC require further adaptations to better simulate soil moisture in Bad Lauchstädt.

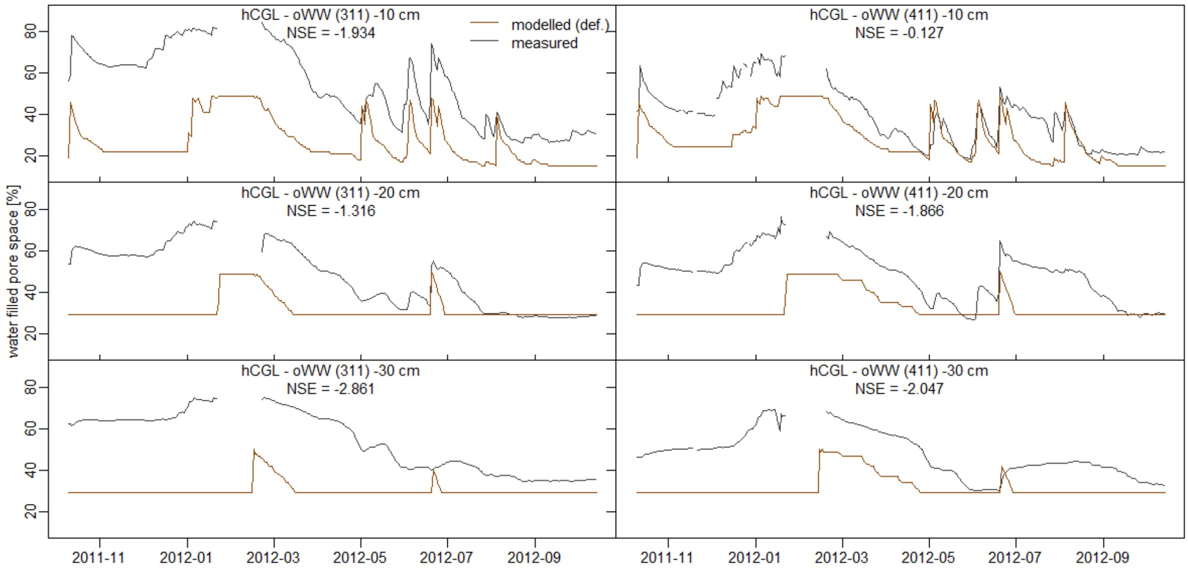

Fig. 6. Measured and modelled water filled pore space (wfps) in 10 cm, 20 cm and 30 cm of depth using the default settings of DNDC (see Tab. 2). The left panes display water content below clover grass ley (311). The right panes show winter wheat (411).

The model quality for estimating yields for winter wheat, spring wheat and clover grass lay differs between years and crops, as can be seen in Fig. 7. Both wheat crops are underestimated, but by different magnitudes. The relative errors for all sites combined for spring wheat and winter wheat are 75.9 % and 44.5 % respectively. The model performs much better for clover grass ley where the relative error is 1.1 %.

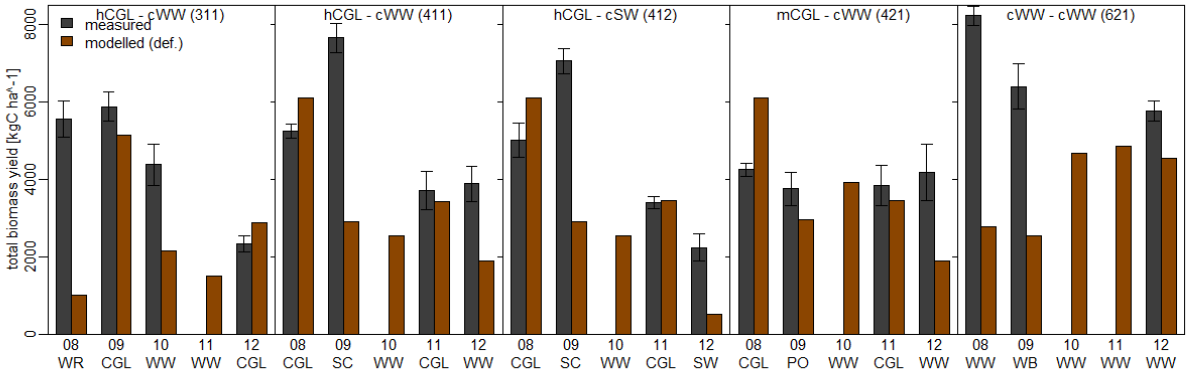

Fig. 7. Measured and modelled yield of all five parameterization sites between 2008 and 2012. The whiskers show the standard deviation of the measured values. The numbers along the x-axis indicate the year and the capital letters identify the crop (WR: winter rye, CGL: clover grass ley, WW: winter wheat, SC: silage corn, SW: spring wheat, PO: potatoes, WB: winter barley).

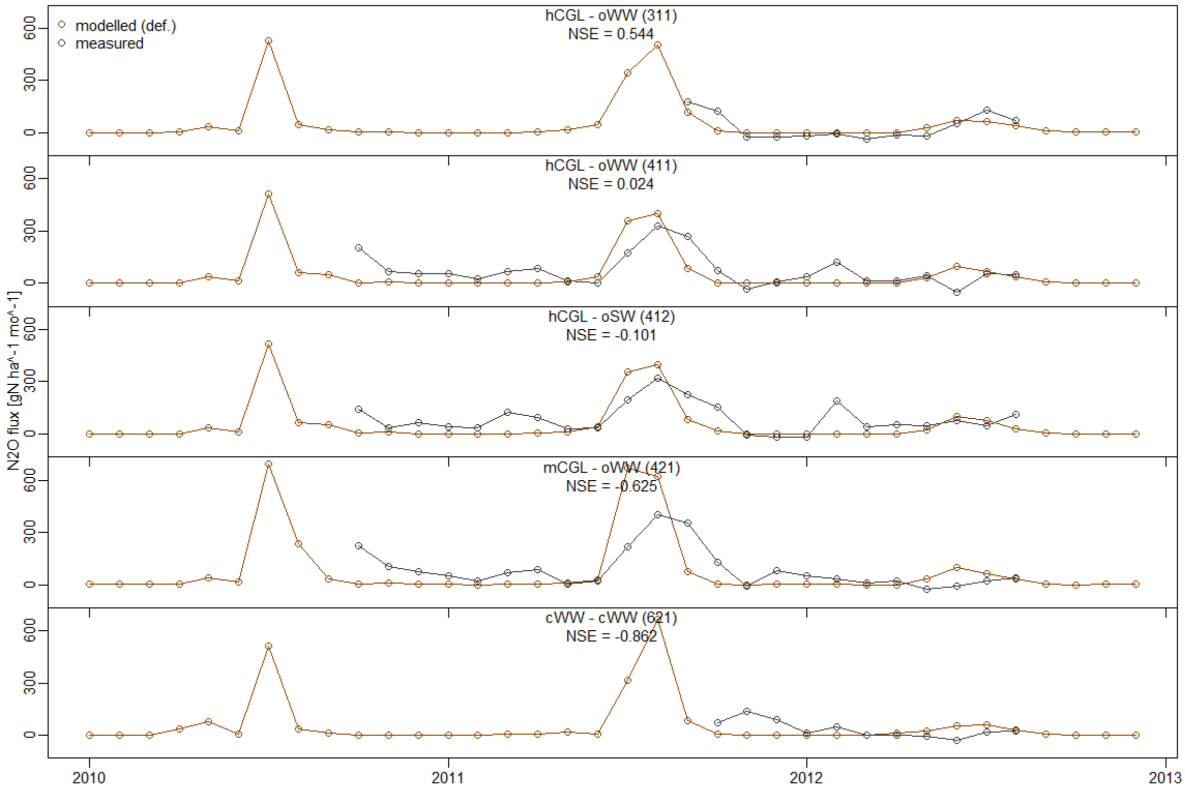

Fig. 8. Monthly measured and modelled N_2O emissions for the plots used for optimization using the default setting of DNDC (see Tab. 2).

Measured monthly N_2O emissions at the organic treatments are higher in July, August and September of 2011 than during the remainder of the measurement period (Fig. 8). This finding is also reproduced by DNDC, although the monthly modelled values are higher during these three months. All other months conform well to the modelled fluxes even though DNDC tends to underestimate emissions during these months (Fig. 8).

Daily modelled N_2O patterns at the organic sites deviate from the observed ones. The daily modelled emissions fluctuate stronger than the measured fluxes and most emissions are caused by few peak events. This becomes particularly evident when comparing the median for July, August and September of 2011 for all four organic treatment sites: The median for the modelled emissions is 0.6 g N ha^{-1} d^{-1} and the median of the measured is 9 g N ha^{-1} d^{-1}.

The conventional treatment shows relatively high measured emissions shortly after sowing during the last months of 2011 (Fig. 9) where fluxes fluctuate strongly (-2.9 g N ha^{-1} d^{-1} to 12.5 g N ha^{-1} d^{-1}) and are characterised by a high standard deviation. These patterns are not reproduced by DNDC and the model underestimates emissions. In 2012 daily modelled and measured values are very low, and therefore are in better agreement with the measured values except for two modelled peak events in late summer. The monthly values show quite opposing trends (Fig. 8); DNDC simulates an increase of N_2O emissions from winter to summer, while the measured values are decreasing. The conventional treatment has the lowest modelling efficiency.

Overall the model is only a good predictor of N_2O emissions on a monthly basis for the hCGL – oWW. All other organic plots show a negative NSE, hence the average measured value is a better predictor of N_2O emissions compared to the default version of DNDC.

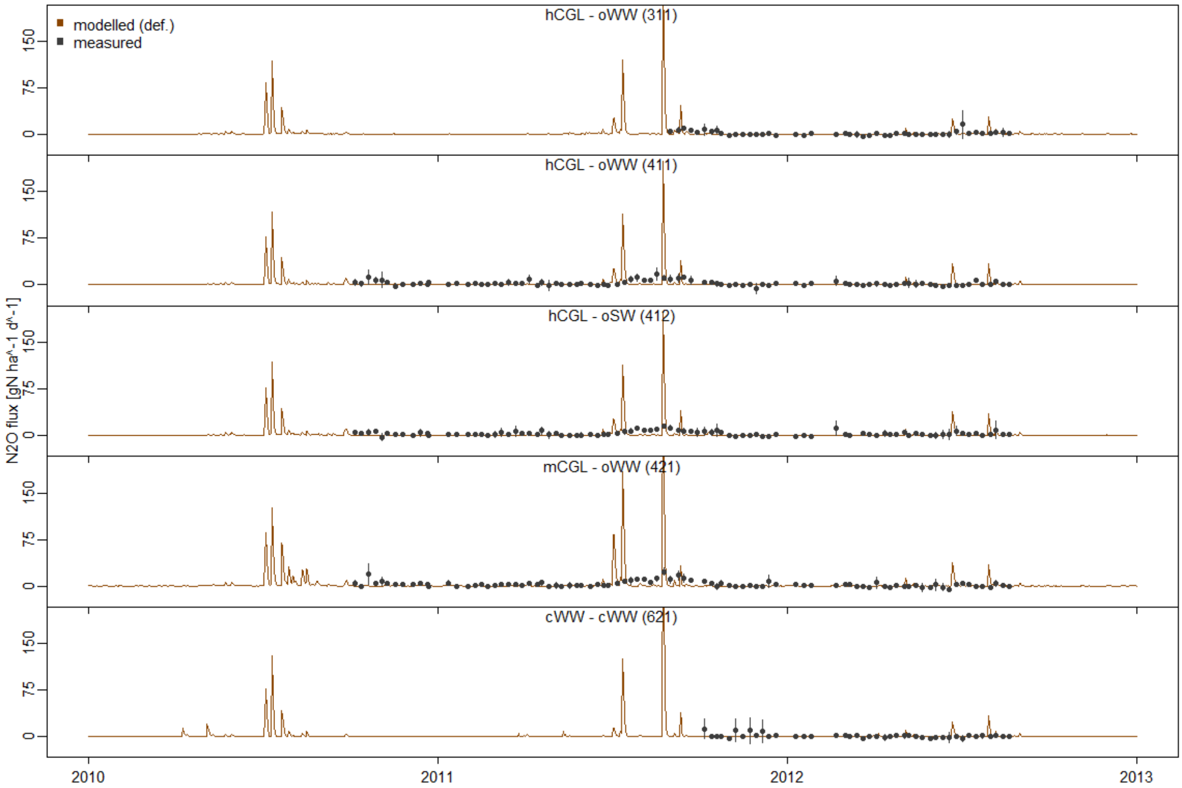

Fig. 9. Daily measured and modelled N_2O emissions using the default settings of DNDC (see Tab. 2) for all plots that were used to optimize DNDC. The black vertical line indicates the standard deviation of the measured N_2O emissions.

5.1.2 Model parameterization

This section describes the parameter sensitivity for the first and second model component. It also provides additional details about the optimization procedure and its results (Fig. 12).

5.1.2.1 First model component: parameter sensitivity of soil environment and crop growth

Parameter sensitivity of soil moisture

Fig. 10 clearly shows that water filled pore space is not very sensitive to any of the investigated parameters. The relative improvement of the mean RMSE for all depths compared to the default settings varies between 0 % and 4.5 % for the clover grass ley plot (311) and between 0 % and 9.6 % for the winter wheat plot (411).

Water retention layer does not affect soil moisture, and the relative improvement of the mean RMSE is 0 %. Hydraulic conductivity has only a minor effect on the model output. The relative improvement of the mean RMSE is below 1 % for both sites.

Field capacity and crop water demand are the parameters with the greatest effect on soil moisture. Both sites combined show the closest correlation between observed and modelled data when field capacity is set to 64.03 % wfps. This leads to a decrease of the RMSE for soil moisture of 4.5 % (311) and 1.9 % (411). Water demand has a very high improvement potential for site 411. The mean RMSE is reduced by 9.6 % when shifting winter wheat water demand from 200 g H_2O g DM^{-1} to 36.5 g H_2O g DM^{-1}. The amendment of the RMSE for 311 is 2 % when water demand for clover grass ley is set to the minimum of the range.

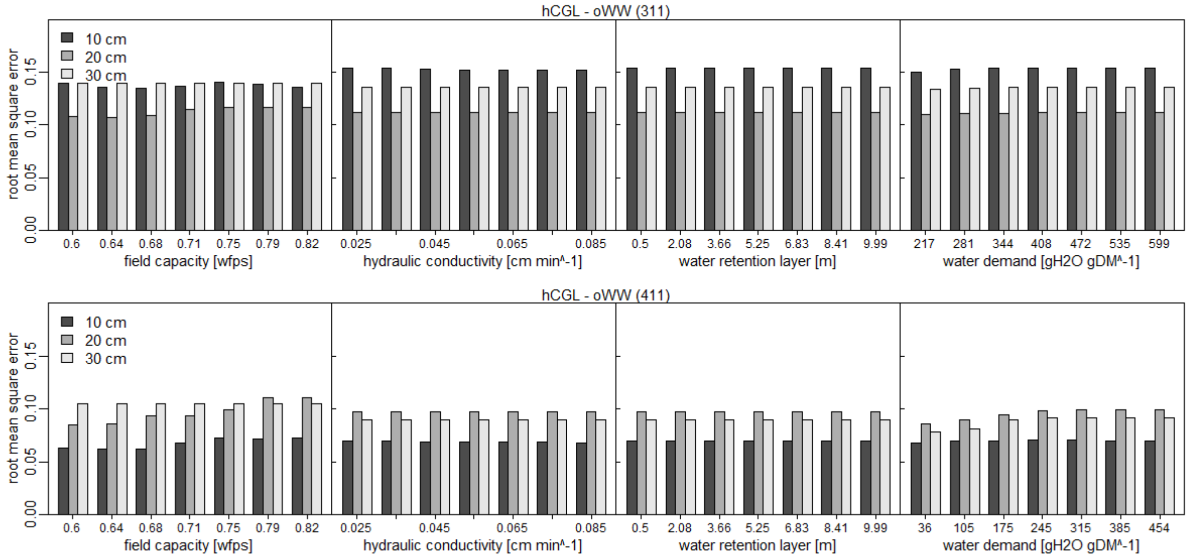

Fig. 10. Sensitivity of soil moisture to field capacity, hydraulic conductivity, water retention layer and crop water demand. The figure depicts the root mean square error for soil moisture between autumn 2011 and summer 2012 at all three depths for plot 311 (clover grass ley) and 411 (winter wheat).

Parameter sensitivity of yield

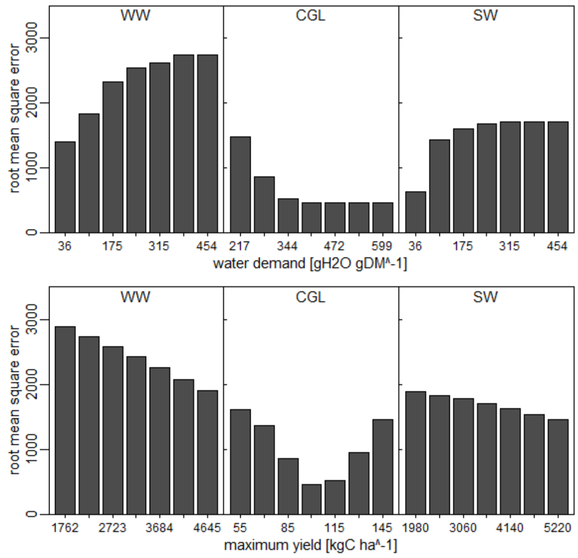

Fig. 11. Sensitivity of winter wheat, spring wheat and clover grass ley yield between 2008 and 2012 to water demand and maximum yield.

Modelled wheat yield is sensitive to crop water demand and maximum yield. The RMSE for both wheat crops, which are characterised by an underestimation of yield, are lower when setting maximum yield to the highest and crop water demand to the lowest value of the range. Changing water demand of wheat has a higher improvement potential than changing maximum yield. Altering the water demand for winter and spring wheat to 35.6 g H_2O g DM^{-1} leads to an RMSE reduction of 28.9 % and 62.9 %, respectively, compared to the default settings. Altering maximum yield lowers the RMSE of winter wheat by 3.3 % and of spring wheat by 14.3 %.

Clover grass ley cannot be further improved by altering water demand and maximum yield individually.

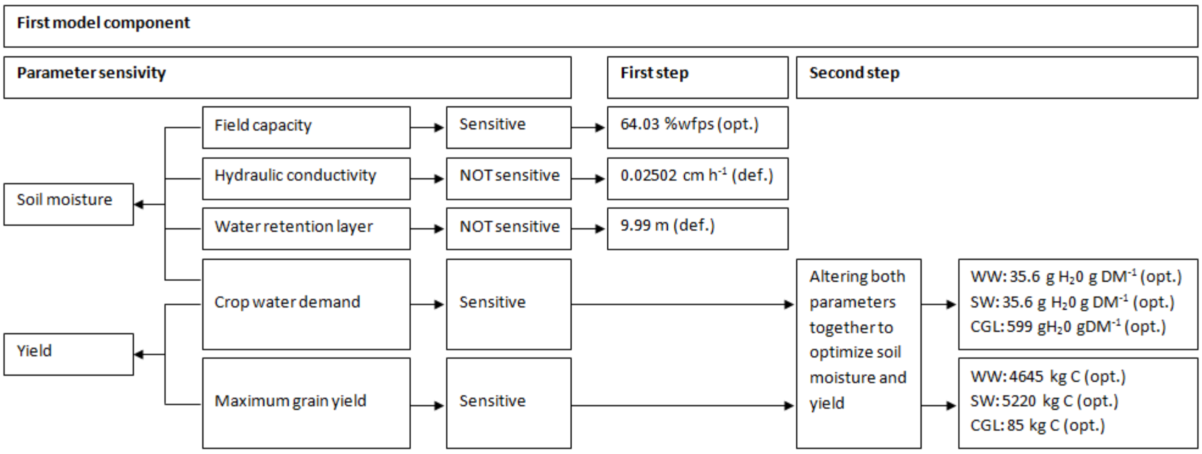

Fig. 12. Workflow for the optimization of the first model component. Def. indicates that the default DNDC values were used, while opt. shows that the values were changed in order to improve model performance.

Parameter sensitivity of soil moisture and yield combined

As mentioned above maximum yield and water demand affect crop growth, thus their combined potential for improving DNDC was investigated. Water demand is also crucial for improving the soil moisture modelling. Therefore, the focus lies on the reduction of the combined error.

The root mean square error is not dimensionless; therefore it cannot be utilized to compare the model accuracy for yield and soil moisture. This problem was avoided by substituting the root mean square error by the Nash Sutcliffe modelling efficiency.

The lowest combined NSE for yield and soil water is in very good agreement with Fig. 11. The best model fit is linked to a maximum yield of 4645 kg C ha^{-1} (WW) and 5220 kg C ha^{-1} (SW) and a water demand of 35.6 g H_2O g DM^{-1}. The optimum parameter combination for clover grass ley is 85 kg C ha^{-1} and 599 g H_2O g DM^{-1}.

5.1.2.2 Second model component: parameter sensitivity of nitrous oxide emissions

The microbial activity index has a great effect on N_2O emissions (Fig. 13). Still, this effect is very different for the various treatments and sites. The NSE decreases when the activity index for the conventional experiment is increased, while harvested clover grass ley – winter wheat (311) shows a better model accuracy with higher microbial activity.

The optimization of soil hydrology and yield led to a worse mean NSE if microbial activity is not changed. The default settings of DNDC have a mean NSE of -0.204 and the optimized soil moisture and yield DNDC version has a mean NSE of -0.574. The best model performance is achieved when shifting the microbial activity index to 0.6, which then gives a mean NSE of -0.103. The large error for the conventional winter wheat is partly due to the measurement period, which does not cover the full amplitude of emissions in Bad Lauchstädt.

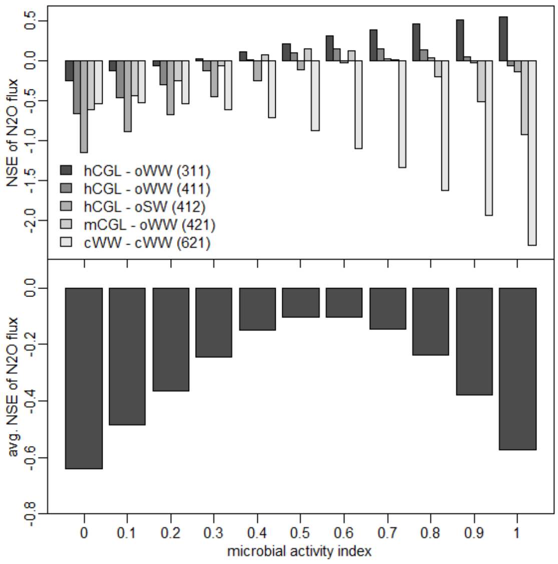

Fig. 13. Sensitivity of nitrous oxide emissions to the microbial activity index, displayed as Nash Sutcliffe modelling efficiency (NSE) for monthly modelled and measured nitrous oxide emissions. The top figure shows all five sites that are used to parameterize DNDC. The bottom figure depicts their mean.

The optimized parameters are displayed in Tab. 4. Tab. 5 lists all model runs that have been conducted to improve DNDC and their parameter settings.

Tab. 4. Optimized parameter settings of DNDC.

Optimized run			
Number of years:	6	*Plots:*	311, 411, 412, 421, 621
Time period:	2008 – 2012		

Soil settings:

Soil type:	loam		
Clay content:	21 %		
Bulk density:	1.37 g cm^{-3}		
Porosity:	49.14 %		
Permanent wilting point:	29.16 % wfps	*Field capacity:*	64.03 % wfps
Water retention layer:	9.99 m	*Hydraulic conductivity:*	0.025 cm h^{-1}

Crop settings:

	winter wheat	*spring wheat*	*clover grass ley*
water demand:	35.6 g H_20 g DM^{-1}	35.6 g H_20 g DM^{-1}	599 g H_20 g DM^{-1}
maximum grain yield:	4645 kg C	5220 kg C	85 kg C
C:N ratio grain:	40	50	24
C:N ratio shoot:	95	80	24
C:N ratio root:	95	80	27.5

Tab. 5. All model runs conducted in order to optimize the performance of DNDC in Bad Lauchstädt. For the first model component (soil environment), each range was subdivided into seven steps to assess the impact of the parameter. The impact of microbial activity was evaluated using eleven steps hence a step size of 0.1.

		parameter	**range**		**sites**	**runs**
First model component	Par. snes.: soil moisture	Field capacity	0.604 - 0.822	% wfps	311, 411	2x7
		Hydraulic conductivity	0.025 - 0.085	cm min^{-1}	311, 411	2x7
		Water retention layer	0.5 – 9.99	m	311, 411	2x7
		Crop water demand	WW: 35.6 – 454.5 CGL: 217 – 599	g H_2O g DM^{-1}	411 311	2x7
	Par. sens.: yield	Crop water demand	SW: 35.6 – 454.5	g H_2O g DM^{-1}	412	1x7
			WW: 35.6 – 454.5		311, 411, 412, 421, 621	5x7
			CGL: 217 – 599		311, 411, 412, 421, 621	5x7
		Maximum grain yield	SW: 1980 – 5220	kg C ha^{-1}	412	1x7
			WW: 1762 – 4652		311, 411, 412, 421, 621	5x7
			CGL: 55 – 145		311, 411, 412, 421, 621	5x7
	Opt. soil moisture and yield combined	Crop water demand and maximum grain yield	SW: 35.6 – 454.5 1980 – 5220	g H_2O g DM^{-1} kg C ha^{-1}	412	1x7x7
			WW: 35.6–454.5 1762 – 4652	g H_2O g DM^{-1} kg C ha^{-1}	311, 411, 412, 421, 621	5x7x7
			CGL: 217 – 599 55 – 145	g H_2O g DM^{-1} kg C ha^{-1}	311, 411, 412, 421, 621	5x7x7
Second model component	Opt. N_2O emissions	Microbial activity index	0 – 1		311, 411, 412, 421, 621	5x11

5.1.3 Parameterized model

Modelled soil hydrology has improved for the top 20 cm, due to a reduced offset in the first half of the measuring period (Fig. 14). The amendment is particularly pronounced at the winter wheat plot (411) at 10 cm of depth where modelling efficiency is positive. The modelling accuracy for the second half has decreased. DNDC still greatly underestimates soil moisture for almost the entire period. Both sites have a reduced modelling efficiency at 30 cm, where water filled pore space remains at wilting point level for the entire period.

The parameterization has improved soil moisture modelling, but DNDC results are still not in line with observations.

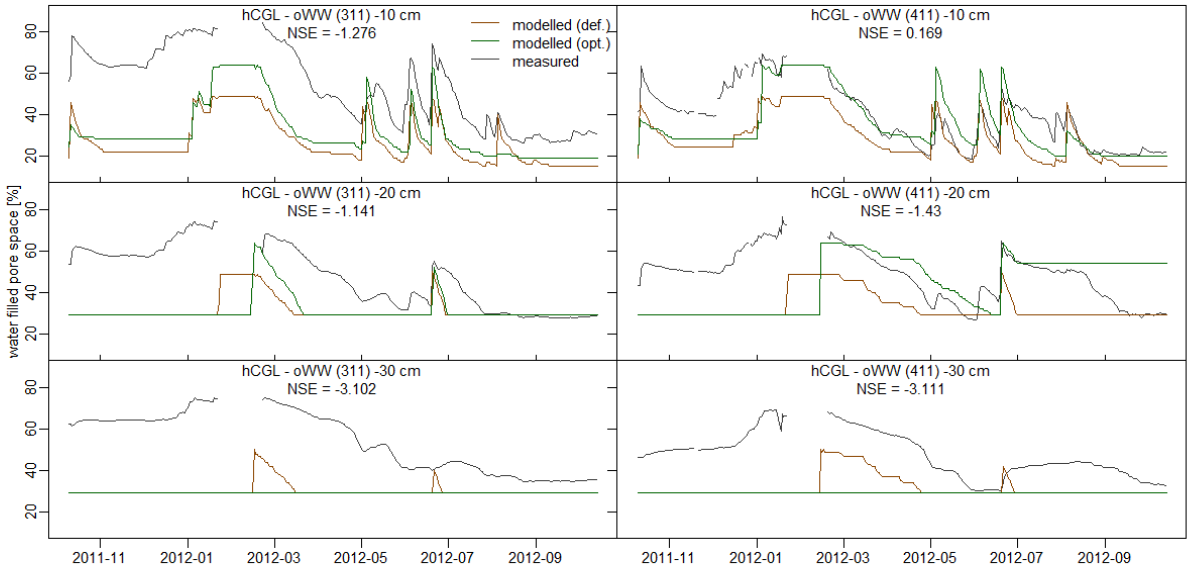

Fig. 14. Modelled (default: see Tab. 2, optimized: see Tab. 4) and measured soil moisture in 10, 20 and 30 cm of depth. The left panes display water content below clover grass ley (311). The right panes show winter wheat (411).

The optimization of the plant growth related parameters have increased the model accuracy for yield for both wheat crop treatments (Fig. 15). The relative error for spring wheat and winter wheat are down to 6.6 % and 22.2 %, respectively. However, the NSE for the wheat yields remains negative. DNDC still underestimates yield for all organic grown wheat and overestimates conventional wheat yield. Conversely, the clover grass ley yields are slightly overestimated after optimization of DNDC, although NSE for CGL yield remains positive at 0.6.

The model performance for monthly N_2O emissions improves at site 411, 412 and 421. As already mentioned the average NSE of all parameterization sites increases from -0.204 to -0.103 after optimization. The improvement is primarily due to the reduced overestimation during July, August and September. There is almost no difference between the default and the optimized version of DNDC when comparing the months that show low emissions. With the optimized set of parameters, DNDC has increased its ability to represent the general N_2O emission dynamics (Fig. 16).

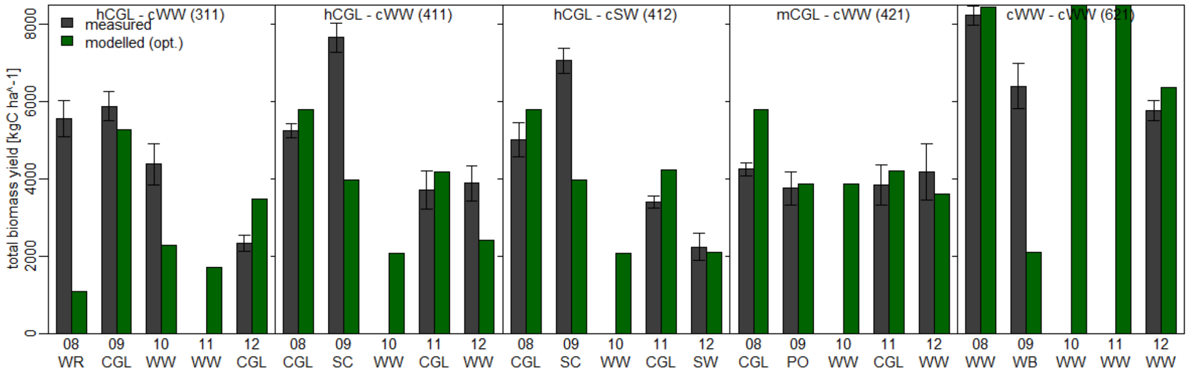

Fig. 15. Measured and modelled yield of all five sites that were used for all parameterization between 2008 and 2012 using the optimized parameters (see Tab. 4). The whiskers show the standard deviation of the measured values. The numbers along the x-axis indicate the year and the capital letters give the grown crop (WR: winter rye, CGL: clover grass ley, WW: winter wheat, SC: silage corn, SW: spring wheat, PO: potatoes, WB: winter barley).

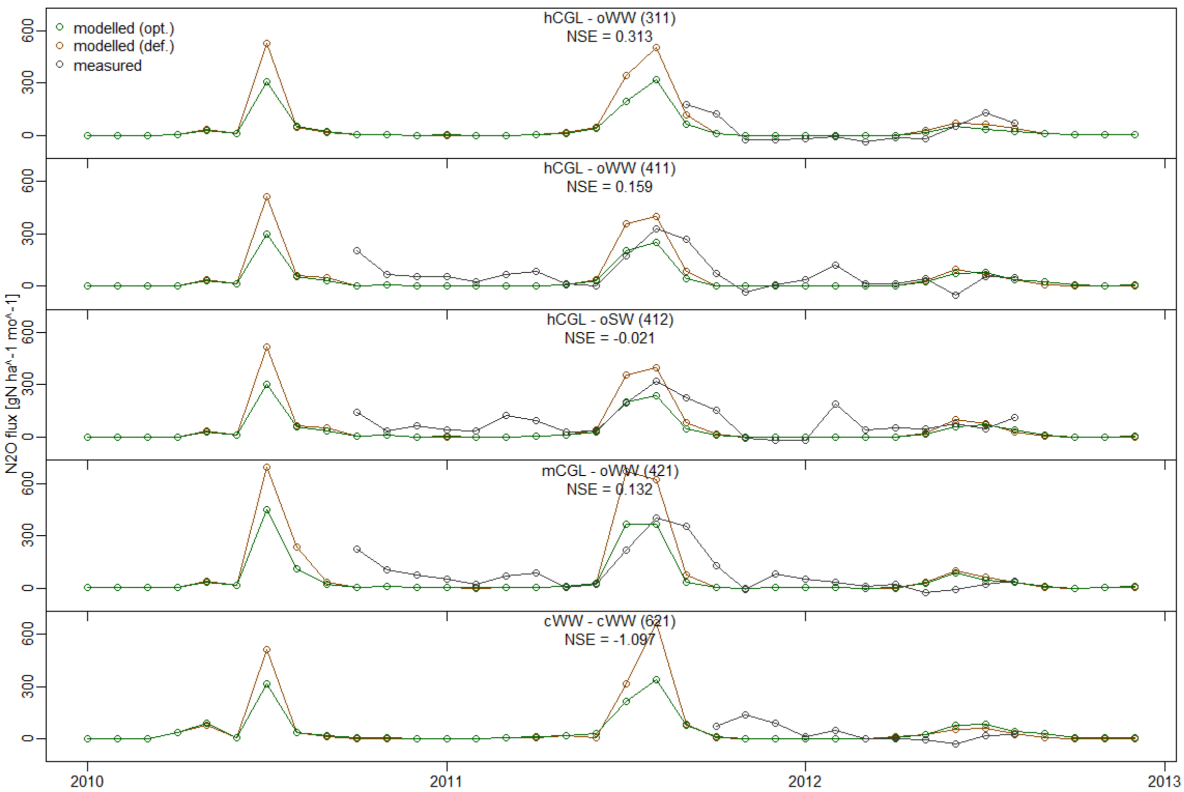

Fig. 16. Monthly measured and modelled N_2O emissions for all optimization plots. The modelled values are linked to the default (brown) and parameterized (green) settings of DNDC (see Tab. 2 and Tab. 4).

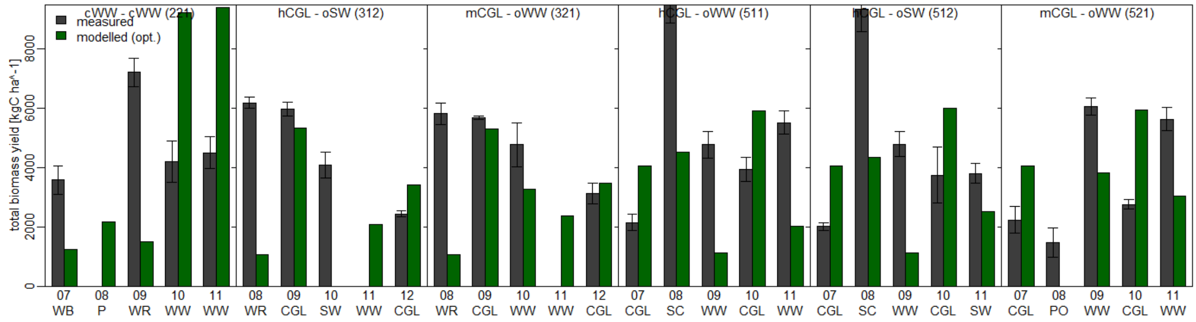

Fig. 17. Measured and modelled yield of all validation sites between 2008 and 2012 using the revised version of DNDC (see Tab. 4). The whiskers show the standard deviation of the measured yield. The numbers along the x-axis indicate the year and the capital letters give the grown crop (WR: winter rye, CGL: clover grass ley, WW: winter wheat, SC: silage corn, SW: spring wheat, PO: potatoes, WB: winter barley).

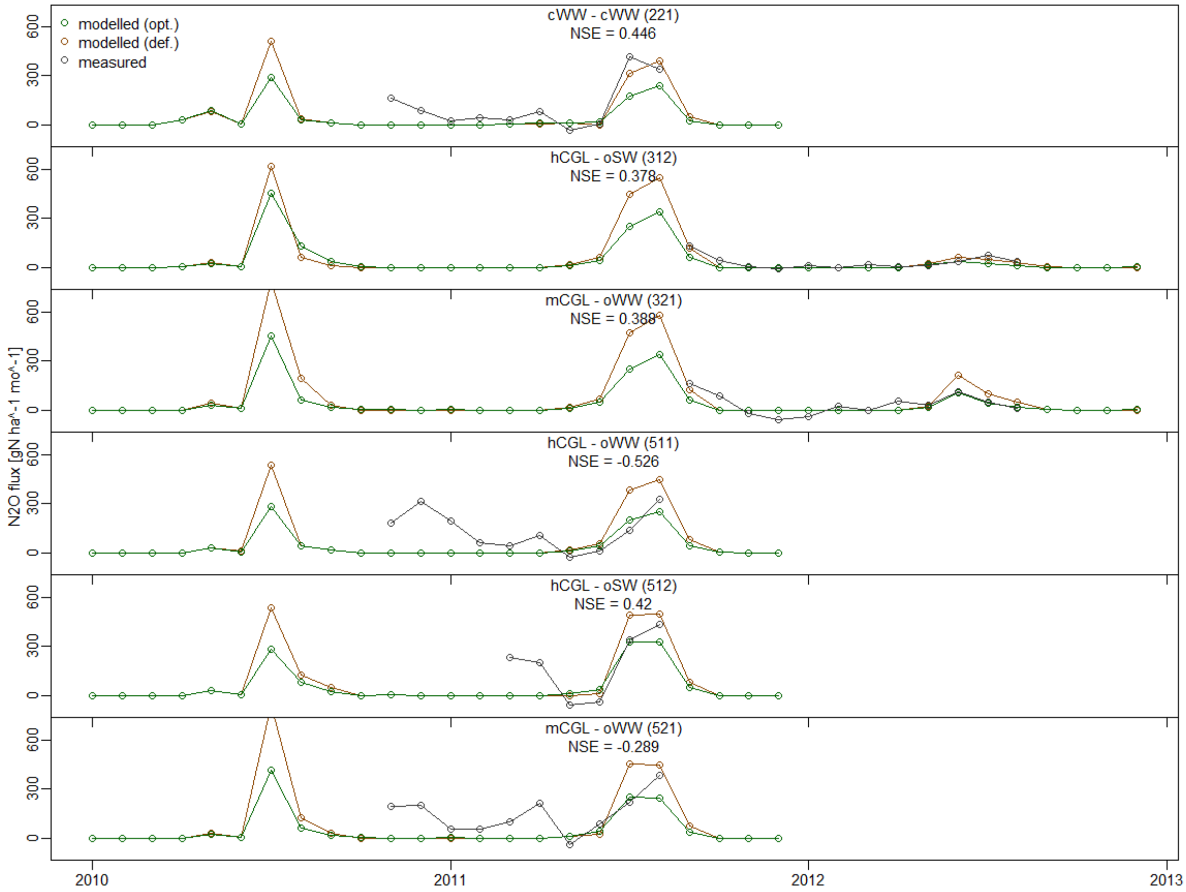

Fig. 18. Monthly measured and modelled N_2O emissions for all validation plots. The parameter settings are displayed in Tab. 2 and Tab. 4.

5.1.4 Validation

Relative error for winter and spring wheat harvest is lower at the validation runs compared to the default runs of DNDC. Winter wheat is underestimated by 12.7 % and spring wheat by 24.6 % when using the optimized DNDC. In contrast to organic winter wheat yield, conventional winter wheat harvest is greatly overestimated similar to previous model runs. The relative error for clover grass ley has decreased to -36.9 %, showing the least accurate result of all crops at the validation plots.

DNDC is able to represent the N_2O emission dynamics at the validation sites, except in fall 2010 where emissions are underestimated (Fig. 18). Furthermore modelled spring emissions in 2011 do not match measured fluxes at plot 512. The great offset in fall 2010 results in a negative NSE at plot 511 and 521. All other sites have a NSE of around 0.4 indicating a good fit of modelled and observed emissions. The mean NSE of all six sites is 0.136.

The validation and optimization plots are measured over a different time span making the results not entirely comparable. In general, the offset and the variability of measurements between November 2010 and late summer 2011 are bigger compared to the following year. This strongly influences the NSE and makes comparison difficult. The different periods have a different weighting in the optimization and validation of DNDC. The 2010 - 2011 period is measured four times for the validation sites and three times for the optimization sites.

5.2 Comparison of different treatments

The following section looks into the differences between the treatments using the observed and modelled data.

5.2.1 Measured nitrous oxide emissions

Inter-annual variability is much higher than treatment variability. Fig. 19 displays the distribution of all N_2O measurements between January and August 2011 and 2012. Measured N_2O emissions in year 2011 are significantly higher than in 2012. This dissimilarity is particularly evident during July and August of 2011 and 2012, regardless of treatment (Fig. 20). For example, average measured emissions at site 421 (mCGL – oWW) in July and August of 2011 are 10.5 g N ha^{-1} d^{-1} compared to 0.9 g N ha^{-1} d^{-1} in 2012.

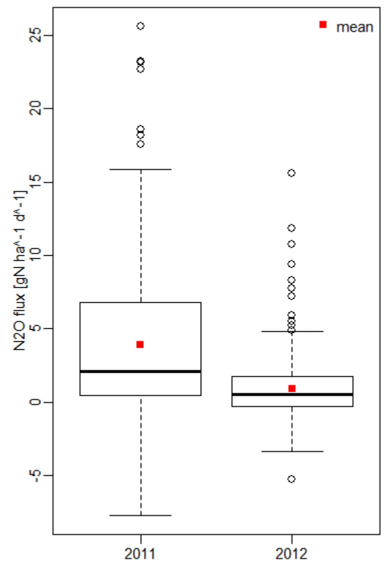

Fig. 19. Comparison of all nitrous oxide flux measurements between January and August 2011 and 2012, regardless of treatment.

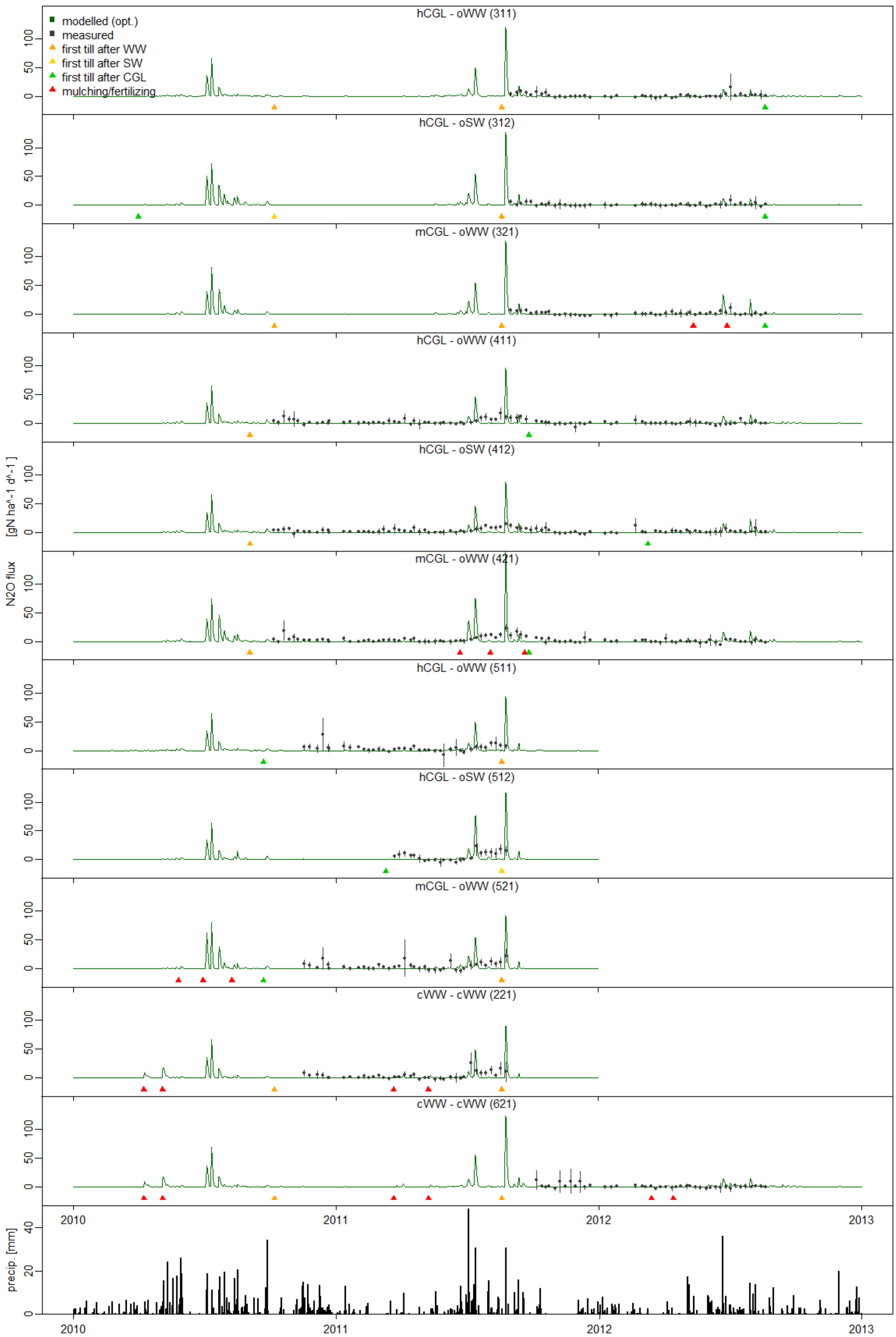

Fig. 20. Measured and modelled N_2O emission and precipitation. The vertical lines visualize the standard deviation of the measurements. The arrows indicate management events.

The small difference between treatments becomes evident when the average emissions of each crop are studied (Fig. 21). Emissions by clover grass ley are highest when mulched. The lowest emissions are at sites where clover grass ley is tilled in spring. However, there are no significant differences between CGL treatments.

Organic winter wheat after mulched CGL has a slightly higher mean emission than the other organic winter wheat treatment (Fig. 21). However, the differences are only 0.8 g N ha^{-1} d^{-1} (2011) and 0.2 g N ha^{-1} d^{-1} (2012) and are not significant. Conventional winter wheat has the highest average emissions of all winter wheat sites in 2012, but the lowest in 2011. Spring wheat has higher N_2O fluxes when compared to all winter wheat sites for the same year.

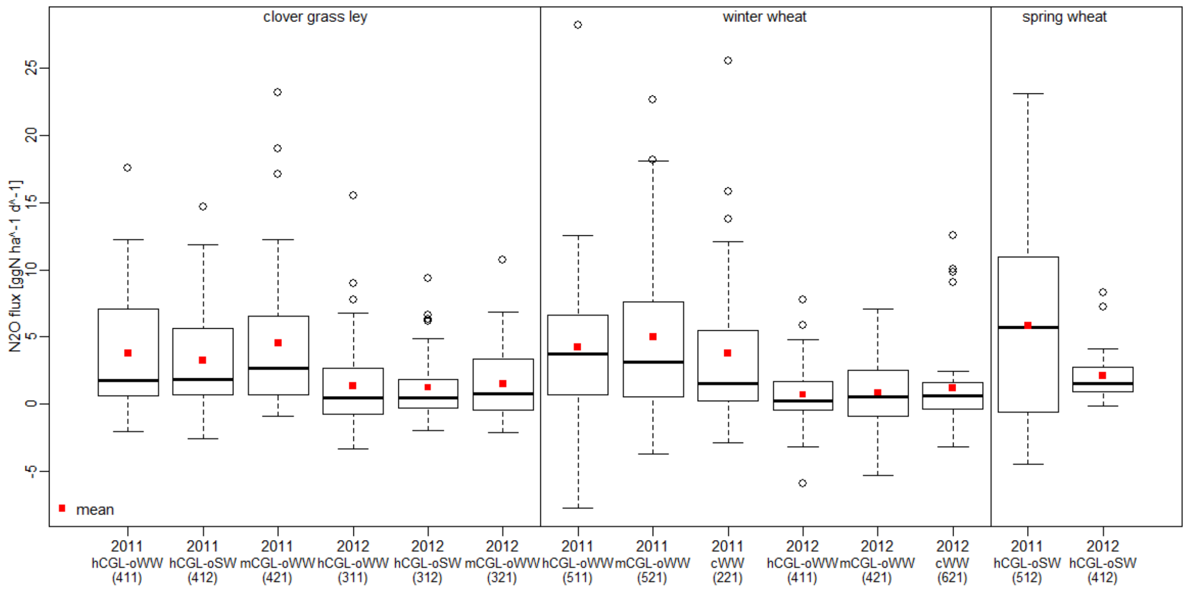

Fig. 21. N_2O flux measurements for the different crops displayed as boxplots. The x-axis gives the harvesting year, the crop rotations the measurements belong to as well as the plot number where the crop was grown.

N_2O emissions in Bad Lauchstädt are much more weather-dependent than treatment-dependent. This finding is further supported by the fact that most emissions in 2011 are emitted before the first till after harvest (Fig. 20). Furthermore, the measurements of hCGL – oSW (412) during spring 2012 show very low fluxes even though clover grass was tilled in the beginning of March.

The above argument finds further support when fluxes of entire crop rotations are compared (Fig. 22). There are no significant differences between the measured monthly mean of all the four treatments. Average emissions range from 73 g N ha^{-1} mo^{-1} to 88 g N ha^{-1} mo^{-1}.

However, there are small differences if all emissions between October 2010 and August 2012 are accumulated (Tab. 6). The highest emissions are found in harvested clover grass ley – spring wheat treatment and the lowest at harvested clover grass ley – winter wheat treatment. The conventional treatment shows similar fluxes as the mulched treatment. Still, all treatments are characterised by very low annual emissions.

Tab. 6. Cumulative emissions between October 2010 and August 2012. Measured emissions have been interpolated linearly. The total sums have been downscaled to yearly emissions.

	Measured emissions [g N ha^{-1} a^{-1}]	Modelled emissions [g N ha^{-1} a^{-1}]
hCGL – oWW (411)	645.5	414.7
hCGL – oSW (412)	1044.2	397.4
mCGL – oWW (421)	842.9	544.0
cWW – cWW (221,621)	836.2	386.1

5.2.2 Modelled nitrous oxide emissions

As indicated above, it is obvious that DNDC fails to simulate N_2O emissions on a daily basis. The model predicts no background emissions and the entire flux of nitrogen into the atmosphere is due to few discrete peak events.

Still, DNDC can reproduce the higher emissions between January and August 2011 compared to 2012, conforming closely to observed patterns (compare to Fig. 19). The model also predicts that the difference between crops is marginal compared to annual fluctuations (Fig. 20, Fig. 22, Tab. 6).

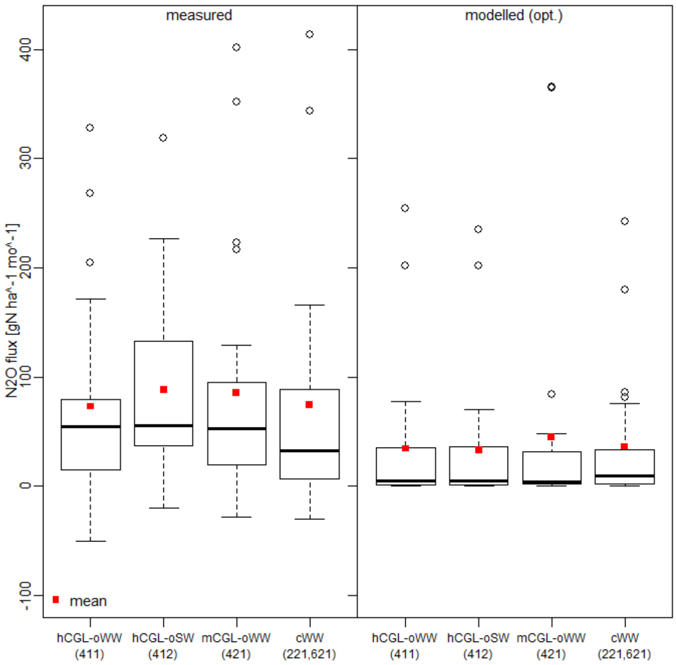

Fig. 22. Comparison of monthly measured and interpolated N_2O fluxes and monthly modeled N_2O fluxes between September 2010 and August 2012. The conventional sites (cWW) are combined.

In summary, DNDC suggests that weather conditions have a greater impact on N_2O emissions than treatment in Bad Lauchstädt. The four different farming practices do not lead to significantly different fluxes (Fig. 22). The strong weather dependency of emissions in DNDC becomes more apparent when looking into peak emission events. At site 421 the days of the four strongest rain events plus the four following days cause 86.5 % of the total emissions in 2011 (Fig. 20). However, the amount of rain during these peaks does not correlate with emissions. As described in section 2.2, other factors such as temperature, initial soil moisture as well as nitrogen availability also have an influence on N_2O flux rates.

5.3 Climate Sensitivity of DNDC and nitrous oxide

The following section briefly describes the results of the sensitivity analysis, thus will help to understand model results and observations.

5.3.1 The model's sensitivity to temperature and precipitation

The treatment mCGL – oWW shows the highest sensitivity of N_2O flux to precipitation and temperature (Fig. 23). Average annual N_2O flux between 2051 and 2060 increases from 504 g N ha^{-1} a^{-1} to 1169 g N ha^{-1} a^{-1} when precipitation is increased from minus 20 % to plus 20 %. This increase is even higher when temperature is changed from minus 2 °C to plus 2 °C, where the flux increases from 548 g N ha^{-1} a^{-1} to 1377 g N ha^{-1} a^{-1}. The same pattern is true for the other treatments. The emissions increase with higher precipitation and temperature.

The effect of precipitation change on SOC is not as uniform as it is for N_2O (Fig. 23). Precipitation has almost no impact on the SOC of mCGL – oWW and cWW – cWW. The maximum change of SOC for these treatments is 430 kg C ha^{-1} - less than 0.5 %. SOC at hCGL – oWW is much more sensitive to precipitation change and increases by 3277 kg C ha^{-1} when precipitation is altered from minus to plus 20 %. All treatments show a similar reduction of soil carbon content in response to increased temperature.

The modelled yield in DNDC is sensitive to a reduction of rainfall (Fig. 23). This is particularly pronounced for the hCGL – oWW treatment where yield is reduced by 1110 kg C ha^{-1} a^{-1} when altering precipitation to minus 20 %. An increase of precipitation has no effect on yield at the mCGL – oWW and cWW – cWW treatment, but enhances plant growth at the hCGL – oWW treatment. The temperature effect on plant growth is much lower than the effect of precipitation. The greatest effect is observed when temperature is reduced by 2 °C. Both organic sites show a negative trend with higher temperatures. The conventional treatment shows a reduced yield for any change of temperature. However, this change is not bigger than 32 kg C ha^{-1} a^{-1}.

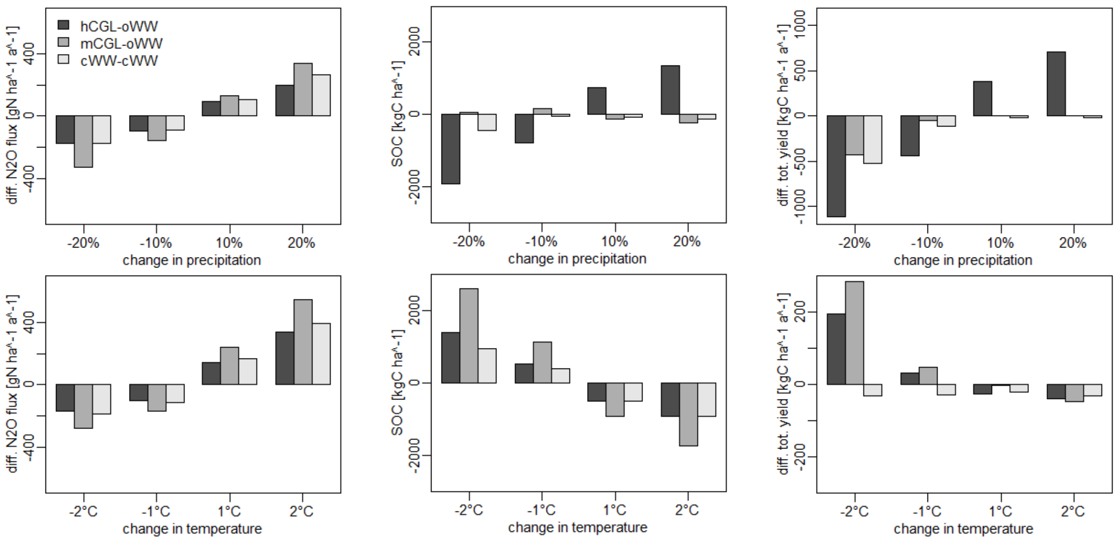

Fig. 23. Sensitivity of N_2O flux (left), SOC (centre) and total yield (right) to change in precipitation and temperature. Sensitivity is estimated by running a STAR climate scenario until 2060 and block-shifting temperature and precipitation. The sensitivity is displayed as difference of the average N_2O flux, SOC and total yield between the climate scenario and the block-shifted scenarios between 2051 and 2060.

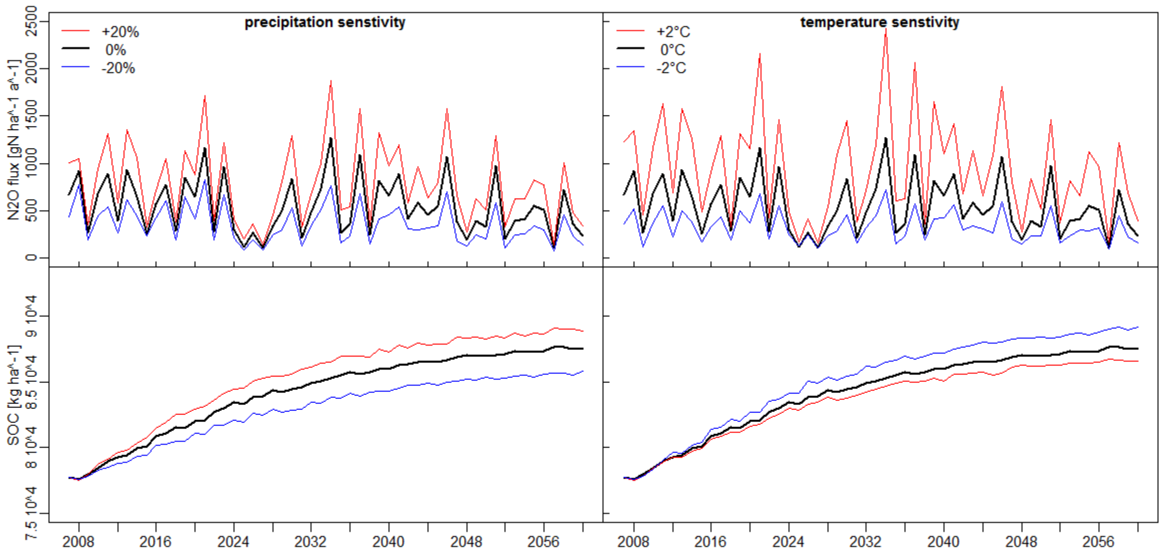

Fig. 24. Sensitivity analysis of N_2O emissions (upper panes) and SOC (lower panes) for hCGL – oWW. The left panes display the effect of a change in precipitation and the right panes when temperature is altered.

Fig. 24 depicts the impact of block-shifting temperature and precipitation over time for the hCGL – oWW treatment. Higher precipitation and temperature lead to a higher emission rates as already seen in Fig. 23. Differences in N_2O emissions are much greater during years of high fluxes, while years with low emissions are much more alike. This is especially pronounced when shifting temperature.

SOC increases by around 10 MgC ha^{-1} over 53 years at the hCGL – oWW treatment. An increase of precipitation and a decrease of temperature would further enhance this shift.

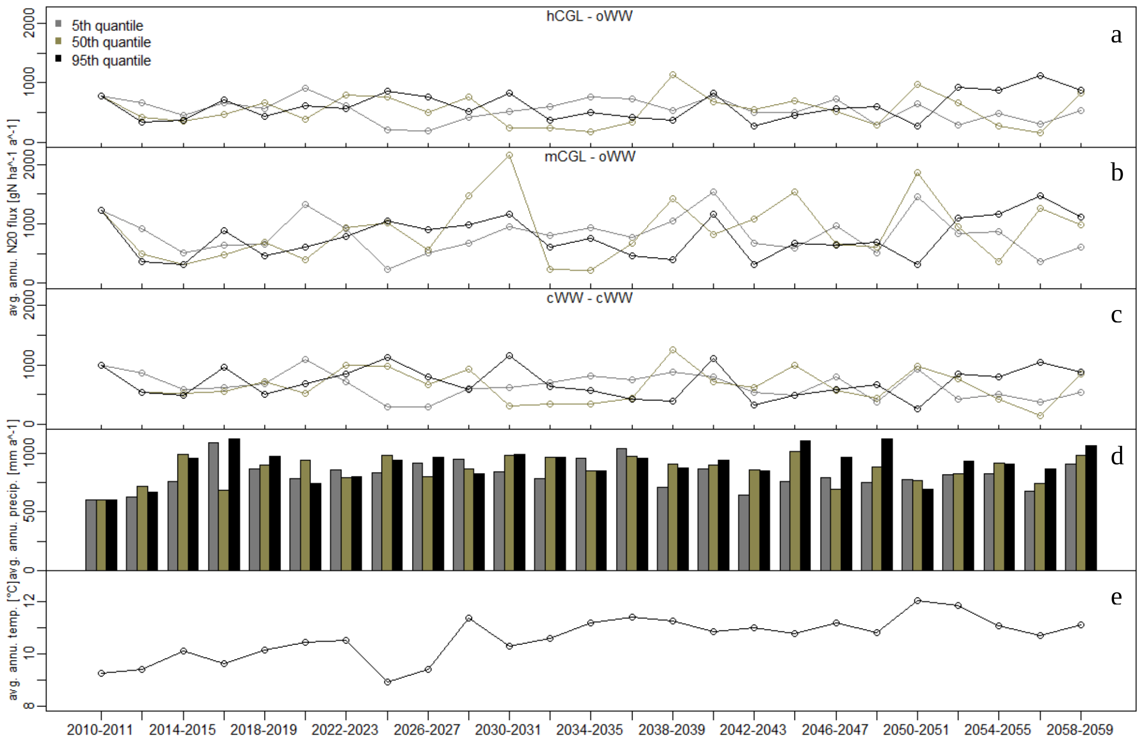

Fig. 25. N_2O fluxes of the different climate scenarios and treatments. The climate scenarios are derived from the statistical climate model STAR. The model produces several different realizations for future precipitation. DNDC was driven using median, 5^{th} and 95^{th} percentile precipitation scenario of the STAR model. The first three panes display the emissions of the different treatments: hCGL – oWW (a), mCGL – oWW (b) and cWW – cWW (c). The fourth pane displays the annual precipitation according to the three STAR scenarios assessed in this study (d). The last pane depicts the average annual temperature according to the STAR model (e).

5.3.2 Scenario analysis

The scenarios do not differ much regarding their precipitation and are characterised by strong inter-annual variations (Fig. 25). The average temperature clearly trends towards a warmer climate. However, the trend is not linear.

None of the treatments and scenarios shows a significant trend towards higher or lower emissions (Fig. 25). Treatment hCGL – oWW and cWW – cWW are characterised by much lower fluctuations compared to mCGL – oWW.

Fig. 26 compares N_2O emissions of the different scenarios. There are no significant differences between the three precipitation scenarios at any of the treatments. Treatment hCGL – oWW shows slightly higher emissions with higher precipitation, while mCGL – oWW shows the

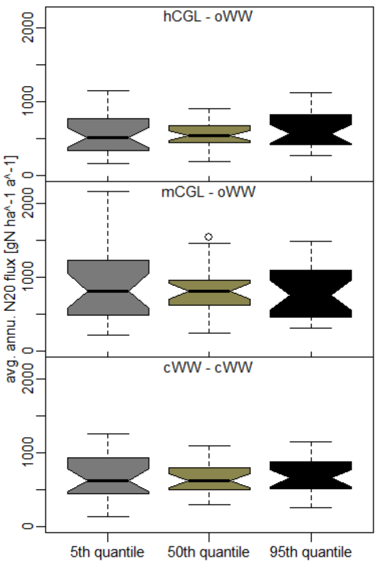

Fig. 26. Modelled annual N_2O emissions of the three different STAR scenarios, which vary with respect to their average annual precipitation for treatment hCGL – oWW, mCGL – oWW and cWW – cWW.

opposite trend. The conventional plot has the lowest emissions for the median precipitation scenario. The median scenario has the lowest variability for all treatments compared to the 5th and 95th percentile scenario at all sites.

In contrast, there are differences between the various treatments. Lowest emissions can be observed at the treatment where clover grass ley is harvested. Highest emissions are at the other organic experiment, where clover grass is mulched. Emissions increase from 540 g N ha^{-1} a^{-1} to 810 g N ha^{-1} a^{-1}, when comparing the median precipitation scenarios. The conventional treatment has median emissions of 620 g N ha^{-1} a^{-1} and is therefore only 80 g N ha^{-1} a^{-1} higher than the organic treatment without mulching.

6 Discussion

The discussion follows the order in which the results were presented: model fitting, treatment comparison and emissions under future climate conditions.

6.1 DNDC performance and fitting procedure

6.1.1 First model component: Soil moisture and plant growth

The fitting procedure of the first model component improves the fit for soil moisture in the first 20 cm. However, DNDC is only able to represent the general pattern within the first 10 cm and underestimates measured values at all depths. The underestimation remains pronounced even after fitting.

In accordance with other studies, adjusting field capacity improves soil moisture modelling (Beheydt et al., 2007). The default value of DNDC is 49 % wfps and linked to a clay content of 19 %. This value is not reasonable if compared to pF measurements on site. The optimized field capacity of 64.03 % wfps corresponds to a pF-value of 2.35, which is at the upper end of the reasonable range (Fiedler, 2001). The offset to DNDC default values is probably linked to a clay content of 21 % in Bad Lauchstädt. This shows that DNDC requires either measurements of wilting point and field capacity on site or an optimization routine.

Modelled soil water is characterised by overly rapid drying and excessively low maximum soil moisture. According to DNDC there are no leaching events into deeper soil layers during the measuring period, thus the offset is caused by excessively high modelled evaporation and transpiration. However, transpiration appears to be the dominant factor, because soil moisture is at wilting point below 10 cm almost the entire time. Drivers of evaporation and transpiration are among others humidity, global radiation, wind speed, vegetation and precipitation. DNDC uses the Priestly and Taylor equation to determine potential evapotranspiration (Pathak et al., 2006). This approach determines daily potential evapotranspiration based only on temperature and radiation (Pathak et al., 2006; Li et al., 2006). Actual evapotranspiration is then limited by plant growth and soil water content. DNDC is not driven with solar radiation in this study, hence it is based on DNDC datasets for radiation, which is a great source of uncertainty. The strong offset of actual evapotranspiration indicates that the procedure in DNDC is too simplistic to simulate soil conditions in Bad Lauchstädt.

This study suggests that the simulation of soil moisture in DNDC could be improved by reducing the model’s water demand for wheat crops. Such reduction, however, is criticised by Ludwig et al. (2011), because the water demand for wheat in DNDC is already low. The underestimation of soil moisture is therefore also linked to the implementation of crop growth within DNDC. This sub-model of DNDC is purely empirical and not process-based: Growth is dependent on temperature sums and limited by nitrogen and water (Brown et al., 2002; Kröbel et al., 2011). This drawback also comes into play when looking into biomass accumulation. Parameterization increases the fit for wheat yield. Still, the fit is poor and the optimized parameter set using minimum water demand and maximum potential yield for wheat is rather unrealistic. The validation runs confirm that the plant growth routine is too simplistic to reproduce yields in Bad Lauchstädt. This problem was addressed by Zhang et al. (2002) who developed an improved crop growth algorithm and combined that with DNDC (Giltrap et al., 2010).

Further improvement for soil water and plant growth can be achieved by using the revised crop algorithm of Zhang et al. (2002). More input data, however, are required to accomplish this enhancement. A better fit can be also attained by altering all parameters that affect the first model component simultaneously. A general underestimation of actual soil moisture was reported by Beheydt et al. (2007) at various sites. Nevertheless, there is no other study comparing DNDC with continuous soil moisture measurements in three depths. Bad Lauchstädt is among the driest areas in Germany (DWD, 2013). DNDC may give much better results for soil moisture and plant growth at different sites in Germany, where precipitation is closer to the German mean and water is not as limiting to plant growth as in Bad Lauchstädt.

6.1.2 Second model component: Nitrous oxide emissions

DNDC is able to represent the seasonal patterns of N_2O emissions on a monthly basis, but it fails to simulate daily and long-term emissions. Beheydt et al. (2007) stated that a process-based model must be able to reproduce the seasonal pattern. Many locations used in the Beheydt et al. (2007) study did not conform well to measured seasonal dynamics. DNDC models very low baseline emissions and shows high and short peaks on a daily basis. Overly frequent, high and sharp peaks were published by other studies as well (Beheydt et al., 2007; Li et al., 1992a; Ludwig et al., 2011). These events are triggered by precipitation and are probably due to too high diffusion rates of N_2O (Li et al., 1992a). The reason for the underestimation of baseline emissions is more complex: Production of N_2O is governed by, among other factors, soil moisture, SOC, microbes and availability of nitrate or ammonium. DNDC underestimates microbial biomass, nitrate, ammonium and soil moisture. The mean ammonium and nitrate concentrations in the top 10 cm are underestimated at the optimized calibration sites by 99.7 % to 95.2 % and 96.3 % to 74.9 %, respectively. Beheydt et al., (2007) concluded in their study, that DNDC is not able to predict soil N and N_2O emissions with the same high accuracy and an increase in modelling efficiency at one of them is equal to a decrease at the other. The share of microbial biomass of total SOC varies between 0.015 % and 0.051 % at calibrated sites during 2011. Anderson and Domsch (1989) found a microbial biomass fraction of total SOC of 2.3 % to 4 % at sites in Central Europe, thus DNDC is likely underestimating microbial biomass in Bad Lauchstädt. However, this is crucial for substrate and N_2O production. Due to the fact that DNDC is such a comprehensive generic model it is very difficult to track back dependencies and thus identify the main cause for the underestimation of background emissions.

Monthly as well as long-term emissions show an underestimation of the observed N_2O flux. This may not only be linked to DNDC itself. The measurements as well as the linear interpolation between weekly measurements is a source of uncertainty (Beheydt et al., 2007; Freibauer and Kaltschmitt, 2003). Parkin (2008) analysed automated chamber measurements and concludes that the offset between actual emissions and interpolated emissions is strongly dependent on the measurement frequency. The difference between interpolated measurements and actual fluxes increase from ± 10 % to + 60 % and -40 % when changing measurement interval from every third day to every 21st day (Parkin, 2008). In contrast to Parkin (2008), Smith and Dobbie (2001) found no significant differences comparing manual chamber and automated chamber measurements. Flechard et al. (2007, 2005) used automated chambers to find diurnal fluctuations with highest emissions in the afternoon. The measurements in Bad Lauchstädt were conducted mostly before noon and may therefore be representative. Despite that, chamber measurements themselves are subject to uncertainties, especially for locations with low emissions, as described in Rochette and Eriksen-Hamel (2008).

Altering microbial activity is an efficient method to improve the second model component and thus N_2O emission modelling. It is important to keep in mind that the actual microbial activity is not known and a validation is not possible. Still, it is not the sole method available to improve the second model component. N uptake by crops should also be investigated to improve soil N concentration. Also, the uncertainty range within SOC measurements needs further consideration (Abdalla et al., 2009; Beheydt et al., 2007; Ludwig et al., 2011). Abdalla et al. (2009) found that an increase in SOC of 20 % enhanced N_2O emissions by 58 % for a spring barley field in Ireland. Therefore, varying SOC by only the standard deviation of measurements could be used to trim DNDC and lead to more accurate estimates. The monthly fitting routine in the Bad Lauchstädt study led to a decrease of microbial activity. This however reduced the annual fit. Thus, an annual parameterization routine is more suitable for determining yearly emissions factors.

In general, DNDC is able to reproduce monthly emissions and seasonal dynamics in Bad Lauchstädt. The model has difficulties in reproducing the underlying drivers such as soil moisture and substrate availability in this study. As already stated by Ludwig et al. (2011), DNDC requires site specific calibration. Some countries such as Belgium, New Zealand and the UK have developed revised DNDC models (Beheydt et al., 2004; Brown et al., 2002; Saggar et al., 2004). Despite the fact that DNDC has performed well for other German agricultural sites, this could be an approach that would particularly improve crop growth (Ludwig et al., 2011). A country-specific empirical growth curve could lead to a better yield, soil N, soil water and SOC simulation (Ludwig et al., 2011).

6.2 Treatment comparison

Mean measured emissions of the different crops in Bad Lauchstädt are very low, ranging from 0.8 g N ha^{-1} d^{-1} to 5.8 g N ha^{-1} d^{-1}. Jungkunst et al. (2006) summarised all N_2O measurements in Germany prior to 2006 lasting longer than one year and gave a range of N_2O emissions of 0.1 g N ha^{-1} d^{-1} to 9.3 g N ha^{-1} d^{-1} for unfertilized and 0.2 g N ha^{-1} d^{-1} to 46.8 g N ha^{-1} d^{-1} for fertilized fields on an annual basis. The following section discusses the crops individually before analysing the entire crop rotations. Comparison of the crops is based on the mean measurements, while comparison of treatments also uses cumulative emissions over the entire observation period.

6.2.1 Nitrous oxide emissions from clover grass ley

According to the measurements, clover grass ley emits on average between 1.2 g N ha^{-1} d^{-1} and 4.5 g N ha^{-1} d^{-1}. Emissions are thus at the lower range given by Jungkunst et al. (2006). In Bad Lauchstädt fluxes vary strongly between years, but not between treatments. The highest N_2O losses are at the mulched sites. This may be caused by additional N input, higher soil organic matter, higher microbial population and enhanced microbial activity (Dahlin et al., 2011; Helmert et al., 2004; Jungkunst et al., 2006; Kaiser et al., 1998; Nadeem et al., 2012). Green manure at the mulched sites further amplifies emissions by increasing substrate availability during July, August and September of 2011. This stimulation of emissions is also simulated by DNDC. Still, the increase due to mulching is very small and not significant. This is in contrast with a study in Norway by Nadeem et al. (2012), where mulching led to a significant increase of 370 g N ha^{-1}. Helmert et al. (2004) investigated N_2O emissions by mulched clover grass ley in Viehhausen, Bavaria and found 3290 g N ha^{-1} higher loss of N_2O compared to the cut treatment. Our measurements mesh well with the findings of Lampe et al. (2006), which stated that soil N pool is the greatest source of N_2O emissions and thus management is less important. Clover grass ley plots that are tilled in spring show the lowest emissions in our study in Bad Lauchstädt. This is linked to winter measurements, which show generally low emissions if they are not influenced by freeze and thaw cycles due to the strong temperature dependency of N_2O production (Dobbie et al., 1999; Nadeem et al., 2012). Because the other two CGL treatments of 2011 are tilled in fall and sown with winter wheat, this period is not part of their mean. If measured winter emissions of 2011 at the three long term sites (411, 412, and 421) are compared, clover grass ley emissions are the lowest. Fall-sown winter wheat is not well established yet and is therefore not able to take up as much soil N as clover grass ley. This leads to slightly higher N_2O fluxes at the two winter wheat sites. The nitrate uptake by CGL is indicated by significantly lower measured nitrate concentration in the topsoil between November 2011 and January 2012. DNDC is not able to simulate these differences in winter emissions. This may be caused by low temperatures which constrain plant growth and N_2O production in DNDC.

There is no nitrogen fixing effect on N_2O emissions during the growth of clover grass in Bad Lauchstädt. The emissions are not significantly different when compared to winter wheat during the same year.

6.2.2 Nitrous oxide emissions from wheat crops

The two conventional winter wheat plots emitted on average 3.8 g N ha^{-1} d^{-1} and 1.2 g N ha^{-1} d^{-1} and are therefore also quite low in comparison to the range given by Jungkunst et al. (2006). The organic wheat emissions range from 0.7 g N ha^{-1} d^{-1} for winter wheat in 2012 to 5.8 g N ha^{-1} d^{-1} for spring wheat in 2011.

The conventional wheat sites show no effect of fertilizing in both the modelled and the measured data, and thus contrast significantly with many other studies that showed clear effects of N application (Baggs et al., 2000; Röver et al., 1998; Ruser et al., 2001; Smith et al., 1997). Röver et al. (1998) measured 740 g N ha^{-1} higher emissions during the period from March through November at a fertilized field in Lower Saxony. Due to strong fluctuations of N_2O fluxes, there is a great chance for missing peak events that may occur after fertilizing, in particular when fluxes are measured weekly as in our study. Still, N_2O production seems to be limited by soil physical conditions rather than by nitrogen in Bad Lauchstädt. The model results provide evidence for a strong moisture limitation of N_2O emissions. In contrast to 2011 and 2012, the weather data for 2010 is derived from the weather station in Freyburg, which has significantly higher precipitation as compared to Bad Lauchstädt (mean annual precipitation in Freyburg: 536 mm and Bad Lauchstädt: 483 mm). In addition, there is above average precipitation in 2010 with 724 mm falling in Freyburg. The higher precipitation induces emission peaks in DNDC shortly after fertilizer application in 2010.

According to measurements organic winter wheat emits N_2O within the same range as conventional winter wheat (0.7 g N ha^{-1} d^{-1} to 4.9 g N ha^{-1} d^{-1}), which again supports the hypothesis that emissions are not nitrogen limited. Emissions from wheat are not significantly different from mulched treatments versus harvested treatment, but they tend to be a slightly higher. This is consistent with the findings of Nadeem et al. (2012), who found no effect of mulching or harvesting of clover grass ley for the subsequent crop.

Spring wheat shows higher N_2O fluxes (5.8 g N ha^{-1} d^{-1} and 2.1 g N ha^{-1} d^{-1}) compared to all other crops. This is mainly caused by the timing of measurements compared to winter wheat. Spring wheat is not measured in winter and is therefore hard to compare with winter wheat and clover grass ley at this point. Still, additional factors must be considered. At the time of spring wheat measurements, winter wheat has grown already for several months and is therefore able to withdraw nitrate and ammonium more efficiently then spring wheat. Thus, more soil N is available for N_2O production at the spring wheat sites. This is visible at the spring wheat plot in 2011 where emissions exceed emissions at all other plots shortly after sowing (Fig. 20). Similar patterns have been observed for spring barley by Nadeem et al. (2012).

6.2.3 Nitrous oxide emissions of entire crop rotations

This study does not reveal significant differences between any of the treatments, neither in the individual measurements nor in the modelled. As mentioned above, Bad Lauchstadt is among the driest areas in Germany, which has consequences on soil water (DWD, 2013). According to Blume et al. (2009) N_2O production and emission is highest when soil moisture is at 60 % wfps to 70 % wfps, because N_2O is primarily produced when complete denitrification and nitrification cannot occur. Observed soil moisture at harvested clover grass ley – winter wheat is only within this range for 30 (311) and 66 (411) days between October 2011 and 2012. Velthof and Oenema (1995) found only small fluxes when water filled pore space was below 50 % wfps. This was the case for 166 (311) and 273 (411) days in the measurement period in Bad Lauchstädt. Thus, water filled pore space is too low to allow for a greater production of N_2O for most of the time. Jungkunst et al. (2006) disaggregated Germany regarding the potential to produce N_2O using precipitation and frost days. Bad Lauchstädt has less than 600 mm of rain, and therefore belongs to that category of sites where N_2O emissions are low and strongly constrained by soil moisture. Aerobic conditions lead to complete oxidation of ammonium to nitrate and N_2O production is constrained to microsites within the soil matrix (Blume et al., 2009; Brady and Weil, 2007; Smith, 2012). This moisture dependency becomes apparent when comparing emissions in 2011 and 2012. Emissions in 2011 are significantly higher. This inter-annual variability is a strong indicator for the weather dependency of fluxes and comports well with other studies (Jungkunst et al., 2006). Precipitation was 484 mm in 2011 and 460 mm in 2012. However, not only total rainfall but also timing influences N_2O production. Heavy rain after a dry spell has been reported to trigger high N_2O losses (Cabrera, 1993; Ruser et al., 2006; Skiba and Smith, 2000). DNDC is able to simulate part of this strong dependency on soil moisture dynamics.

N_2O emissions are not primarily limited by soil nitrogen for several reasons. (i) Fertilizer application does not induce higher fluxes compared to non-fertilized plots. This in strong contrast with earlier field studies (Baggs et al., 2000; Röver et al., 1998; Ruser et al., 2001; Smith et al., 1997). (ii) Tilling after clover grass ley or wheat does not promote emissions even though extra nitrogen becomes accessible in our experiments. Several studies reported high emissions shortly after tilling due to higher N availability (Baggs et al., 2000, 2003; Pinto et al., 2004). (iii) Different crops do not lead to significant different emissions in Bad Lauchstädt. Kaiser et al. (1998) and Nadeem et al. (2012) measured emissions by different crops and discuss that different crops substantially alter soil N cycling and hence N_2O losses.

Even though emissions for all treatments are very low, the cumulative emissions vary slightly between treatments at plots that cover full crop rotations. The highest emissions are found at the spring wheat site. As already mentioned, this is due to low soil nitrogen uptake early in the growing season. Another reason is one measurement of 11.8 g N ha^{-1} d^{-1} on the 21st of February 2012, after two to three weeks of soil frost at site 412. Freezing and thawing events are a great source of N_2O emissions, but are hard to track (Dobbie et al., 1999; Flessa et al., 1995). Therefore, this thawing-induced flux may have been missed at the other sites. Linear interpolation between measurements amplified the thawing effect. Emissions between the previous and the following measurement on the spring wheat plot (26.01.2012 and 02.03.2012) accumulate to 203 g N ha^{-1}. Emissions by conventional winter wheat and mulched clover grass ley – winter wheat show similar emissions, indicating that mulching and fertilizer application have similar effects on N_2O emissions. The lowest emissions are at the hCGL – oWW site, because there is no additional nitrogen input. However, reliable comparison of treatments requires several years of observations especially if differences are quite small (Dobbie et al., 1999).

Improved data quantity may help provide more reliable estimates of best farming practices. Especially long-term effects as for example increase of soil organic matter and soil nitrogen pool cannot be captured in a two year study. Still, these effects may increase emissions substantially.

6.3 Future emissions

This section discusses future climate scenarios after analysing the model sensitivity. The first part focuses only on the effect of temperature and precipitation shift and disregards the effect of climate change on the model results which are investigated in section 6.3.2.

6.3.1 Model sensitivity

N_2O emissions

DNDC simulates a strong dependency of precipitation and temperature on N_2O emissions. The strongest effect is found at the mulched site.

Precipitation alters soil moisture and thus has a great impact on N_2O emissions. Higher soil moisture promotes N_2O formation, but it also affects the break-down of organic matter in DNDC, hence it also changes the supply of ammonium and DOC. Decomposition is influenced in two ways: (i) It halts after every rain event until soil moisture is less than 40 % wfps or for a maximum of 10 days (Li et al., 1992b). Therefore, rain amount is a determining factor for the length of time that decomposition pauses. (ii) Decomposition also increases with higher soil moisture content. Maximum decomposition rate in DNDC occurs when soil moisture is around 60 % wfps (Li et al., 1992b). The mulched treatment is particularly affected by precipitation if looking at total changes, which may be due to slightly higher emissions at this treatment under future climate conditions in comparison to the other treatments. However, the relative change is similar for all treatments. Precipitation alters also nitrogen availability by wet deposition. Higher rainfall increases the soil nitrogen pool.

The strong temperature dependency is linked to several processes. Higher microbial activity increases decomposition and reduces oxygen content. N_2O emissions are also mediated by microbes. Higher temperatures therefore have an increasing effect on N_2O production. Temperature has a greater impact on the mulched treatment, because decomposition rates alter N release from green manure.

Soil organic carbon

SOC is not strongly influenced by precipitation at the mulched and fertilized treatment, but at the harvested site. SOC is influenced by two opposing factors in DNDC: (i) new input of organic matter via crop management as well as (ii) breakdown of organic compounds. The general patterns of yield and SOC sensitivity to precipitation match well. Hence crop growth seems to be the major driver on SOC of these two opposing factors. Decomposition rates are strongly temperature dependent and increase with higher atmospheric energy input. The mulched treatment is most dependent due to green manure decomposition. However this treatment has also the highest SOC pool and the relative change is comparable to the other crop rotations.

Plant growth

A decrease in precipitation reduces yields at all sites. An increase of rainfall amplifies yield only at the harvested clover grass treatment indicating that water supply is considered sufficient by DNDC in the median scenario, because the same crops are grown at both organic treatments. The sensitivity to higher precipitation at the hCGL – oWW treatment may be linked to wet N deposition. This study assumed that all atmospheric N input is due to wet deposition of 10.35 mg l^{-1}. Hence an increase in precipitation is equal to an increase of N input. The harvested CGL treatment is the only treatment that has no additional N application, thus the yield increase may be actually triggered by N and not by water. The described feedback is also relevant for the other two treatments and should also be taken into account when interpreting model outputs.

Temperature influences plant growth mainly via its impact on the temperature sum that drives crop growth and via its importance for evapotranspiration. However this impact is negligible compared to the effect of precipitation, especially for the conventional winter wheat treatment. A shift of minus 2 °C results in a yield increase for the two organic treatments. All crops are able to reach their growing degree days till maturity between 2051 and 2060 regardless of temperature shift. Hence these model runs are more affected by high transpiration and water scarcity than by the crop specific temperature sums. The crop growth model does not simulate heat stress, and growth is only limited by nitrogen and water. This is a great drawback if applied for future climate conditions. Due to warmer temperatures, growth is accelerated, leading to much faster N and water uptake. Modelling of future crop yield requires a more mechanistic treatment of crop growth that considers among others carbon dioxide fertilization effect, change of water use efficiency due to higher carbon dioxide level in the atmosphere and heat stress.

DNDC is, therefore, not applicable for modelling future climate conditions, which is also stated by Fumoto et al. (2008) and Zhang et al. (2002).

6.3.2 Scenario discussion

DNDC simulates no increase of N_2O emissions by either of the treatments. This is in strong contrast with other studies that find higher emissions under future climate for agricultural sites (Eckard and Cullen, 2011; Hickman et al., 2011; Hsieh et al., 2005; Mosier and Kroeze, 2000).

Hsieh et al. (2005) used DNDC to model N_2O emissions by fertilized grassland in Ireland. According to their study, a business as usual scenario leads to an increase of 7000 g N ha^{-1} a^{-1} by the end of the 21st century. Another study investigated emissions by pasture in Australia using the mechanistic model EcoMod at four different sites (Eckard and Cullen, 2011). Three sites showed a clear trend towards higher emissions (Eckard and Cullen, 2011).

The STAR model simulates an increase of temperature, but no general increase of precipitation over the next decades. However, there is an increase of precipitation in the beginning of the simulation period due to the fact that the STAR scenario data is taken from the closest climate station, but not directly from Bad Lauchstädt. This station is characterised by higher rainfall. The median STAR scenario has an average rainfall of 879 mm a^{-1}. The long-term mean precipitation in Bad Lauchstädt is 484 mm a^{-1}. Future studies should down-shift scenario precipitation to closer match conditions on site. This could be done by subtracting the difference of average rainfall of the scenario and the mean precipitation in Bad Lauchstädt from the scenario data. DNDC is run with three different rain scenarios. The difference between scenarios is minor compared to the variation between Bad Lauchstädt and the used climate station.

The temperature and precipitation increase does not lead to higher emissions even though the sensitivity analysis indicates that higher temperatures generate higher emissions. The following points support higher N_2O production and emissions:

a) DNDC shows a strong increase in soil organic carbon. According to Li (2007), N_2O emissions in DNDC are very sensitive to SOC.
b) DNDC simulates higher soil organic nitrogen in 2060 compared to 2012. Treatment mCGL – oWW shows an increase of 1812 kg N ha^{-1} for the median scenario. Higher nitrogen availability leads to higher emissions of N_2O. According to Brady and Weil (2007) 1.5 % to 3.5 % of SON are mineralized annually and hence are available for denitrification or nitrification.

c) Higher temperatures increase decomposition and N_2O production, thus this should accelerate emissions.
d) According to DNDC microbial biomass increases and hence should accelerate decomposition and increase available nitrogen in the soil matrix.
e) Scenario precipitation is much higher compared to the long-term average in Bad Lauchstädt. The sensitivity analysis indicates that this will generate higher emissions.

However there are also factors that support a reduction of emissions:

a) Warmer temperatures have a strong effect on plant growth in DNDC. They accelerate plant growth, which leads to a higher plant nitrogen uptake. Average plant N uptake at the mCGL – oWW treatment between 2011 and 2020 is 89 kg N ha^{-1} a^{-1} and increases to 127 kg N ha^{-1} a^{-1} between 2051 and 2060.
b) Plant growth in DNDC is partly limited by water in our study. Due to higher precipitation crop growth is not constrained anymore leading to higher N uptake.
c) Higher soil nitrogen concentration positively affects leaching. Average leaching is 20 times higher between 2011 and 2020 than between 2051 and 2060 at the mCGL – oWW treatment.
d) The increase of SON over the next decades indicates that nitrogen is immobilised and hence is inhibited from out-gassing into the atmosphere (Brady and Weil, 2007).
e) The annual average stored water within the first 50 cm of the soil profile stays almost constant over the entire modelling period. Therefore emissions may still be soil moisture limited

This list is not exhaustive, but shows that many factors are counteracting in DNDC and the nitrogen cycle.

There is no difference between the three different future precipitation scenarios. This may be due to several reasons: (i) N_2O emissions are not only dependent on the annual precipitation, but also on the distribution and intensity of rain events during the year. For example rain events after dry spells can trigger great emissions (Ruser et al., 2006; Skiba and Smith, 2000). (ii) Another reason is that the rain amount is not very different between the three scenarios, especially, if the scenarios are compared to the initial increase. (iii) The scenarios are based on historic precipitation records and fluctuate strongly between years and show no gradual increase. This characteristic may be another reason for the lack of distinguishability.

In sum, DNDC simulates no increase of emissions, and small differences between treatments. Due to the empirical simulation of plant growth within the process-based model DNDC these results are not very reliable.

7 Conclusion

This report shows that DNDC is able to simulate N_2O emissions from clover grass ley - winter wheat rotations on a monthly basis in Bad Lauchstädt. The model underestimates long-term emissions and baseline emissions. The offset of long-term emissions is linked to the fitting procedure that focused on monthly sums to cover the seasonality of fluxes. Regardless, the modelled N_2O fluxes should be treated with caution, because DNDC underestimates soil moisture, plant growth and microbial biomass in Bad Lauchstädt. Thus model applications on a regional or national scale, or for future climate conditions are not reliable, unless further adaptations are made. Ongoing research should focus on improving the results for soil environment, in particular evapotranspiration, and plant growth.

N_2O emissions in Bad Lauchstädt are low compared to emissions from other arable land in Germany. Emissions are mainly limited by low soil moisture and not by nitrogen availability in the soil profile. If conditions allow for a greater production of N_2O, there are short-term differences between treatments. Neither the measurements nor DNDC resolve significant differences between all four crop rotations. A higher temporal resolution of measurements over a longer period may, however, reveal small differences between treatments. N_2O fluxes in DNDC are linked to strong rain events and peak emissions differ slightly between crop rotations. Modelled baseline emissions are not different and close to zero.

DNDC does not show any increase of emissions until 2060 despite an increase in average annual temperature. However, this finding is not reliable, due to the described drawbacks in the modelling of soil conditions and plant growth. Further improvement of DNDC is needed to reduce modelling uncertainties and to give better estimates for future emissions.

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