StartClim2012.A

Zwischenfruchtbegrünungen als Quelle oder Senke bodenbürtiger Treibhausgas-Emissionen?

Department für Nutzpflanzen-wissenschaften (DNW),

Abteilung Pflanzenbau

Universität für Bodenkultur Wien
Department für Nutzpflanzen-wissenschaften

Autoren: Gernot Bodner, Andreas Klik, Sophie Zechmeister-Boltenstern

ProjektmitarbeiterInnen: Mathias Märzendorfer, Michael Harant, Christoph Imböck

Diese Publikation sollte folgendermaßen zitiert werden:

Bodner, G., Klik, A., Zechmeister-Boltenstern, S. (2013): Zwischenfruchtbegrünungen als Quelle oder Senke bodenbürtiger Treibhausgas-Emissionen? Endbericht von StartClim2012.A in StartClim2012: Anpassung an den Klimawandel – erste Beiträge zur Umsetzung der österreichischen Anpassungsstrategie: BMLFUW, BMWF, ÖBF, Land Oberösterreich

Wien, im August 2013

StartClim2012.A

Teilprojekt von StartClim2012

Projektleitung von StartClim2012:

Universität für Bodenkultur, Department für Wasser – Atmosphäre – Umwelt

Institut für Meteorologie, Peter Jordan-Straße 82, 1190 Wien

URL: http://www.austroclim.at/startclim/

StartClim2012 wurde aus Mitteln des BMLFUW, des BMWF, der ÖBf und des Landes Oberösterreich gefördert.

Inhaltsverzeichnis

Kurzfassung

Der Zwischenfruchtbau ist eine zentrale Maßnahme im österreichischen Agrarumweltprogramm ÖPUL mit Relevanz für die Klimawandelanpassung der Landwirtschaft. Dieses Projekt untersuchte den Einfluss von Zwischenfrüchten auf Treibhausgas-Emissionen von landwirtschaftlich genutzten Böden an zwei klimatisch unterschiedlichen Orten (Niederösterreich, Oberösterreich). Dabei wurden vier Zwischenfruchtvarianten mit Schwarzbrache verglichen. Darüber hinaus wurde der Einfluss organischer Düngung und des Vor-Winter-Umbruchs der Begrünung analysiert.

Es konnte gezeigt werden, dass Begrünungen im Vergleich zu Düngung und Bodenbearbeitung in der Hauptfrucht nur ein geringes Potential von N_2O Emissionen aufweisen. Ein Anstieg wurde nur bei Senf in Reinsaat, vor allem unter Bedingungen hoher Lachgasbildung festgestellt. Auch die CO_2 Emissionen zwischen Spätherbst und Frühjahr waren durch die niedrigen Bodentemperaturen gering. CH_4 Emissionen waren vernachlässigbar. Höhere CO_2 Emissionen der begrünten Flächen weisen auf die Förderung des Bodenlebens durch die leicht abbaubare Gründüngung hin. Während Zwischenfrüchte also dem Boden organisches Material zuführen, sind CO_2 Emissionen einer Brachfläche als Nettoverluste anzusehen. Wichtige Umweltfaktoren für die Treibhausgas-Bildung waren ein hoher Wassergehalt des Bodens (Anstieg von N_2O), ein hoher Gehalt and wasserlöslichem Kohlenstoff (Anstieg von CO_2 und N_2O) und ein hoher N Gehalt der Pflanzenbiomasse (Anstieg von CO_2 und N_2O).

Die Ergebnisse zeigen, dass Zwischenfrüchte kein wesentliches Potential für erhöhte Treibhausgas-Emissionen von Ackerflächen aufweisen. Daher ist ihre Bedeutung für die Umwelt und die Klimawandelanpassung (Erosion, Grundwasser) klar dominant. Künftige Agrarumweltprogramme sollten Mischkulturen fördern und Reinsaaten von Senf vermeiden. *Brassica*-Arten sind effiziente Zwischenfrüchte und führen, sofern sie in Mischung mit geringerer Saatstärke angebaut werden, auch zu keinen erhöhten Lachgasemissionen.

Abstract

Cover cropping is a key measure in the Austrian agro-environmental programme with relevance for climate change adaptation and mitigation. This study analyzed the effect of cover crops on greenhouse gas emissions from soil at two climatically different sites (Lower Austria, Upper Austria). Four different cover crop variants were compared with bare soil and also studied the influence of organic fertilizer addition and pre-winter ploughing of cover crops.

It could be shown that cover cropping is only a minor source of N_2O emissions compared to other measures (fertilization, tillage). An increase in N_2O emissions from a mustard cover crop in pure stand was found, particularly for situations with high emission potential. Also CO_2 emissions were generally low between late autumn to early spring due to low soil temperatures. CH_4 emissions were neglible. Higher CO_2 from cover cropped fields reflected the enhanced biological activity of soil due to the input of easily decomposable organic carbon. While cover crops contribute organic matter to the soil, CO_2 emissions from a bare soil have to be considered as net losses. Important environmental drivers of greenhouse gas emissions were high soil water content (increase in N_2O), dissolved organic carbon (increase in N_2O and CO_2) and plant N content (increase in N_2O and CO_2).

From these results it can be concluded that cover cropping is only of minor importance for greenhouse gas emissions from agricultural soils. The importance of cover crops for environment and climate change adaptation (erosion, groundwater) is clearly dominant. Future agro-environmental programmes should promote mixed cultures, while avoiding mustard in pure stand. *Brassica* species are efficient cover crops and when grown in mixture at a lower seeding density do not have an enhanced N_2O emission potential.

A-1 Introduction

A-1.1 State of science

Cover cropping is a key agro-environmental measure in several European countries. The main target is to reduce negative environmental impacts related to intensive agricultural production, particularly nitrate leaching to the groundwater and soil erosion. Due to the efficiency of cover cropping to achieve these environmental targets, that has been demonstrated in several research studies (e.g. e.g. Wyland et al., 1996; Dabney, 1998; Meyer et al., 1999; Shepherd and Webb, 1999; Hartwig and Ammon, 2002; Logsodon et al., 2002; van Dam, 2006) and evaluations of past agro-environmental programmes (e.g. Liebhard und Bodner, 2005; Feichtinger et al., 2005; Strauss, 2006), and the rather simple integration of cover crops into common crop rotations, it has become a central aspect in several European agro-environmental programs such as the Austrian ÖPUL programme (BMLFUW, 2000). Since the first ÖPUL programme has been started in 1995, cover cropping has become a wide spread element in crop rotation in Austrian agriculture with a total amount of 33 % of the agricultural land with yearly use of cover crops (Grüner Bericht, 2011).

A-1.1.1 Cover crops and climate change adaptation

Cover crops are considered an important measure for climate change adaptation and therefore they have been integrated in the Austrian climate change adaptation strategy (BMLFUW, 2010).

Easterling et al. (2000) showed that climate change will lead to an increased frequency of extreme weather events such as high intensity rainfall and prolonged dry periods. Soil erosion is one of the most severe soil problems in Europe and it is commonly agreed that more frequent weather extremes under climate change will increase rainfall erosivity and soil losses (Klik and Eitzinger, 2010). Strauss (2006) estimated that around 25 % of the Austrian crop land is currently endangered by soil erosion. Thus climate change requires extension of all measures preventing erosion. Cover crops primarily protect against soil erosion due to continuous soil coverage after cash crop harvest, avoiding prolonged periods of bare soil. Particularly in late summer there is a high probability of thunderstorms with erosive rainfall and high risk of runoff and erosion losses from bare soil. Also in spring, snow melting and subsequently high rainfall has led to high runoff and erosion damage, particularly in row crops with late soil coverage (maize, sugar beet, oil pumpkin). Quinton et al. (1997) showed that erosion decreases exponentially with increasing soil coverage. A coverage of 50 % leads to a reduction of erosion by around 80 %, while coverage of > 70 % results no or negligible erosion losses (Gonzales-Lanteri et al., 2004).

Beside soil coverage, cover cropping contributes to reduced erosion risk via higher aggregate stability. This is related to organic matter input, enhanced soil microbial activity and root entanglement of primary particles. Kabir and Koide (2002) and Liu et al. (2005) showed higher aggregate stability and mean weight diameter of soil aggregates under cover crops. Better soil structure also implies a higher macroporosity and also higher stability of soil pores. Particularly enhanced formation of biopores from earthworms and root channels have been described in cover cropped field compared to fallow. The increase in soil infiltrability by higher macroporosity lowers runoff losses (Joyce et al., 2002) and eventually also contributes to mitigate the risk of flooding.

Olsen and Bindi (2002) and Hungate et al. (2003) studied the changes in nitrogen dynamics to be expected under global change. Increasing temperatures will result in higher organic matter turnover and thereby higher leaching risk of nitrate losses if the available N is not readily taken up by plants. The enhanced organic matter turnover can be further exacerbated by higher residual fertilizer N after cash crops when crop production is more frequently limited by drought. Already by now, semi-arid regions such as the Marchfeld area show high risk of nitrate leaching and low groundwater quality because of a residual high fertilizer N-pool in soil (e.g. Cepuder, 1999): Nitrate is accumulated during dry years in soils with high water storage capacity, leading to a concentrated soil solution when leached to groundwater in years with groundwater recharge. Beside a reduction in fertilizer input to the main crops, cover cropping is the only measure to avoid leaching of post-harvest nitrate stocks in the soil .

Recently stabilization and increase of stable organic carbon in soil is discussed as a contribution of agriculture to climate change mitigation. Dersch and Duboc (2011) reported an increase in humus content of Austrian agricultural soil between 0.1 % and o.4 %. Among other factors (reduced tillage, prohibition of straw burning) the authors considered the increased organic matter input from cover crops as a main factor underlying this trend. Although cover crop residues are readily mineralized, root derived organic carbon is considered an essential input to the stable fraction with lower turnover times. Cover crop induced stabilization of soil aggregates could enhance physical stabilization of carbon, while deep root growth can increase carbon storage in sub-soils with lower saturation of mineral surfaces with organic matter. These two aspects of carbon cycling are considered essential for C-stabilization and sequestration in soils (Schmidt et al., 2011).

A-1.1.2 Cover crops and greenhouse gas emissions

Estimates by IPCC (2007) and Smith et al. (2008) attribute around 10-12 % of global greenhouse gas emissions to agriculture, with a dominant role of N_2O (60-84 %) and CH_4 (50 %). For Austria Amon et al. (2006) estimate a contribution of agriculture to total greenhouse gas emissions of 8 %, with 36 % from agricultural soil use. Again agriculture is a dominant source for N_2O (61 %) and CH_4 (51 %) emissions. Soil borne N_2O emissions are mainly related to N-fertilization, with estimates of about 1.25 % ± 1 % of total fertilizer N lost via N_2O emission (Moisier et al., 1998). Thus N uptake from soil by cover crops could be assumed to reduce the potential losses and thereby contribute to climate change mitigation from agriculture.

Most studies on cover crop effects on greenhouse gas emission were conducted in the US. Introduction of a winter legume cover crop (hairy vetch) increased both CO_2 as well as N_2O emissions, with a peak of emissions at the onset of the rainy season (Kallenbach et al., 2010). For a non-legume cover crop McSwiney et al. (2010) suggested a decrease on N_2O emissions because of lower excessive N in soil not extracted readily by plant. Liebig et al (2010) compared greenhouse gas emissions from spring wheat after a rye cover crop and fallow. Cumulative fluxes of CO_2, CH_4, and N_2O did not differ between the bare soil and green-manure treatment. Bavin et al: (2009) found an enhanced CO_2 release due to additional fresh organic matter input by a rye cover crop while they did not find significant differences in N_2O emissions between cropping systems with and without a cover crop. N fertilization and fertilizer type were the dominant factors controlling N_2O fluxes. Also Jarecki et al. (2009) observed no significant effect of a cover crop on cumulative N_2O emissions in the field. Also in their study the primary factor influencing N_2O emission was N application rate, regardless of form or timing. Steenwerth and Belina (2008) studied the influence of cover crops (rye, triticale) in a vignyard. Mean daily N_2O efflux was greater in cover crops, but annual N_2O efflux was low as compared to the influence of fertilization. Potential nitrification, N mineralization and denitrification were generally 2-4-fold greater in the cover crop treatments. Among environmental variables, N dynamics was more sensitive to changes in soil water content than temperature. The authors concluded that potential impacts of greater N_2O emissions from cover cropped soils have to be evaluated with reference to other benefits of cover cropping, such as increased soil organic matter content, improved microbiological activity, and N availability. Parkin et al. (2006) evaluated the effect of a rye cover crop on the N balance after pig slurry application and showed that the rye cover crop lowered cumulative N_2O emission in case of high manure application. Rosecrance et al. (2000) compared the N-balance including denitrification for rye, rye-vetch, vetch cover crops with fallow. They showed greater potential N losses from vetch than rye or rye-vetch mixtures due to rapid N-mineralization in conjunction with denitrification and potential leaching, prior to significant N-assimilation by the subsequent main crop. Aulakh et al. (1991) measured N_2O losses from hairy vetch under different water contents in a laboratory study. Denitrification losses were 20-200 µg N kg^{-1} from each soil when 60 % of the soil pore space was filled with water and increased from 14.0 to 18.6 mg N kg^{-1} at 90 % water-filled-pore space. The major denitrification losses occurred during the first 10 days in residue-amended soils. The supply of C from incorporated legume crop residue was a major factor influencing denitrification especially when soil wetness restricted aeration and adequate nitrate was present.

Under subtropical conditions in Brazil, Gomes et al. (2009) measured N_2O emissions in a no-tillage maize system including a grass (Avena strigosa) and different legume cover crops. They found that the system with legume cover crops had largest cumulative emissions, which were directly related to the quantity of N and inversely related to the lignin:N ratio of the cover crop residues. The annual soil N_2O emission represented 0.39-0.75% of the total N added by the legume cover crops.

A literature review showed that there are only very few studies under climatic conditions with frost killed cover crops before winter, soil freezing over winter and high soil saturation in spring after snow melting. A study conducted in Denmark by Petersen et al. (2011) reported slightly higher N_2O emissions from a cover cropped soil (oilseed radish) after freezing events. Still emissions during autumn, winter and early spring were generally low. A peak in emissions occurred in in spring after tillage and organic fertilizer application. Reduced tillage lowered emissions, while there was a positive interaction of conventional tillage and cover cropping. Pattey et al. (2008) investigated N_2O emissions in a pea-cover crop sequence in Canada with particular regard to spring thawing. Total emissions over the one year measurement period were 5.6 kg N_2O-N ha^{-1} with a peak at cattle manure application. Thawing induced emissions were 15 % of the total annual emissions. Emissions during the cover cropping period were mostly influenced by sustained effects of manure application before cover crop seeding. Also Wagner-Riddle and Thurtell (1998) studied the effect of thawing on N_2O emissions in a Canadian field experiment with different management practices. Nitrous oxide emissions between January and April over four years ranged between 0 and 4.8 kg N ha^{-1}. The study indicated that fallowing, manure application and alfalfa incorporation in fall lead to high spring emissions, while the presence of perennial plants (as in their case alfalfa or grass) resulted in negligible emissions during thaw.

Velthof et al. (2002) compared N_2O emissions from different crop residues and influence of NO_3 addition in two soils in an incubation study. For a sandy soil, emissions from residues of wheat, maize and barley were legible, while total N_2O emission from white cabbage, Brussels sprouts, mustard, sugar beet residues and broccoli ranged from 0.13 to 14.6 % of the amount of N added as residue and were higher with additional NO_3 than without additional NO_3. In the clay soil similar ranking of emissions was observed, but the magnitude of the N_2O emission was much smaller than that in the sandy soil: less than 1 % of the residue N evolved as N_2O. The C-to-N ratio of the residue accounted for only 22-34 % and the mineralizable N content of the residue for 18-74 % of the variance in N_2O emission.

Among studies on cover cropping and greenhouse gas emissions published so far, only few were done under comparable climatic conditions to temperate Central Europe. A further shortcoming of most studies is that they did not include different cover crop species or species mixtures. Often cover crops were only part of a system assessment such as reduced tillage and therefore not considered with a higher number of treatments. The laboratory results of Velthof et al. (2002) with different residue types as well as some field studies comparing legumes and non-legume cover crops suggest that there might be substantial differences among species. The work of Velthof et al. (2002) as well as the study of Petersen et al. (2011) indicates a potential increase in N_2O emissions from brassica cover crops.

Therefore it can be conclude from a literature survey that there is still a need for field studies on greenhouse gas emission from different cover crop treatments in temperate environments; particularly during moments that are considered as hot moments with high emission potential (spring thawing, high water content, short after cover crop incorporation).

A-1.2 Study objectives

A re-design of the Austrian agro-environmental programme is currently in preparation in order to adapt to the new requirements and targets of the European agricultural policy and taking into account the evaluation of past agro-environmental programmes.

It is to be expected that future EU agro-environmental funding schemes will request a more explicit consideration of climate change adaptation and mitigation in agriculture. Thus a new regulation of cover cropping must consider impacts specifically related to climate change adaptation and mitigation, beyond the well known benefits for groundwater protection and soil erosion.

In this context an evaluation study of the Austrian ÖPUL programme (Hartl et al., 2010) reported high gaseous N losses from cover crop residues up to 38 % of total N stored in the cover crop biomass. Highest losses were found for mustard, being the most wide spread cover crop species in Austria.

The present study therefore aims to provide data on field soil emission of greenhouse gases from different cover crop treatments compared to bare soil using a standard measurement methodology (“closed chamber method”).

The main objectives are:

(1) To provide an estimate of cover crop related greenhouse gas emission potential in relation to other management effect (tillage, fertilization).

(2) To analyse the different emission potential for commonly used cover crops and cover crop mixtures in Austria with particular regard to the emission potential of mustard.

(3) To evaluate key environmental drivers for greenhouse gas emissions and their relation to cover cropping.

The main hypothesis is that cover crops increase soil CO_2 emissions due to an enhanced input of organic residues, while they reduce N_2O emissions compared to fallow because of reduced nitrate content in the surface soil. This hypothesis is tested within a field experiment at two sites in different climatic regions of Austria.

A-2 Material and methods

A-2.1 Field experiments

Field experiments were established at two sites with different climatic and pedological conditions. A first experiment was located near Lichtenwörth, Lower Austria (47° 49′ N, 16° 16′ O, 254 mAA.). Lichtenwörth is situated in the Southern Viennese Plain near Wiener Neustadt and belongs to the semi-arid climate zone of Eastern Austria. Long-term averages of rainfall are 599 mm, while mean annual temperature is 9.4 °C. The soil at the site is a chernozem soil with sandy loam texture and high content of calcium carbonate. Depth of the humic A_h horizon is 60 cm, overlaying a D horizon of coarse fluvial sediments. The soil is characterized by high water permeability and air capacity.

The second experimental site was located near Pötting, Upper Austria (48° 17′ N, 13° 46′ O, 381 mAA). Pötting belongs to the humid climate zone influenced by north-eastern Atlantic currents. Geographically Pötting forms part of the hilly pre-alpine region. Long term average rainfall is 817 mm and mean annual temperature is 7.9 °C. The soil at the site is a typical stagnosol of silty loam texture and a moderately acidic pH value. Depth of the A_p horizon is 25 cm, followed by a P horizon of 40 cm depth which is periodically water saturated, particularly in spring, due to low permeability of the underlying S1 and S2 horizons.

At both sites experiments were established on farmer's fields with conventional farming machinery as they intended to measure greenhouse gas emission under current agricultural practices. Therefore generally the predominant local practices where followed, while still unifying the main experimental factors at both locations to allow intercomparison of the two experimental sites.

Beside location, experimental factors included (i) cover cropping vs. bare soil after harvest of the preceding main crop (winter wheat at Lichtenwörth, winter barley at Pötting) and (ii) addition of organic fertilizer (30 kg ha^{-1} N) vs. no fertilization to the cover crops. At Pötting additionally (iii) the effect of ploughing cover crops before winter vs. maintenance of cover crop residues at the soil surface was considered.

Cover cropping followed the regulations of the Austrian Agro-environmental programme (ÖPUL) as well as recommendations of local extension services. The ÖPUL programme requires seeding of cover crops before 20th of August and earliest tilling at 15th November (ÖPUL variant A). For ÖPUL variant D, cover crop mixtures of at least two species are required and the earliest allowed date for tillage is 15th February to keep a residue cover as long as possible. Extension services generally recommend advancing of seeding dates as early as possible in order to prolong the available autumn growing period of cover crops. Therefore at both sites, seeding was already done at the End of July, except for mustard at Pötting. The later seeding of mustard (15th August) is due to the photoperiodic reaction of this species inducing early flowering and reduced vegetative growth in case of early seeding. At Lichtenwörth a different mustard species (*Brassica juncea* CZERN.) was used with a lower photoperiodic sensitivity. For this reason here also mustard was sown together with the remaining cover crops at End of July.

Cover crops consisted of four different variants. A first variant was mustard, which is the most common cover crop in Austria and was reported to be at risk for high gaseous N losses. It was sown with a seeding rate of 15 kg ha^{-1} for both mustard species (*Sinapis alba* L., *Brassica juncea* CZERN.). The other cover crops were species mixtures according to ÖPUL variant D. The focus on mixtures was due to the fact that they will be required for all variants according to the draft of the next ÖPUL programme. Mixtures were (i) a commercially available mixture of mustard (*Sinapis alba* L.; 3 kg ha^{-1}) and phacelia (*Phacelia* JUSS.; 7 kg ha^{-1}), (ii) a mixture of cress (*Lepidium sativum* L.; 2 kg ha^{-1}), Mungo (*Guizotia abyssinica* CASS.; 1.5 kg ha-1) and oilseed radish (*Raphanus raphanistrum* L.; 4 kg ha^{-1}), and (iii) a commercially available mixture without *brassica* species and containing a legume, consisting of Alexandrian clover (*Trifolium alexandrinum* L.; 8 kg ha^{-1}), Mungo (1.5 kg ha^{-1}) and phacelia (2.5 kg ha^{-1}).

Organic fertilization before or during cover cropping is a common practice in regions with animal husbandry as well as biogas production. At Pötting organic fertilizer was pig slurry while at Lichtenwörth it was biogas slurry. The total amount of N organic N fertilizers applied before seeding of cover crops was 30 kg ha^{-1}, being the near the permitted maximum N fertilization to cover crops when including legumes according to the ÖPUL programme (35 kg N ha^{-1}).

A first measurement campaign was performed at the end of the cover crop growing period to capture immediate effects at the onset of residue mineralization before winter (22nd November Lichtenwörth, 28th November Pötting). Two further measurement series were done at times with potentially high emissions, i.e. with high soil moisture content and recent thawing of the soil. One such situation occurred at the beginning of February 2013 '(measurement at 1st February at both sites), the next at the beginning of March 2013 (measurement Lichtenwörth at 6th March, Pötting at 7th March), each time with high soil moisture due to previous snow melting and soil thawing.

The experimental plots had a size of 60 m length and 6 m width (360 m^2). In total 10 plots (5 soil cover treatments x 2 fertilization treatments) were established. Measurements were done along a line transect with three equally spaced measurement points per plot (2 m distance), resulting in a total number of 30 measurements per transect. Thus a total number of 180 measurements (3 dates x 2 sites x 30 plots) for most parameters were done.

In a subset of the main experiment additionally (i) the effect of before winter ploughing vs. surface residues remaining until spring tillage, and (ii) greenhouse gas emissions in the subsequent maize main crop was tested. The intention of a continued measurement series was to provide data that allow comparing the cover crop related emissions with emissions due to management measures in the main crop. This experiment was established on the site and plots with high emission potential (humid site, fertilized plots). Half of the experimental plots were ploughed at 16th November while the other half remained without tillage and cover crop residues on the soil surface until tillage before maize seeding on 26th April. Due to analytical constraints only a subset of soil cover treatments consisting of fallow, mustard, and the non-brassica mixture (clover-mungo-phacelia) were considered. Emissions measurements for this subset were performed at the same dates as for the main experiment and thereafter in a time series until end of June with a weekly measurement interval (in total 108 measurements; 18 dates x 3 soil cover treatments x 2 subsamples per plot).

Subsequently the main experiment will be referred as "transect experiment" and to the subset measurements as "time series experiment".

A-2.2 Measurement methods

A-2.2.1 Greenhouse gas measurements

Measurements of greenhouse gas emissions from the soil were done using the closed chamber method (e.g. Rochette et al., 1992). PVC cylinders of 10 cm height and 20 cm diameter were inserted into the soil to a depth of about 3 cm. This gives in a volume of 2200 cm^3 where changes in greenhouse gas concentration over time were measured. The cylinders were closed airtight with a lid which contained a rubber septum from which the gas samples were collected by a syringe of 30 ml sampling volume. Before extracting a sample the gas volume in the cylinder was mixed thoroughly via repetitious aspiration of the syringe to avoid that all gases heavier than air accumulate at the soil surface. Three samples per cylinder were taken over time, one immediately after closing the chamber, representing the initial concentration, a second after 15 minutes and a third after 45 minutes. Finally the gas samples were injected in evacuated cups and transported for further analysis to the laboratory. Analysis of greenhouse gas concentration (CO_2, N_2O and CH_4) was done by gas chromatography in the laboratory of the Institute of Soil Sciences of the University of Natural Resources and Life Sciences. Gas flux (µg resp. mg m^{-2} h^{-1}) was calculated from the change in gas concentration over time.

A-2.2.2 Plant biomass and CN ratio

At the end of November, coincident with the first greenhouse gas measurement, aboveground biomass samples of cover crops were taken. One square meter was cut, predried at 50°C and thereafter dried for 24 hours at 105°C to constant weight to determine dry matter. After weighing the samples, they were milled and analysed for carbon and nitrogen content of the biomass. Each of the 24 biomass samples per site was further sub-divided into two subsamples to get a better mean. CN analysis was done with a Carlo Elba CNS Elemental analyser in the laboratory of the Department of Crop Sciences.

A-2.2.3 Soil water content and soil temperature

Soil water content and soil temperature were measured with a Vitel Hydra Probe that simultaneously measures both parameters. The probe was connected to a hand held data logger. Conversion of the registered dielectric constant to volumetric soil water content was done by an equation given by the customer.

When evaluating soil temperature measurements it was noticed that in some cases the temperature sensor was not inserted sufficiently long into the soil to equilibrate with soil temperature, particularly for the first measurements in the transect. Therefore only an average of all measurements for each date was used without analysing treatment effects that might have been biased by a systematic error. For soil water content no equilibration time with soil is required and data inspection did not reveal any systematic error (e.g. from inappropriate soil-sensor contact). Thus treatment effects and treatment specific causal relations could be tested for this parameter.

A-2.2.4 Soil mineral N and dissolved organic carbon

Soil mineral N (N_{min}) and dissolved organic carbon (DOC) are two important soil parameters related to greenhouse gas emissions. In the case of N_2O, NO_3 constitutes an electron acceptor under (locally) anaerobic conditions, while DOC is an easily decomposable (oxidation) energy supply to the relevant soil microbial communities. Beside the direct relation of DOC to the process of soil borne greenhouse gas formation, DOC has been shown to be a particularly sensitive indicator for agricultural management impacts on soil organic matter dynamics and thus appropriate to study short term cover crop effect.

Soil samples for N_{min} and DOC were taken from surface near soil (0-5 cm) when greenhouse gas measurements were done. N_{min} samples were frozen before analysis while DOC samples were air dried. Analysis of N_{min} was done following ÖNORM L1091 after extraction of the sample with calcium chloride and photometric determination of N content in the solution.

DOC was determined for selected samples only due to limited analytical capacity. A mixed sample (mixture of three replicate samples; 10 samples per site) of each treatment was analysed for the first measurement date as expected most evident differentiation in DOC was expected immediately after the cover crop vegetation period. A second set of DOC analysis was made for those measurement dates when highest N2O emissions were registered, i.e. the 1st February at Lichtenwörth and the 7th March at Pötting. Again a mixed sample for each treatment was made. Analysis was done by infrared spectroscopy after extraction of the samples by deionized water.

A-2.3 Statistical data analysis

Establishment of the experiments at farmer's fields and use of common agricultural machinery did not allow a design with randomized plots for replication. Therefore measurements were done along an equally spaced line transect with three replicate measurements in each plot which were located at a common distance of 2 meter between each measurement point. All parameters were sampled at the same position with only small shifts in the longitudinal direction in case of destructive sampling. This sampling arrangement allowed testing spatial correlation (trends) between the data points via autocorrelation analysis. In case of significant spatial correlation, further explanatory data analysis could be done via cross-correlation and state-space-models. The existence of treatment effects would have been detected via a significant autocorrelation over a lag distance of three (i.e. between measurement points in a plot with the same soil cover and fertilization treatment). If no spatial correlation between sampling points could be identified, the three neighbouring sampling points in each plot could be considered as independent from each other and in this case analysis of variance would be feasible without being bias by a soil trend.

Generally no significant soil trend in the measurement parameters was discovered. Particularly greenhouse gas measurements were clearly spatially uncorrelated. It is well known that particularly those emissions related to anaerobic conditions can show very small scale variability due to anaerobic micro-sites in the soil (e.g. Parkin, 1987). Thus the 2 meter distance between measurement points was beyond a possible spatial correlation.

Thus wall data were treated as spatially independent and subject to an analysis of variance to test for treatment effects. Dates were treated as repeated measures and analysis of variance was consequently done using a mixed model with an unstructured correlation structure of the repeated factor (Piepho et al., 2004).

Another analytical method used to highlight treatment effects for the greenhouse gas emissions was joint regression analysis. This technique originates from plant breeding to reveal a distinct variety response in different environments (e.g. Annicchiarico, 1997). Environments are characterized as the overall mean of a given parameter and are plotted against treatment means. For this analysis the two sites were pooled together, thereby defining six "environments" (2 sites x three measurement dates) from low to high emission potential. Then regression analysis of soil cover treatment means vs. the overall mean for each environment was applied.

Finally regression analysis was performed to analyse any causal relations between plant environmental variables (plant CN ratio, soil water content, soil temperature, N_{min}, DOC) and greenhouse gas emissions.

All statistical analyses were done using SAS 9.1 with PROC MIXED for analysis of variance and PROC REG for regression analysis. Autocorrelation was analysed within the time series viewer of SAS.

A-3 Results and discussion

A-3.1 Environmental conditions

The main measurement period of greenhouse gas emissions at the two experimental sites was between November 2012 and March 2013. Figure A-1 shows the monthly averages of precipitation and temperature for the cover crop growing period (July 2012-December 2012) and the following winter and spring months when gas flux measurements were done.

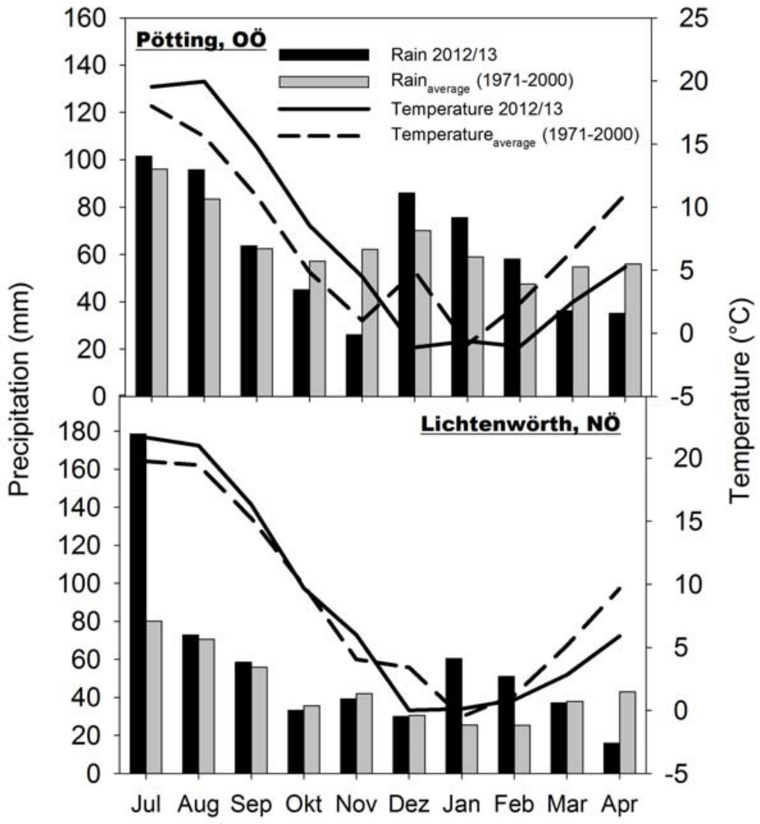

Fig. A-1: Monthly average of precipitation and air temperature at the measurement sites compared to long term average values.

At Pötting, the sum of rainfall between July 2012 to April 2013 was slightly lower (623 mm) compared to the long-term average (648 mm). At Lichtenwörth on the contrary, there was substantially higher total precipitation (577 mm) compared to the long-term average (447 mm) which was mainly due to very high rainfall in July 2012. July rainfall is crucial for cover crop establishment, particularly in semi-arid regions with higher probability of summer drought that might delay cover crop emergence.

Temperature at both sites was higher during the cover crop growing period in autumn, while spring was characterized by substantially lower temperatures compared to the long-term average. Over the whole measurement period, temperatures were slightly lower than the long-term average.

Figure A-2 shows the range of soil temperature and soil water content at the times of measurement of gaseous emissions for the transect experiments (Fig. XX).

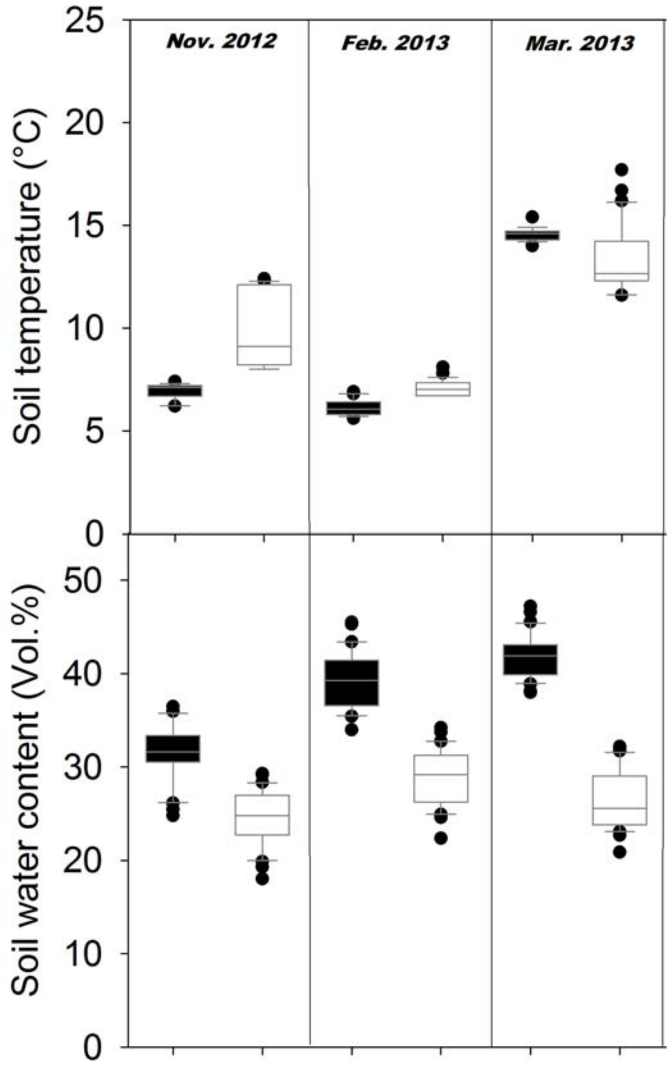

Fig. A-1: Boxplots of soil temperature and soil water content. Black boxes are for the humid site (Pötting, OÖ), while white boxes are for the semi-arid site (Lichtenwörth, NÖ).

As expected, soil temperature was generally lower while water content was higher at the humid compared to the semi-arid site. At Pötting soil temperature ranged from a minimum of 6.2°C in February 2013 to a maximum of 15.4°C in March 2013, soil water content ranged from a minimum of 24.8 Vol.% in November 2012 to a maximum of 47.2 Vol.% in March 2013. At Lichtenwörth the minimum of soil temperature was also registered in February 2013 (6.7 °C) and the maximum in March 2013 (16.7°C). The range of soil water content at Lichtenwörth was between 18.0 Vol. % in November 2012 and 34.4 Vol. % in Februar 2013. Thus the different environmental conditions (climate, soil) at the two sites were reflected clearly in the average conditions during gas flux measurement.

Soil temperature and soil water content over the continued time series at the humid, high emission site Pötting are shown in Figure 3. Soil temperature increased to a maximum of 27.5 °C (9^{th} June 2013) and the range of water content during the time series measurement was from a minimum of 12.4 Vol. % (28^{th} April 2013) to a maximum of 47.6 Vol. % (5^{th} May 2013).

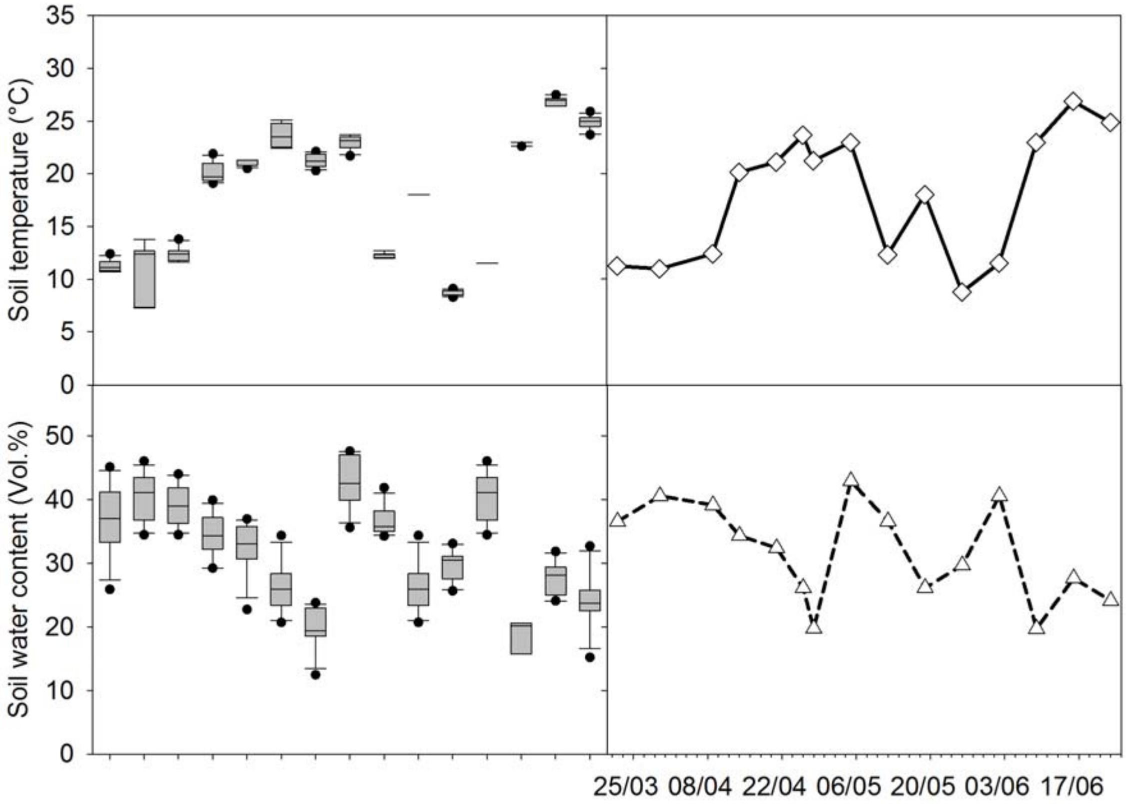

Fig. A-3: Boxplots and time course of mean values of soil temperature and soil water content for the time series at the humid site at Pötting.

Two variables related to the formation of soil greenhouse gas emissions are soil mineral nitrogen (NO_3) as an electron acceptor for N_2O during anaerobic conditions and easily decomposable organic carbon as substrate for soil microorganisms. An appropriate indicator for this fraction of organic carbon is dissolved organic carbon (DOC). The range of both variables is shown in Figures A-4 and A-5.

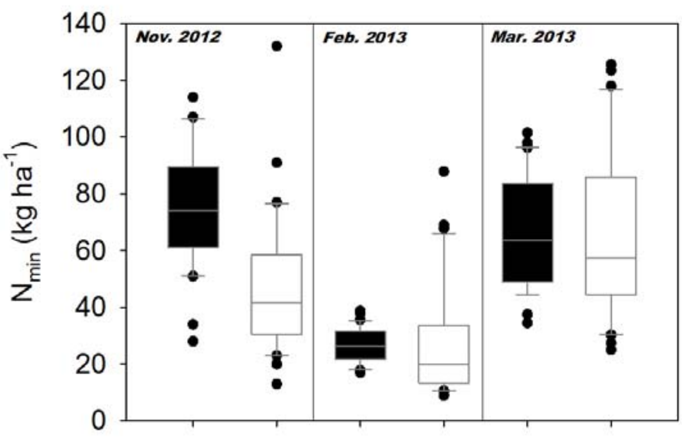

Fig. A-4: Boxplots of soil mineral nitrogen (Nmin) at the two measurement sites. Black boxes are for the humid site (Pötting, OÖ), while white boxes are for the semi-arid site (Lichtenwörth, NÖ).

For soil mineral nitrogen the two sites differed mostly in late autumn 2012 at the end of the cover crop growing period. At this time values at the humid site were 37.7 % higher compared to the semi-arid site. Although there was a higher N_{min} content already before cover crop seeding in July 2012 (85 kg ha^{-1} vs. 104 kg ha^{-1}), the differentiation increased during the cover crop growing period, indicating a more efficient nitrogen remediation for the semi-arid site at this year.

In late winter before onset of spring mineralization, the average N_{min} was similar at both sites and also in early spring there were no substantial differences. Still it should be noticed that the range of values at the semi-arid site at the two spring measurement dates was always higher. This could be related to higher differentiation in the mineralization dynamics of cover crop residues due to higher soil temperature.

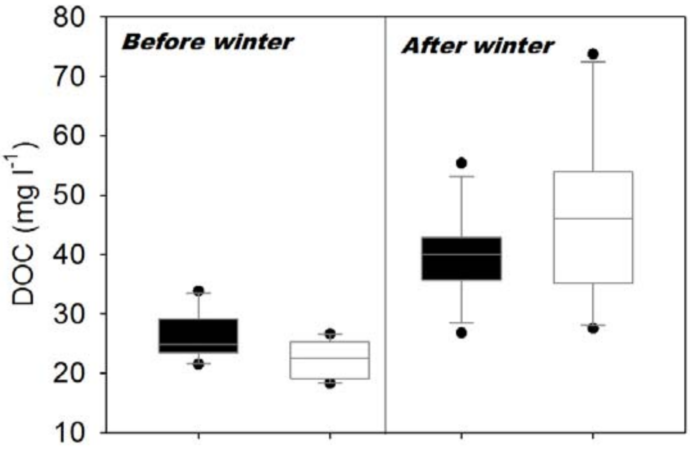

Fig. A-5: Boxplots of dissolved organic carbon (DOC) at the two measurement sites. Black boxes are for the humid site (Pötting, OÖ), while white boxes are for the semi-arid site (Lichtenwörth, NÖ).

DOC was only measured twice, once before winter at the end of cover crop growth and once after winter when highest N_2O emissions were registered. Values increased between late autumn and early spring, indicating the onset of mineralization at the second measurement date. Values were in a similar range at the two sites with slightly higher DOC concentration before winter at Pötting, and after winter at Lichtenwörth.

A-3.2 Cover crop growth

The focus of the study was the influence of different cover crops compared bare soil on greenhouse gas emissions. Figure 6 shows cover crop dry matter at the two sites at the end of the autumn growing period as well as the CN ratio of cover crop biomass. There was a significant interaction between site and surface cover treatment, while CN ratio showed only significant site and crop main effects. Details on N uptake are not reported here which was proportional to total dry matter (Ø 83 kg N ha^{-1} at Pötting and 108 kg N ha^{-1} at Lichtenwörth).

Cover crops achieved a relatively high dry matter at both sites. Literature gives values of around 4000 kg ha^{-1} dry matter (e.g. Lütke Entrup, 2000). In average Lichtenwörth showed higher cover crop dry matter which is related to higher temperatures during the cover crop growing period. In the experimental year there was no water limitation particularly during the early growing period at the semi-arid site. After a quick establishment of the cover crop stand plants could optimally use the higher availability of growing factors (radiation, temperature). At Pötting the autumn vegetation period is shorter and growth is more strongly limited in autumn by low temperatures and lower photosynthetic active radiation.

At the Lichtenwörth site, mustard and the mixture of cress, Mungo and oilseed radish had highest dry matter, while the mustard-phacelia mixture and the mixture of Alexandrian clover, Mungo and phacelia were at similar lower level. At Pötting on the contrary mustard had lowest dry matter while all other cover crops were at a similar level. This is obviously related to the later sowing of mustard in this region.

CN ratio was lowest for mustard and highest for the mustard-phacelia mixture. Also here the later sowing of mustard was probably decisive, leading to less lignification of plant tissues. The mustard species used at the semi-arid site had a later maturity and therefore also a lower CN ratio of the final biomass. In average the semi-arid site showed a significantly higher CN ratio of biomass indicating that in average plant development was more advanced at this site at the end of November at sampling.

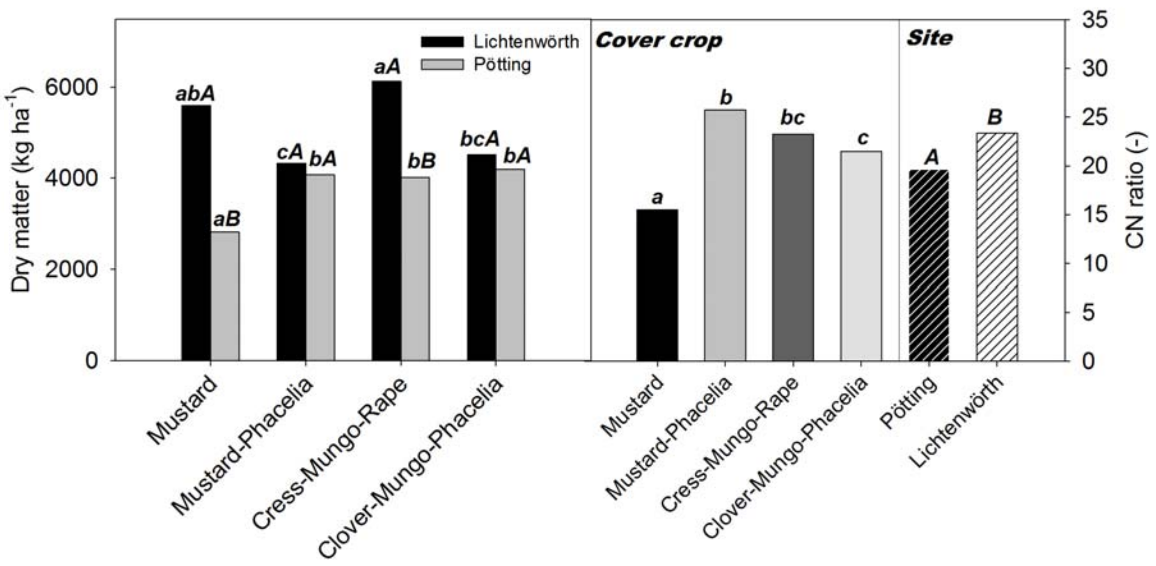

Fig. A-6: Cover crop dry matter and CN ratio at the two experimental sites. Significant differences for p<0.05 between sites are indicated by upper-case letters, while differences between cover crop species at one site (dry matter) and average species differences (CN ratio) are indicated by lower-case letters.

A-3.3 Range of greenhouse gas emission potential

Similar to environmental conditions (A-3.1) first the range of greenhouse gas emissions at each sampling date during the measurement period is reported. This should indicate the different emission potential between dates and sites. It also reveals the high small scale variability of soil greenhouse gas emissions that has been described in several studies (e.g. Partkin, 1987; Rochette et al., 1991).

Figure A-7 shows the box-plots from the three measurement dates for the transect experiment at both sites, while -Figure A-8 shows box-plots for the subsequent time series at Pötting. N_2O emissions were generally low. The median of values was near zero in all cases. The highest emission value at Pötting was registered in March 2013 (31.4 mg m^{-2} h^{-1}). At the Lichtenwörth site the highest emission was measured in February 2013 (46.6 mg m^{-2} h^{-1}). The two dates are coincident with highest average water content measured at both sites.

CO_2 emissions were higher at Pötting compared to Lichtenwörth which might be related to higher humus content of the A horizon at the finer textured soil at Pötting. It is obvious that at Pötting there is a stronger influence of measurement date with a clear depression of CO_2 emissions in February 2012. During February lowest soil temperatures were registered and thus reduced microbial activity can be expected compared to the other measurement dates.

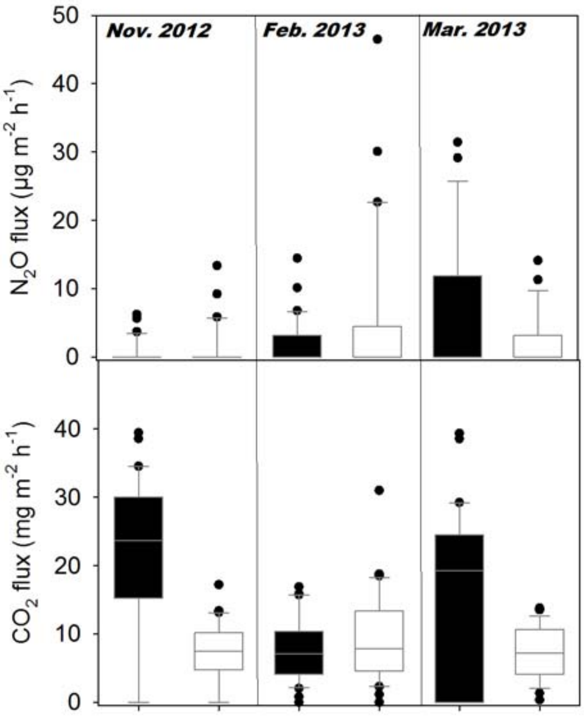

Fig. A-7: Boxplots of N_2O and CO_2 emissions from soil at the two measurement sites. Black boxes are for the humid site (Pötting, OÖ), while white boxes are for the semi-arid site (Lichtenwörth, NÖ).

Figure A-8 shows the range of emissions for the time series at Pötting. Also CH_4 emissions are reported here as there were some dates with emissions differing from zero. It should be noticed that the y-axes for N_2O is drawn on a logarithmic scale, which indicates the high temporal variability for this trace gas. CO_2 and N_2O emissions showed a common increase to a first emission peak at 5th May after organic fertilizer application (21st April 2013) and tillage before maize seeding (26th April 2013). For CO_2 emissions a second peak occurred at 16th June which is coincident with a marked increase in soil temperature. For N_2O a second peak can be seen at 2nd June. In this case we suggest that both near saturated soil water content and concomitant high soil temperature explain this emission peak. Also CH_4 had a peak at this date which indicated that under certain environmental conditions there is also an emission potential for this trace gas in temperate soils. For the first CH_4 peak at 30th March a straightforward explanation cannot be provided.

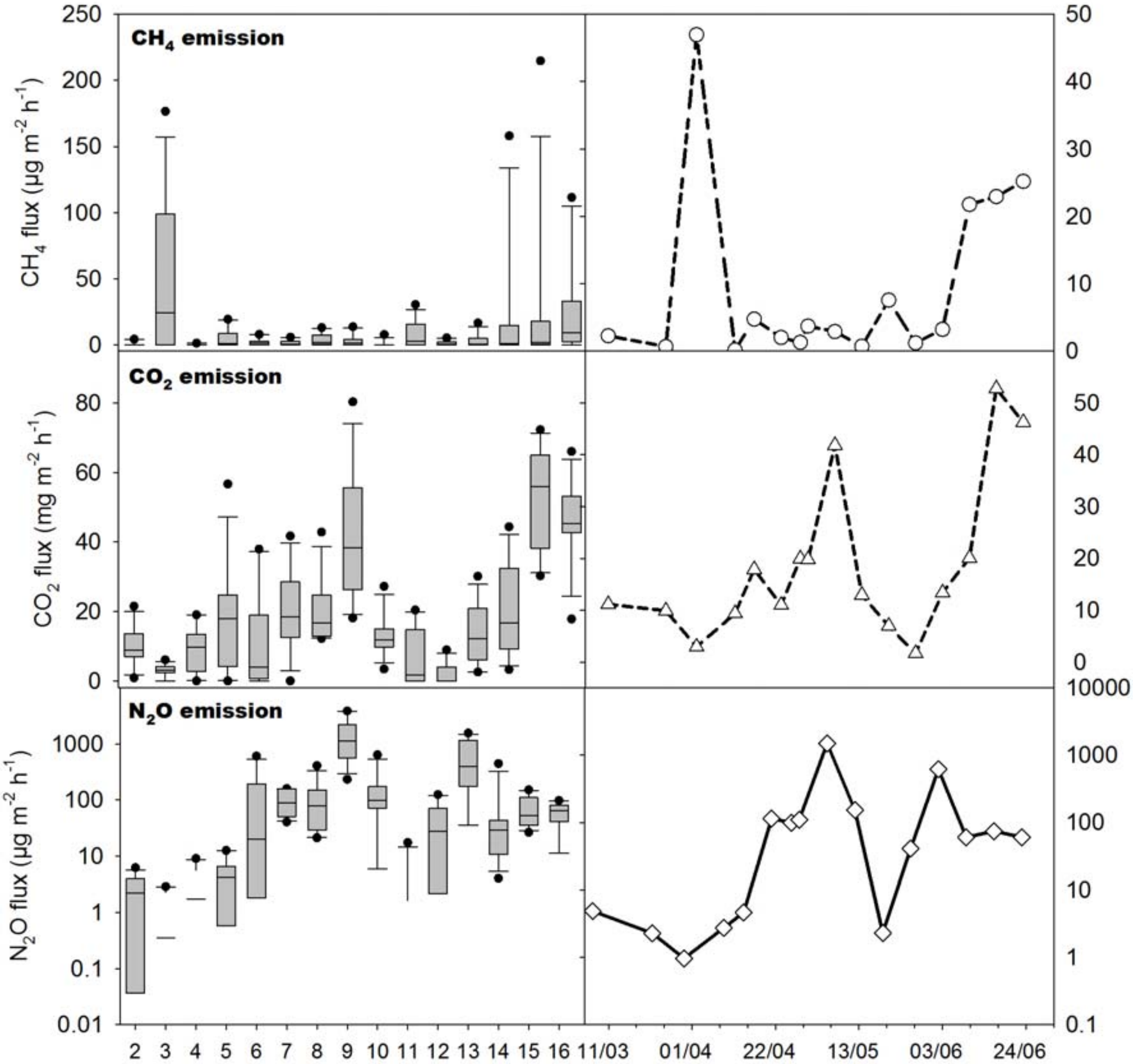

Fig. A-8: Boxplots and time course of mean values of trace gas emissions from soil for the time series at the humid site at Pötting.

A-3.4 Cover crop influence on greenhouse gas emissions and related soil parameters (soil water content, N_{min}, DOC)

After having described environmental (climate, soil) conditions as well as the range of the measured parameters, now results from analysis of variance are reported, testing for significant treatment effects (site, soil cover type, fertilization) on the measured parameters, particularly on greenhouse gas emissions. For all parameters there was a significant influence of the different sites. Thus in all cases treatment effects will be shown separate for the two sites.

A-3.4.1 Greenhouse gas emissions

Figure A-9 shows the influence of different cover crops and fallow on N_2O and CO_2 emissions of the transect experiment. For the semi-arid site only CO_2 emissions showed a highly significant cover crop effect ($p<0.0001$), while differences in N_2O flux were non-significant. For the humid site Pötting, both, N_2O ($p=0.0350$) as well as CO_2 ($p=0.0072$) emissions showed a significant cover crop effect. For N_2O both sites showed highest emissions from the soil after a mustard cover crop. Still statistical significance of this finding could only be demonstrated at the humid site. At Lichtenwörth, cover crop treatments including brassica species were higher compared to the non-brassica mixture and bare soil. Also in Pötting the non-brassica mixture had lowest N_2O emissions among cover crops. However, differences to the other variants except mustard were non-significant.

Concerning CO_2, fallow had lowest emissions at both sites as expected. After an additional input of organic carbon from cover crops, these plots showed significantly higher emissions. Among the cover crops, the non-brassica mixture (Clover-Mungo-Phacelia) had lowest CO_2 emissions among all cover crops. Also a significant difference in CO_2 response to fertilization at both sites should be mentioned. While Lichtenwörth did not show a significant fertilizer effect (+ fertilizer: 7.3 mg m^2 h^{-1} –fertilizer: 8.4 mg m^2 h^{-1}), at Pötting fertilization significantly increased average CO_2 emission (17.0 mg m^2 h^{-1} vs. 13.2 mg m^2 h^{-1}). Fertilizer effect on N_{min} values did not explain these differences as fertilization increased N_{min} in upper soil layers only slightly at both sites with even higher differences in Lichtenwörth (24.8 % increase vs. 7.2 % at Pötting). Also average DOC values measured in November did provide an explanation. Other possible effects of different fertilizer quality could not be tested from these data.

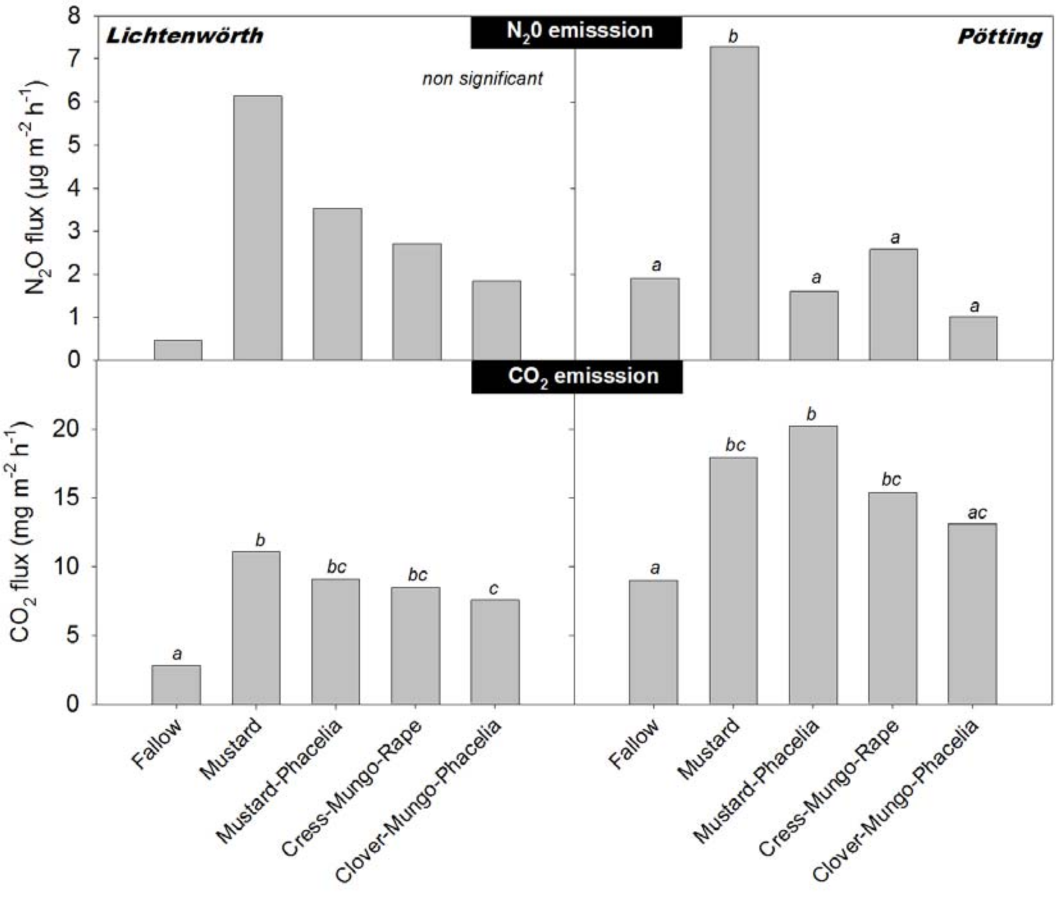

Fig. A-9: Greenhouse gas emissions (N_2O and CO_2) from different cover crop treatments and fallow at two climatically different sites. Treatments sharing a common lower-case letters do not differ significantly ($p<0.05$) among each other.

ANOVA results for the time series at Pötting are shown in Figure A-10. For N_2O significant differences between cover crop treatments coincided with the date of organic fertilizer application (21st April) and the date of high emission potential due to soil moisture near saturation (4th June). At 21st April there was a clearly lower emission from the mustard treatment compared to fallow and clover-Mungo-phacelia mixture. On 4th June mustard had significantly higher emissions compared to clover-Mungo-phacelia, while fallow had intermediate emissions. Generally it can be observed that until tillage on 28th April mustard was at the lower end of emissions, while afterwards it was at the higher end. This might be related to a distinct mineralization dynamics from the other treatments that are enhanced by organic fertilizer application and tillage.

For CO_2 emissions differed significantly between 14th April and 5th May (except 28th April) as well as at 9th and 23rd June. Again the first period of significant differences coincided with a change in the ranking between treatments, with mustard having lowest emissions before fertilizer application and tillage (14th April) and thereafter changing position with the fallow treatment. Bare soil thereafter was mostly lowest in its CO_2 emissions, which was also statistically significant at 9th June. At the last measurement date (23rd June) the clover-Mungo-phacelia mixture had lowest emissions while mustard was at the upper end and fallow had an intermediate position. A straightforward explanation for the abrupt change of the mixture between 16th and 23rd June can not be given from these data.

Ploughing of cover crops before winter effected N_2O emissions significantly only at the first measurement date after the tillage intervention on 28th November 2012 with increasing emissions (ploughing: 17.0 mg m^2 h^{-1}, no ploughing: 5.3 mg m^2 h^{-1}) and on 16th June 2013 when the ploughed treatment had significantly lower emissions (ploughing: 48.9 mg m^2 h^{-1}, no ploughing: 100.1 mg m^2 h^{-1}). In the first case an increased N and C release by tillage enhanced mineralization is suggested that might have led to denitrification at anaerobic micro-sites in spite of soil loosening. The reason for the differentiation on 16th June is unclear.

As mentioned above, there were some dates with CH_4 emissions differing from zero. Still at most dates there were no clear treatment effects and values showed very high variability. Only at the last measurement date (23rd June) there was a significant interaction between cover crop treatment x tillage (p=0.0019) which is shown in Figure A-10. Here the treatment which was ploughed before winter had substantially higher emissions for the cover crop mixture compared to all other treatments.

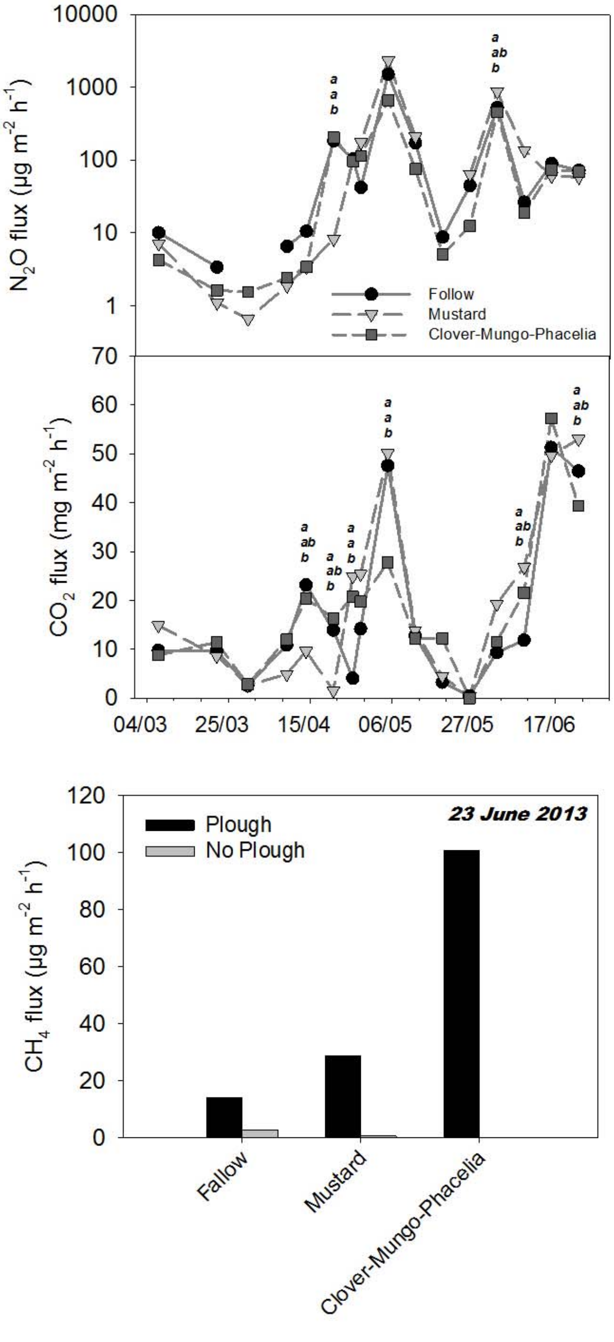

Fig. A-10: Greenhouse gas emissions (N_2O, CO_2, CH_4) from different cover crop treatments and fallow at different dates for the humid experimental site at Pötting. Significant differences ($p<0.05$) are indicated by lower-case letters.

In order to highlight differences in potential emissions among treatments joint regression was used. Figures A-11 and A-12 show the average emission potential on the x-axis and the corresponding emissions of the single treatments on the y-axis.

For N_2O application of organic N-fertilizer to the cover crops resulted in higher emission over the whole range of emission levels. However there was a trend to amore pronounced N-fertilization effect in case of high emission potential.

For the different cover crops there is a clear difference of mustard that leads to substantially higher emissions compared to the other treatments in high emission environments.

There seems to be also a slight tendency of the fallow treatment to higher emissions in case of increasing emission potential compared to the remaining cover crop treatments.

It is suggested that a major reason for the substantially higher N_2O emissions for mustard is related to the decomposition of glyscolinolate which is a compound of this cover crop. Furthermore lowest CN ratio of mustard biomass (cf. Fig. A-6) in these experiments may have contributed to higher emissions. All relevant environmental parameters (N_{min}, DOC, soil water content; cf. Fig. A-13 and A-15) did not show a sufficiently clear distinction from the other variants to explain the higher denitrification losses of mustard. Glucosinolate content is about 1 % of fresh weight, with composition and content varying between plant organs and with plant age (Fahey et al., 2001). During decomposition of the mustard glucosinolate sinigrin, allylisothiocyanat and $SO4^{2-}$ are formed. Gucose is subject to fermentation under anaerobic conditions, further lowering oxygen content. In this process H_2S is formed, further lowering the soil redox potential and acting as a bactericide, thereby providing additional substrate for anaerobic decomposition (Fahey et al., 2001, Mentler, personal communication). Thus several aspects in this process (oxygen consumption, lowering of rH, and addition of easily decomposable substrate) increase the process of denitrification beyond other residues under similar environmental conditions.

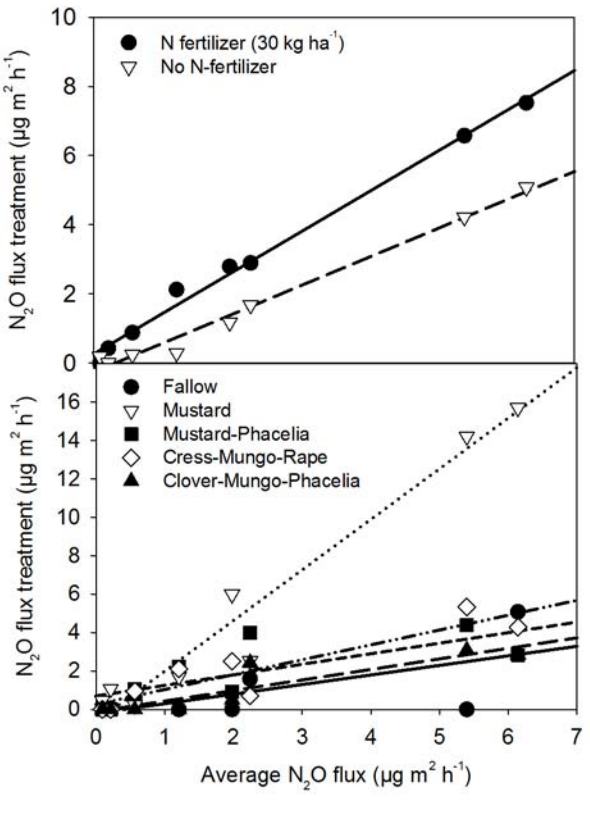

Fig. A-11: Joint regression analysis of N_2O emissions for different cover crops compared to fallow.

Figure A-12 shows the joint regression for CO_2. Again there was a trend of higher CO_2 emissions under conditions of higher emission potential for the fertilized treatment.

Comparing the soil cover treatments, fallow had lowest emissions over the whole range of emission potential, with differences to cover crops increasing towards high emission conditions. Also differences among the cover crop treatments became more evident at high emission scenarios, with mustard-phacelia mixture at the top and the clover-mungo-phacelia mixture at the lower end.

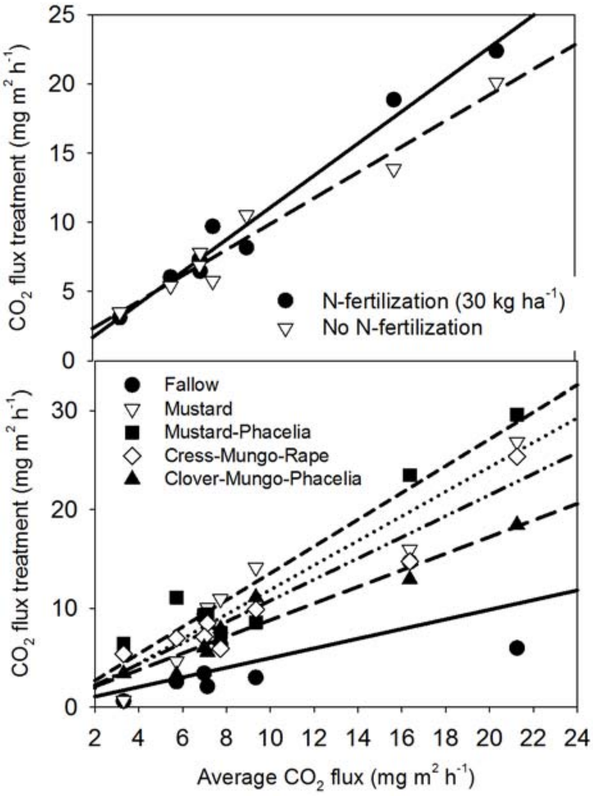

Fig. A-12: Joint regression analysis of CO_2 emissions for different cover crops compared to fallow.

A-3.4.2 Soil water content, N_{min} and DOC

Figure A-13 reports effects of different soil cover treatments on soil water content and Nmin at the dates of greenhouse gas measurement (ANOVA showed significant site x date x cover crop interaction with p=0.0365 for soil water and p=0.0003 for N_{min}).

Interestingly at the semi-arid site fallow had always the lowest surface near water content, indicating a dominant water saving effect from residue cover compared to the water consumption during active cover crop growth for the surface near soil layer. Most distinct differences between fallow and cover crops can be seen in February at Lichtenwörth. At the humid site, differences were less obvious which is related to higher precipitation equilibrating the mulch cover induced differences in surface near soil water content.

Differences in N_{min} showed the reduction of soil nitrogen by cover crops before winter. Cover crop effects were more evident at the semi-arid site. The lower N_{min} for fallow in February at the semi-arid site is probably related to higher N-leaching to deeper layers. The increase in N_{min} between February and March indicates the onset of spring mineralization with highest values for bare soil and mustard and lowest for the non-brassica mixture. Interpretation of distinct spring mineralization dynamics between variants however is complicated from these data and should be done with care.

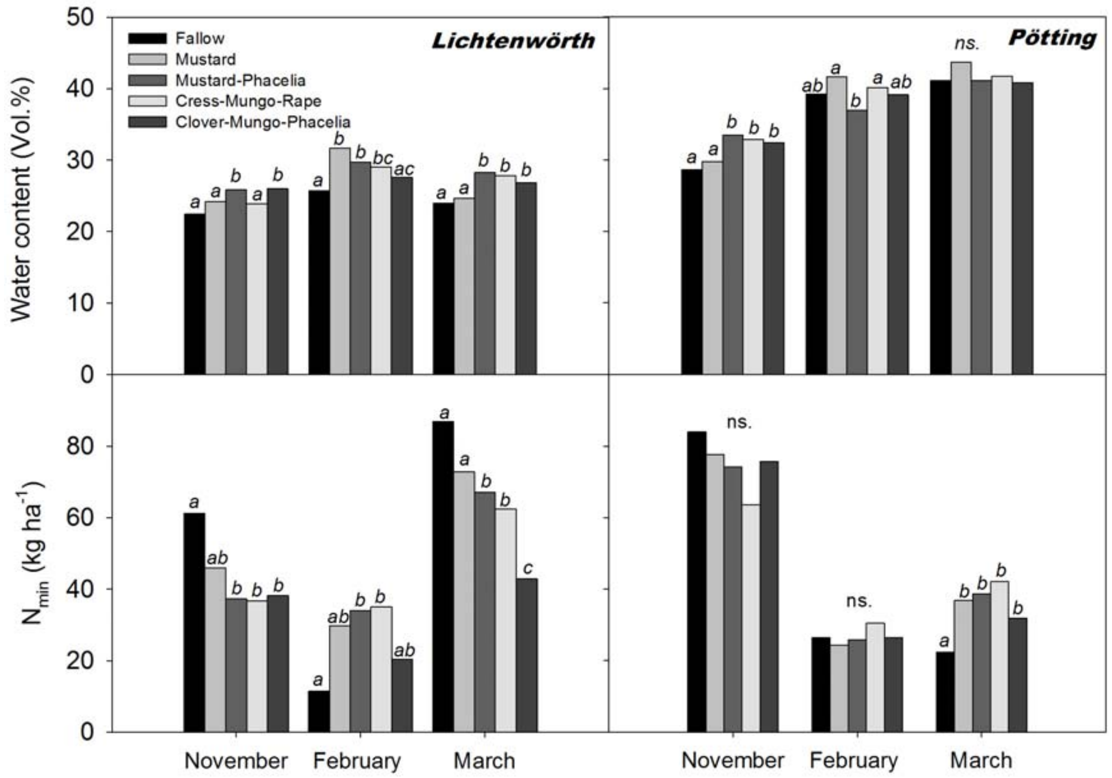

Fig. A-13: Soil water content and N_{min} from cover cropped and fallow soil at different measurement dates and at two climatically different sites. Significant differences between treatments at each measurement date ($p<0.05$) are indicated by lower-case letters.

Figure A-14 shows soil water for the time series at Pötting. It is difficult to identify a consistent patter of differentiation between treatments. Differences seem to become more evident at higher water contents and generally lower over time. In average the clover-Mungo-phacelia mixture had a slightly higher water content (32.6 Vol.%) compared to the other treatments (31.7 Vol%).

Significant differences between ploughing of cover crops before winter and surface mulching could be found. Interestingly the mulch treatment had a slightly lower water content compared to the ploughing. Visual observation indicated a slower rainfall infiltration and frequent occurrence of stagnant water in the ploughed treatment which was related to a more pronounced micro-relief at the soil surface after ploughing. As mentioned above, the mulch effect had obviously less importance for surface near water content at this site compared to a semi-arid site.

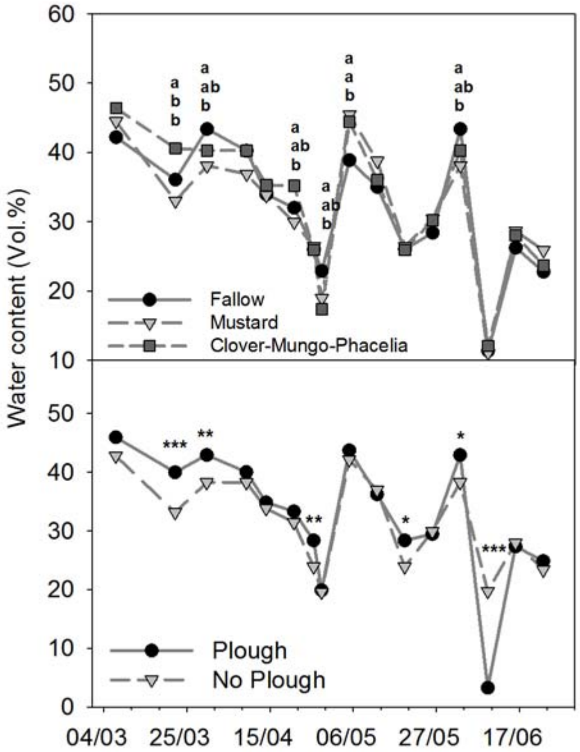

Fig. A-14: Soil water content at different measurement dates at Pötting for two cover crop treatments and fallow soil as well as for ploughing vs. residues remaining at the soil surface. Significant differences between cover cropping vs. fallow at each measurement date ($p<0.05$) are indicated by lower-case letters, differences between tillage treatments are indicated by asterisk (*** $p<0.001$, ** $p<0.01$, * $p<0.05$).

Finally also DOC content of the soil measured at the end of the cover crop growing season (Fig. A-15) is shown. Analysis was done with a mixed sample of each plot, so no statistical evaluation could be done. For both sites the unfertilized treatment showed higher DOC content compared to the plots having received N-fertilizer. Among soil cover treatments a consistently higher DOC content for the cover cropped plotscould be observed at Pötting, while at Lichtenwörth the DOC level was similar for all treatments, although fallow had the lowest DOC content too.

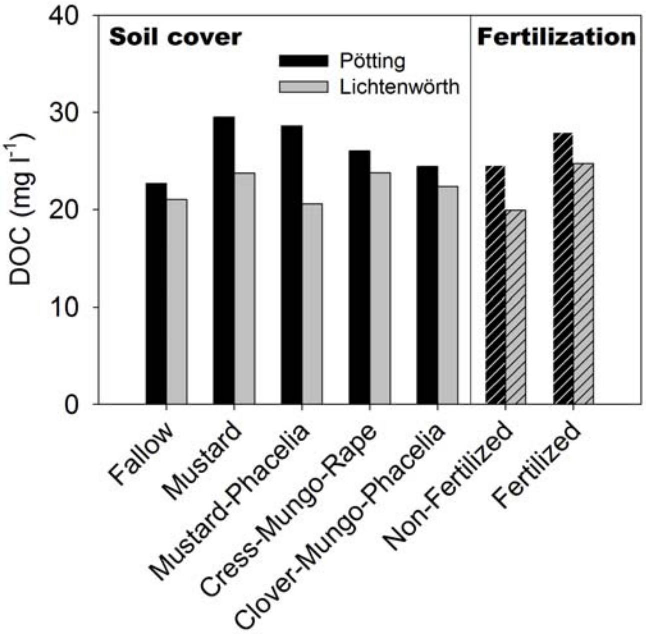

Fig. A-15: Dissolved organic carbon in soil following different cover crops and fallow as well as for organic N-fertilizer addition to cover crops vs. unfertilized cover cropping. Samples were taken at the end of the cover crop growing season (28th November 2012) at two climatically different sites.

A-3.5 Driving factors of soil greenhouse gas emissions

In the present study selected plant and environmental variables were registered at the time of greenhouse gas measurements. The objective was to find out crucial variables underlying greenhouse gas emission from soil in a cover cropped field. It should be noticed that for some variables, analysis was done only for selected sampling points (DOC) and in one case (soil temperature) sensor problems only allow an evaluation for the time series.

Figures A-16 and A-17 show the regression for N_2O flux with soil water content and DOC concentration. At both sites a significant positive relation between these variables could be found. As expected a higher soil water content generally induced higher emission potential. At Lichtenwörth the relation to soil water content was best described by a linear equation, while at Pötting there was a strongly exponential relation between both variables with a strong increase in N_2O emissions at a water content higher 40 Vol. % (> 80 % water filled porosity).

Also the relation between DOC and N_2O emissions was significant at both sites, although r^2 was quite weak at Pötting. It is interesting to note that coefficients in the linear equation for both sites are very similar, particularly the slope parameter. This indicates that there might be a unique causal relation between these two parameters.

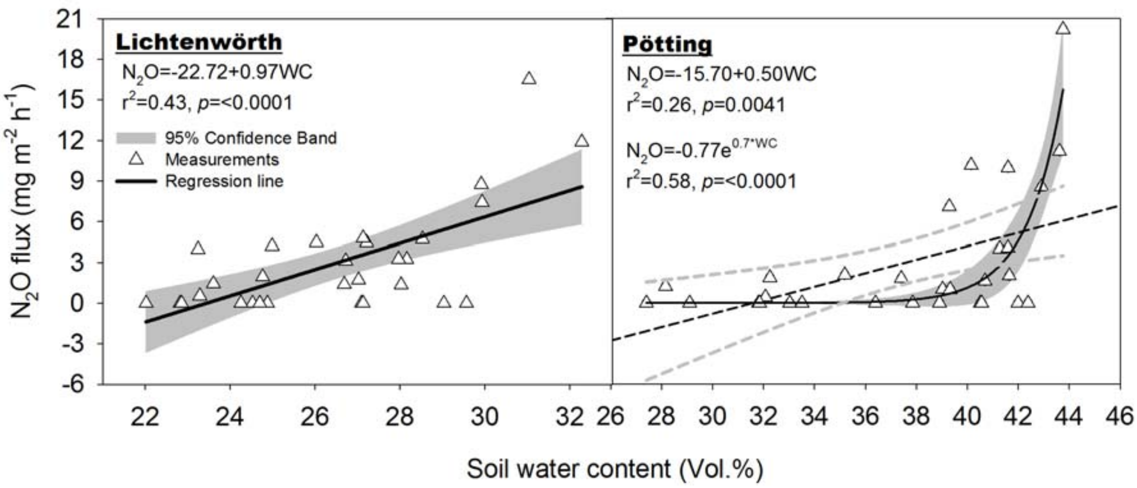

Fig. A-16: Regression relation between soil water content and N_2O emissions at a semi-arid (Lichtenwörth) and a humid (Pötting) site.

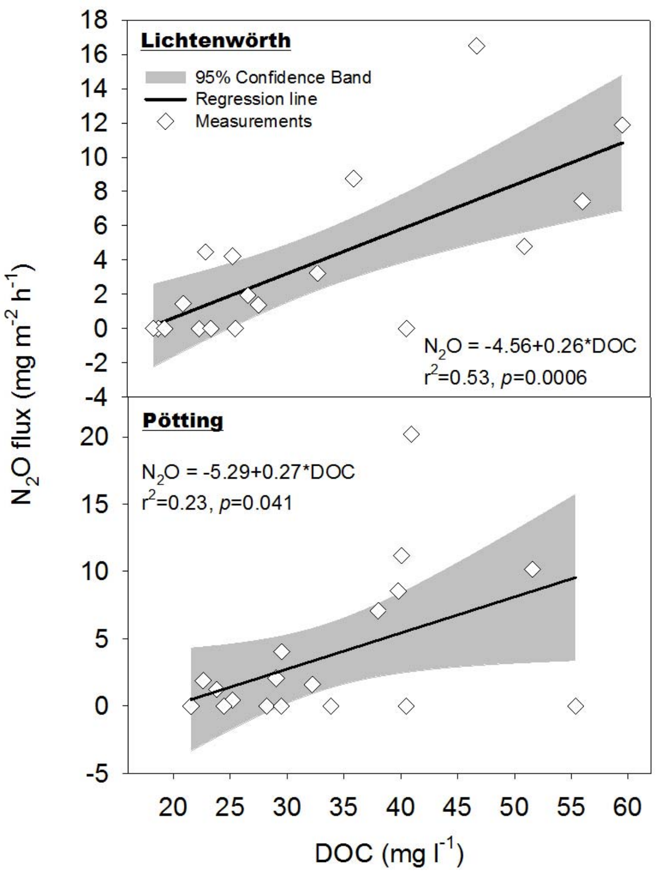

Fig. A-17: Regression relation between dissolved organic carbon and N2O emissions at a semi-arid (Lichtenwörth) and a humid (Pötting) site.

For CO_2 emissions only at the semi-arid site significant relations to environmental variables were found, i.e. soil water content and DOC (Fig. A-18). In both cases r^2 was rather low, indicating that other indicators might be required (e.g. soil microbial activity) to better capture causal factors for CO_2 emissions. Still it can be considered that DOC is a key factor that should be integrated in further analysis as it seems both sensitive to short term effects of cover crops as well as related to greenhouse gas emissions.

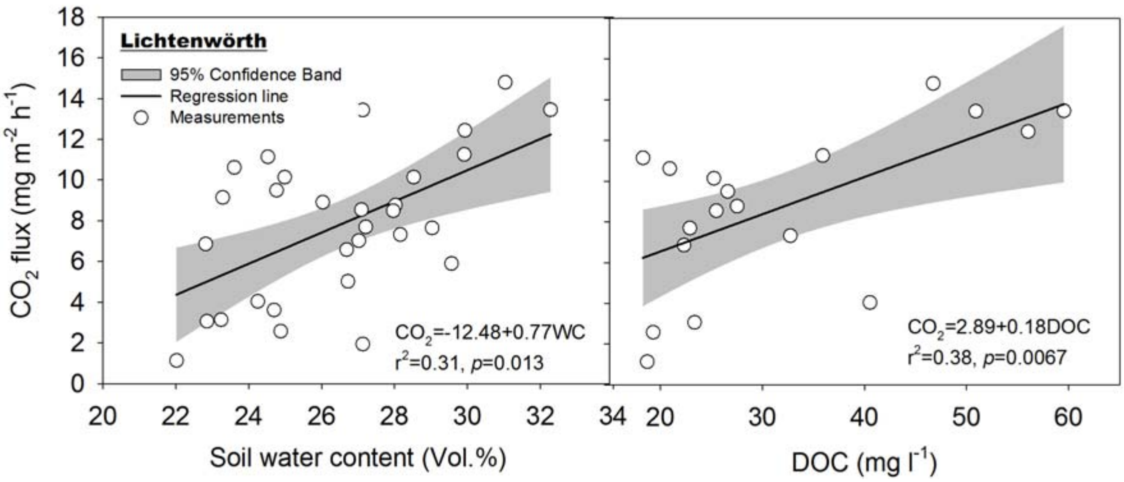

Fig. A-18: Regression relation between soil water content, dissolved organic carbon and CO_2 emissions at a semi-arid site (Lichtenwörth).

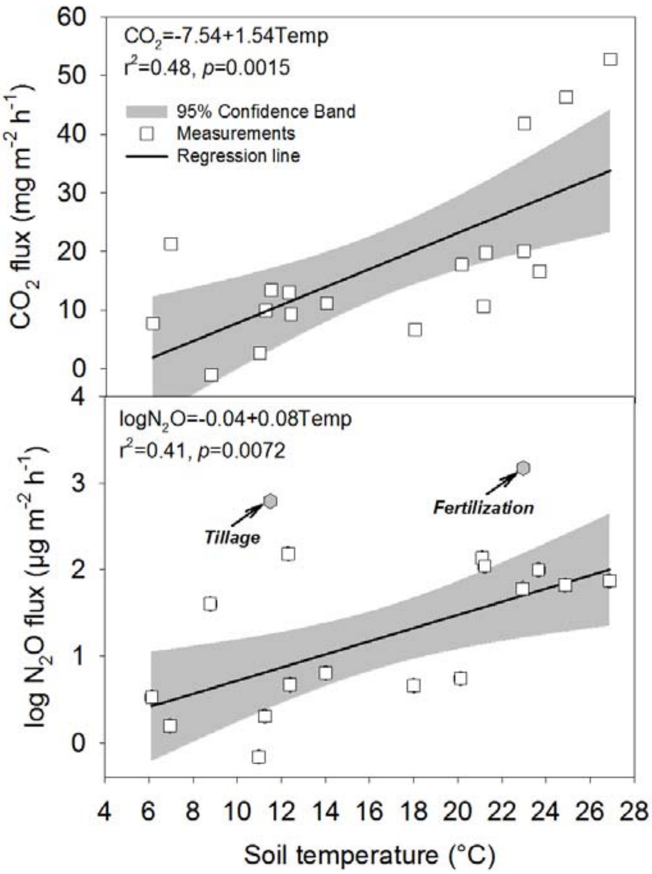

Fig. A-19: Regression relation between soil temperature and trace gas emissions at the humid site (Pötting; times series data).

For Pötting, a significant relation was found between soil temperature and trace gas emissions using the times series data and average values over all treatments (Fig. A-19). For both gases (CO_2 and N_2O) increasing soil temperature induced higher emissions. This was probably due to higher microbial activity. For N_2O the high emissions at fertilization and tillage were removed before applying regression analysis as they would have biased the relation of interest between soil temperature and gas emissions due to the dominant effect of management at these two measurement dates.

Finally also the relation between biomass quality of cover crops and greenhouse gas emissions is reported. Figure A-20 shows the regression between N content of cover crop biomass and CO_2 as well as N_2O emissions. As there were just four points to determine the regression, the relation is only significant at Lichtenwörth in spite of the generally high r^2 at both sites. The strongest relation between the two variables was observed for the measurement date in February except for N_2O at Pötting where the highest r^2 was for the gas flux measurement in March. A similar but slightly weaker relation could be observed for CN ratio (not shown). At the first measurement date, biomass (residue) quality obviously still did not effect as plants as this date was before the onset of mineralization for the bulk of cover crop biomass. The weaker relation for the measurement date in March is simply related to the lower emission potential at this date, except for N_2O at Pötting where also the relation to plant N content was strongest at this date.

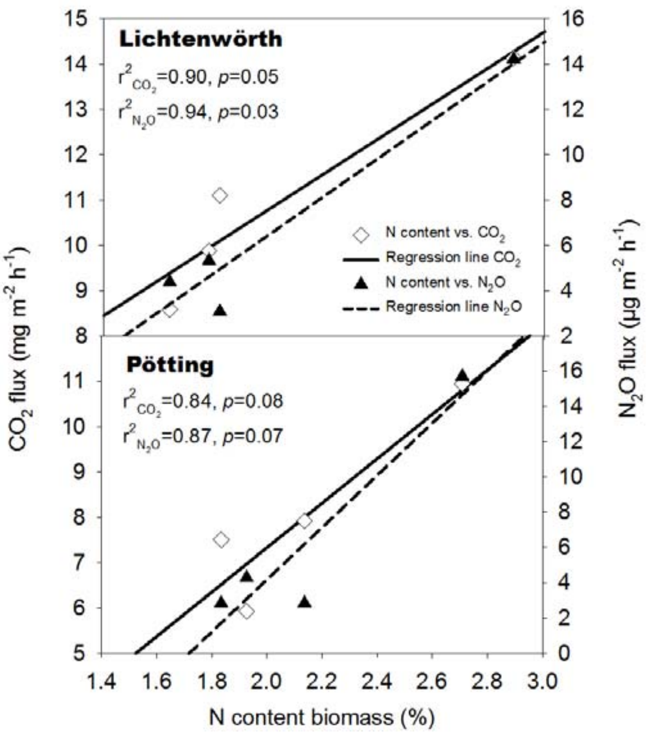

Fig. A-20: Regression relation between the N content of cover crop biomass and greenhouse gas emissions.

A-4 Conclusions

This study presents results of greenhouse gas measurements from cover cropped soil at two field experiments conducted at climatically different sites in Austria. The main objective was to compare different cover crops with a bare soil treatment, study the importance of greenhouse gas emissions related to cover cropping compared to other management influences (fertilization, tillage) and determine main soil and plant related factors underlying greenhouse gas formation.

The main conclusions are:

1. The overall N_2O emission potential related to cover crop residue input and decomposition (from end of cover crop growing season in late autumn until spring of the subsequent year) is low compared to other management impacts, in spite of temporally high soil water content. Also CO_2 emissions are low due to low soil temperature and increase with the onset of the main mineralization period in spring. CH_4 emissions are neglible, although they were detected at some measurement dates (Fig. A-8).
2. Cover crops increase CO_2 emissions which reflect an enhanced biological activity of the soil due to the input of additional easily decomposable organic carbon (Fig. A-9). While cover crops thus contribute organic matter to the soil, CO_2 emissions from a bare soil has to be considered as net losses which are not counterbalanced by any additional input. N_2O emissions were increased by a mustard cover crop in pure stand, particularly for situations with high emission potential (Fig. A-11). It is suggested that the biochemistry of mustard residues (glucosinolate decomposition) is the main reason for the enhanced N_2O emissions. Also a relation between the N content of cover crop biomass and greenhouse gas emissions could be shown (Fig. A-20).
3. Soil water content and dissolved organic carbon (DOC) were the most clearly related to greenhouse gas emissions. Particularly DOC is suggested as an appropriate indicator for cover crop induced ecosystem dynamics related to the carbon and nitrogen cycle. Instead no clear relation between surface near N_{min} content and denitrification could be found, which was probably related to a minor differentiation in this parameter among the variants in these experiments.

From these results it is suggested that future agro-environmental programmes should further strengthen cover crops as a main measure for climate change adaption in agriculture. Mustard in pure stand should be substituted by mixtures containing this species (resp. *brassica* species en general). *Brassica* species are important and efficient cover crops and these results showed that grown in mixture at a lower seeding density not enhanced N_2O emission potential should be expected.

Further investigation of cover crops on greenhouse gas emissions with continuous measurement sites are recommended to determine the overall net losses and balances of input vs. losses for C and N. Furthermore it is recommended to measure greenhouse gas emission of a larger sample of species and mixtures with higher spatial resolution, particularly for N_2O due to its distinct small scale variability. DOC could be used as a good indicator for several cover crop effects. However, also indicators of soil microbial activity would be relevant to better understand the main causal relations leading to distinct greenhouse gas formation between cover crops and compared to bare soil.

References

Amon, B., Fröhlich, M., Amon, T. 2006. Österreichische Emissionsinventur, Bereich Landwirtschaft". In: Klimaforschungsinitiative AustroClim: 9. Österreichischer Klimatag 2006 „Forschung zu Klima, Klimawandel und Auswirkungen in Österreich", 16. – 17. März 2006, Wien, P15

Annicchiarico, P. 1997. Joint regression vs AMMI analysis of genotype-environment interactions for cereals in Italy. Euphytica 94, 53-62.

Aulakh, M.S., Doran, J.W., Walters, D.T., Power, J.F. 1991. Legume residue and soil water effects on denitrification in soils of different textures. Soil Biology and Biochemistry 23, 1161-1167.

Bavin, T.K., Griffis, T.J., Baker, J.M., Venterea, R.T. 2009. Impact of reduced tillage and cover cropping on the greenhouse gas budget of a maize/soybean rotation ecosystem. Agriculture, Ecosystems and Environment 134, 234-242.

BMLFUW 2010. Policy Paper. Auf dem Weg zu einer nationalen Anpassungsstrategie. 2. Entwurf.

BMLFUW. 2000. ÖPUL 2000. Sonderrichtlinie für das Österreichische Programm zur Förderung einer umweltgerechten, extensiven und den natürlichen Lebensraum schützenden Landwirtschaft. Zl. 25.014/37-II/B8/00.

Cepuder, P. 1999. Zur Nitratproblematik in Ostösterreich, dem Tullner Feld, dem Marchfeld und dem nördlichen Burgenland. 8. Gumpensteiner Lysimetertagung, Tagungsband, 1-4.

Dabney, S.M. 1998. Cover crop impacts on watershed hydrology. J. Soil Water Conserv. 53:207-213.

Dersch G, Duboc, O. 2011. Entwicklung der Humusversorgung der Ackerböden. http://www.ages.at/ages/landwirtschaftliche-sachgebiete/boden/aktuelles/entwicklung-der-humusversorgung-der-ackerboeden/

Easterling, D.R., Meehl, G.A., Parmesan, C., Changon, S.A., Karl, T,R,, Mearns, L.O. 2000. Climate Extremes: Observations, Modeling, and Impacts. Science 289, 2068-2074.

Fahey, J.W., Zalcmann, A.T., Talalay, P. 2001. The chemical diversity and distribution of glucosinolates and isothiocyanates among plants. Phytochemistry 56, 5-51.

Feichtinger, F., Scheidl, A., Dorner, J. 2005., ÖPUL 2000 - Evaluierung der wasserwirtschaftlichen Relevanz (Effizienz) einer Begrünung von Ackerflächen im Herbst und Winter.– Bericht, Institut für Kulturtechnik und Bodenwasserhaushalt, Petzenkirchen.

Gomes, J., Bayer, C., de Souza Costa, F., de Cássia Piccolo, M., Zanatta, J.A., Vieira, F.C.B., Six, J. 2009. Soil nitrous oxide emissions in long-term cover crops-based rotations under subtropical climate. Soil and Tillage Research 106, 36-44.

Gonzales-Lanteri, D., A. Huete, and H. Kim. 2004. Estimation of the fraction of canopy cover from multispectral data to be used in a water soil erosion prediction model. Gayana (Concepc.), 68:239-245.

Grüner Bericht 2011. www.gruenerbericht.at

Hartl, W., 2010. Verluste der oberirdischen Biomasse von abfrostenden Begrünungspflanzen durch Ausgasung vor der Einarbeitung in den Boden. Evaluierungssprojekt BMLFUW-LE.1.3.7/0013-II/5/2009, Endbericht.

Hartwig, N.L., and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688–699.

Hungate, B.A., Dukes, J.S., Shaw, M.R., Luo, Y., Field, C.B. 2003. Nitrogen and Climate Change. Science 302, 1512-1513.

IPCC. 2007. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 8: Agriculture. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jarecki, M.K., Parkin, T.B., Chan, A.S.K., Kaspar, T.C., Moorman, T.B., Singer, J.W., Kerr, B.J., Hatfield, J.L., Jones, R. 2009. Cover crop effects on nitrous oxide emission from a manure-treated Mollisol. Agriculture, Ecosystems and Environment 134, 29-35.

Joyce, B.A., W.W. Wallender, J.P. Mitchell, L.M. Huyck, S.R. Temple, P.N. Brostrom, and T.C. Hsiao. 2002. Infiltration and soil water storage under winter cover cropping in California's Sacramento Valley. Trans. ASAE 45:315-326.

Kabir, Z., and R.T. Koide. 2002. Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. Plant Soil 238:205-215.

Kallenbach, C.M. , Rolston, D.E., Horwath, W.R. 2010. Cover cropping affects soil N2O and CO2 emissions differently depending on type of irrigation. Agriculture, Ecosystems and Environment 137, 251-260.

Klik, A., Eitzinger, J. 2010. Impact of climate change on soil erosion and the efficiency of soil conservation practices in Austria. Jourrnal of Agricultural Sciences 148(5), 529-541.

Liebhard, P., Bodner, G. 2005. Expertise zur Wirksamwerdung der Begrünung von Ackerflächen im Herbst und Winter im Rahmen der ÖPUL-Förderung 2000 auf Nitratverlagerung und Grundwasserqualität unter unterschiedlichen hydrologischen, bodenkundlichen und pflanzenbaulichen Rahmenbedingungen in Österreich. Expertise im Auftrag des BMLFUW.

Liebig, M.A., Tanaka, D.L., Gross, J.R. 2010. Fallow effects on soil carbon and greenhouse gas flux in Central North Dakota. Soil Science Society of America Journal 74, 358-365.

Liu, A., B.L. Ma, and A.A. Bomke. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Sci. Soc. Am. J. 69:2041-2048.

Logsdon, S.D., T.C. Kaspar, D.W. Meek, and J.H. Prueger. 2002. Nitrate leaching as influenced by cover crops in large soil monoliths, Agron. J. 94:807-814.

Lütke-Entrup, N. 2000. Feldfutterbau und Ackerbegrünung. In: Lütke-Entrup, N. & Oehmichen, J.(Hg.): Lehrbuch des Pflanzenbaues. Band 2: Kulturpflanzen. Gelsenkirchen-Buer: Verlag Th. Mann, S. 577 - 581, 620 – 654.

McSwiney, C.P., Snapp, S.S., Gentry, L.E. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecological Applications 20, 648-662.

Meyer, L. D., S., S.M. Dabney, C.E. Murphree, W.C. Harmon, and E.H. Grissinger. 1999. Crop production systems to control erosion and reduce runoff from upland silty soils. T. ASAE. 42:1645-1652.

Mosier, A.R., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S. and van Cleemput, O. 1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. Nutrient Cycling in Agroecosystems, 52, 225-248.

Olesen, J.E., Bindi, M. 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur J.Agron. 16, 239-262.

ÖNORM 2012. ÖNORM L 1091: Chemische Bodenuntersuchungen - Bestimmung von mineralischem Stickstoff durch Extraktion mit Calciumchloridlösung - Nmin-Methode.

Parkin, T. B. 1987. Soil Microsites as a Source of Denitrification Variability. Soil Sci. Soc. Am. J. 51, 1194–1199.

Parkin, T.B. , Kaspar, T.C., Singer, J.W. 2006. Cover crop effects on the fate of N following soil application of swine manure. Plant and Soil 289, 141-152.

Pattey, E., Blackburn, L.G., Strachan, I.B., Desjardins, R., Dow, D. 2008. Spring thaw and growing season N2O emissions from a field planted with edible peas and a cover crop. Canadian Journal of Soil Science 88, 241-249.

Petersen, S.O. , Mutegi, J.K., Hansen, E.M., Munkholm, L.J. 2011. Tillage effects on N2O emissions as influenced by a winter cover crop. Soil Biology and Biochemistry 43, 1509-1517.

Piepho, H.P., A. Büchse, and C. Richter. 2004. A mixed modelling approach for randomized experiments with repeated measures. J. Agron. Crop Sci. 190:230-247.

Quinton, J.N., G.M. Edwards, and R.P.C. Morgan. 1997. The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. Soil Use Manage. 13:143-148.

Rochette, P., Gregorich, EG., Desjardins, RL. 1992. Comparison of static and dynamic closed chambers for measurement of soil respiration under field conditions. Canadian Journal of Soil Sciences, 72, 605-609.

Rosecrance, R.C., Mccarty, G.W., Shelton, D.R., Teasdale, J.R. 2000. Denitrification and N mineralization from hairy vetch (Vicia villosa Roth) and rye (Secale cereale L.) cover crop monocultures and bicultures. Plant and Soil 227, 283-290.

Schmidt, M.W.I., et al., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56.

Shepherd, M.A., and J. Webb. 1999. Effects of overwinter cover on nitrate loss and drainage from a sandy soil: consequences for water management? Soil Use Manage. 15:109-116.

Smith, P. et al., 2008. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B. 363 no. 1492, 789-813.

Steenwerth, K. , Belina, K.M. 2008. Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Applied Soil Ecology 40, 370-380.

Strauss, P. 2006. ÖPUL-Maßnahmen in ihren erosionsvermindernden Auswirkungen. Umweltprogramme für die Landwirtschaft und deren Auswirkungen auf die Grundwasserqualität, Gumpenstein, 7.-8.3.2006, Tagungsband, 65-68.

van Dam, A. 2006. Understanding the reduction of nitrogen leaching by catch crops. Published PhD Thesis, Wageningen University, Wageningen, 171 pp.

Velthof, G.L. , Kuikman, P.J., Oenema, O. 2002. Nitrous oxide emission from soils amended with crop residues. Nutrient Cycling in Agroecosystems 62, 249-261.

Wagner-Riddle, C., Thurtell, G.W. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. Nutrient Cycling in Agroecosystems 52, 151-163.

Wyland, L.J., L.E. Jackson, W.E. Chaney, K. Klonsky, S.T. Koike, and B. Kimple. 1996. Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests and management costs. Agr. Ecosyst. Environ. 59:1-17.

Abbildungs- und Tabellenverzeichnis

Abbildungen