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Review of key causes and sources for N_2O emissions and NO_3-leaching from organic arable crop rotations

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Abstract. The emissions of nitrous oxide (N_2O) and leaching of nitrate (NO_3) have considerable negative impacts on climate and the environment. Although these environmental burdens are on average less per unit area in organic than in non-organic production, they are not smaller per unit of product. If organic farming is to maintain its goal of being an environmentally friendly production system, these emissions should be mitigated. We discuss the impact of possible triggers within organic arable farming practice for the risk of N_2O emissions and NO_3 leaching under European climatic conditions, and possible strategies to reduce these. Organic arable crop rotations can be characterised as diverse with frequent use of legumes, intercropping and organic fertilizers. The soil organic matter content and share of active organic matter, microbial and faunal activity are higher, soil structure better and yields lower, than in non-organic, arable crop rotations. Soil mineral nitrogen (SMN), N_2O emissions and NO_3 leaching are low under growing crops, but there is high potential for SMN accumulation and losses after crop termination or crop harvest. The risk of high N_2O fluxes is increased when large amounts of herbage or organic fertilizers with readily available nitrogen (N) and carbon are incorporated into the soil or left on the surface. Freezing / thawing, drying / rewetting, compacted and/or wet soil and mixing with rotary harrowing further enhance the risk for high N_2O fluxes. These complex soil N dynamics mask the correlation between total N-input and N_2O emissions from organic arable crop rotations. Incorporation of N rich plant residues or mechanical weeding followed by bare fallow increases the risk of nitrate leaching. In contrast, strategic use of deep-rooted crops with long growing seasons in the rotation reduces nitrate leaching risk. Reduced tillage can reduce N leaching if yields are maintained. Targeted treatment and use of herbage from green manures, crop residues and catch crops will increase N efficiency and reduce N_2O emissions and NO_3 leaching. Continued regular use of catch crops has the potential to reduce NO_3 leaching but may enhance N_2O emissions. A mixture of legumes and non-legumes (for instance grasses or cereals) are as efficient a catch crop as monocultures of non-legume species.

Abbreviations: BNF: biological nitrogen fixation, C: Carbon, CC: Catch crops or cover crops, CH_4: methane, EF: Emission factor = % of N applied emitted as N_2O-N, N: nitrogen, N_2O: nitrous oxide, PMN: Potentially mineralizable N, SMN: Soil mineral nitrogen, SOC: Soil organic carbon, SOM: Soil organic matter.

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1 Introduction

Biologically available nitrogen (N) or reactive N is limited in most natural terrestrial ecosystems. In modern crop production, addition of N fertilizer has become crucial to achieve high crop yields. This has resulted in cropping systems where a substantial proportion of the N added is lost to the environment, and where the excess reactive N threatens the quality of air, water and ecosystems (Robertson and Vitousek, 2009). The emissions of N_2O have considerable environmental impacts through the contribution to global warming and ozone depletion (Ravishankara et al., 2009). About 16 to 20 Tg N_2O-N is emitted annually to the atmosphere. Of this, close to 40% is anthropogenic, and agriculture accounts for 67–80% of the anthropogenic N_2O emissions (Ussiri and Lal, 2013). About half of the anthropogenic N_2O emissions originate from cultivated soils (Stehfest and Bouwman, 2006). In addition, agricultural soils are sources of indirect N_2O emissions resulting from subsequent downstream microbial turnover of N from nitrate leaching or ammonia volatilization (IPCC, 2006). Nitrate lost by leaching may contaminate drinking water and lead to eutrophication of freshwater and marine ecosystems (Dalgaard et al., 2014).

The area under organic production is increasing worldwide (Willer and Lernoud, 2018). In Europe, 2.7% of the agricultural land is organic, and in nine countries, 10% or more of the agricultural land is managed organically (Willer et al., 2018). In 2016, 43% (6 mill ha) of the organic area in Europe was under arable crops. It is therefore timely to review the impact of organic farming on N_2O emissions and NO_3 leaching, and arable production particularly, as the challenges and the yield gap between organic and non-organic production are large in arable production (De Ponti et al., 2012). We define “organic arable crop rotations” as cropping systems with associated crop and soil management commonly used in European farms dominated by arable cropping and following the Council Regulation (EC) No 834/2007s on organic farming (Council of the European Union, 2007). In organic farming, arable rotations are designed to have fertility building phases as well as fertility exploiting periods (cash cropping) but also to minimise the build-up of weeds, pest and diseases (Stockdale et al. 2001). Manure and/or short-term leys may be used in these rotations. We designate “non-organic crop rotations” as crop rotations that are common on farms dominated by arable cropping which do not follow organic farming regulations, commonly called conventional farming.

The conservation of reactive N in cropping systems and the use efficiency ~~of this N~~ is crucial for the success of organic farming, both from production and environmental perspectives. Increasing yields ~~in~~ organic farming is an important goal to allow it to remain competitive, and this requires more efficient conversion of reactive N into plant material and reduction of associated losses (Röös et al., 2018). Although mineral N fertilizers are not allowed in organic farming, there are substantial amounts of ~~nitrogen~~ used, which derive from manure and other organic fertilizers, organic amendments and crop residues or green manures relying on biological N fixation (BNF). The great diversity of N mineralisation patterns among the organic fertilizers and crop residues is a challenge when farmers aim to synchronize the N release with plant N uptake. If N is released during periods with poor plant uptake, then soil nitrate can accumulate creating a large risk of N losses through gaseous emissions or through leaching. Synchronising N release from residues and amendments and crop uptake is thus crucial for minimizing the risk for large N leaching or denitrification losses.

Here we focus on the causes and sources of N loss through nitrous oxide (N_2O) emissions and nitrate (NO_3) leaching and possible strategies to simultaneously reduce these losses from arable organic crop rotations under European climatic conditions. We identify the main characteristics of organic arable crop rotations and relate these characteristics to the probability for high soil mineral N (SMN) concentrations during periods of the year with high risk of N_2O emission and/or NO_3 leaching. We compare this with observed N_2O emissions and NO_3 leaching in field trials conducted in organic arable crop rotations. There is insufficient robust field data on N_2O emission and NO_3 leaching within organic arable crop rotations to allow for a meta-analysis to quantify the impact of key causes so here we use the available data to identify key causes and sources for N_2O emission and NO_3 leaching in these rotations, and to suggest targeted mitigation strategies.

We address the following questions for organic arable crop rotations:

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1. What determines the dynamics of SMN concentrations, and when do high SMN concentrations occur?
2. What are the main triggers for N_2O emissions?
3. What is the contribution of single high N_2O emission events to total N_2O emissions?
4. When does NO_3 leaching mainly occur?
5. What are the most efficient measures for reducing N_2O emissions and NO_3 leaching?

2. Methodology

Based on the authors own field trials, literature databases and searches through Google Scholar, we compiled data on characteristics of organic arable crop rotations, measurements of soil mineral N (SMN), N_2O emissions and NO_3 leaching from field trials relevant for organic crop rotations in climate and soil conditions present in Europe. SMN is defined as the content of mineral N in the form or ammonium (NH_4) or nitrate (NO_3) in soil. N_2O emission is defined as the cumulative flux reported for one field treatment during the actual measurement period. NO_3 is defined as leached when transported out of the root zone. We defined high emission events (hot moments) of N_2O flux as a brief and disproportionally high short-term N_2O flux event due to the combination of multiple influencing factors (Molodovskaya et al., 2012).

We used data presented in Table S2 to calculate the impact of the explanatory variables site, waterfilled pore space (WFPS), content of NO_3-N and NH_4-N in soil and soil temperature on soil N_2O peak fluxes. We used raw data and published data from the following studies: Ball et al. (2007a), Baral et al. (2017), Brozyna et al. (2013), Chirinda et al.(2010), Krauss et al. (2017b), Li et al. (2015), Nadeem et al. (2012b) and Pugesgaard et al. (2017). For this, we used stepwise regression (α to enter = 0.15; α to remove = 0.15) with two models. In model 1, the main effects, all second order interactions and quadratic terms of all explanatory variables were used as potential terms. In model 2, only the main effects were included without any further selection of variables.

The N_2O flux data were highly skewed and the N_2O fluxes were log-transformed to achieve variance homogeneity according to equation (1).

Response variable = ln (daily N_2O flux +2) (eq. 1)

Where daily N_2O flux = g N_2O-N $ha^{-1}day^{-1}$ is the highest N_2O flux rate in the actual measurement period (Table S2, Highest daily flux rate). To get a response variable that is nearly normally distributed with homogeneous variance we used the transformed variable ln ("daily N2O flux" + 2) as the response variable in the regression models because this gave the best residual plots.

We wanted to analyse the impact of high emission events of N_2O fluxes on the total N_2O emission. However, we lacked daily measurements, and we lacked data for yearly periods. It was thus not possible to identify the full~~y~~ impact of the hot moments as done by Molodovskaya et al. (2012). Because of the differences in measurement period, it was also not possible to compare the different field trials directly. To overcome this, we used a regression model (eq. 2) based on N_2O emissions in the actual period and peak N_2O flux within this period.

$$\ln\left(\frac{C_i}{P_i}\right) = \beta_0 + \beta_1 \cdot \ln\left(N_i + 2\right) + \varepsilon_i \qquad \text{(eq.2)}$$

In eq 2 i indicate observation number i. C_i is ~~cumulated~~ N_2O emission (20 to 7940 g N_2O-N ha^{-1}) ; P_i is measurement period (38 to 490 days) ; C_i/P_i express the average daily N_2O flux in the measurement period; N_i is the highest N_2O-flux rate (0.1 to 605 g N_2O-N ha^{-1} day^{-1}) in the measurement; ε_i is a random variable, normally distributed with expectation 0 and variance σ^2; the ε_i's are independent; β_0, β_1 and σ^2 are parameters that are estimated from the data.

We also calculated the percentage contribution of the highest daily N_2O flux of the total N_2O emissions in the measurement periods for all trials presented in Table S2, and correspondingly the sum of the fluxes for the days with the five highest flux rates as a percentage of the total N_2O emissions.

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3 Characteristics of organic arable crop rotations that might influence N_2O emissions and NO_3 leaching

3.1 Crop rotation

Crop rotations are essential in organic arable farming for nutrient supply, pest and weed management, and both globally and in Europe organic rotations are more diversified than non-organic ~~and the rotations are also longer~~ (Barbieri et al., 2017). Barbieri et al., (2017) found that catch crops and undersown cover crops are 2.4 and 8.7 times more frequent in organic systems compared to conventional systems, respectively. They further found that the share of pulses and temporary fodder crops (such as alfalfa, clover and ryegrass) were higher in organic than in non-organic crop rotations, and that the difference between organic and non-organic crop rotations was greater in this respect in Europe than in North America and the global average. In 2016 there were 2.26 million ha green fodders (plants harvested green from arable land) in organic farms in Europe and 0.42 million ha dry pulses (Table 55, Willer et al., 2018). This constituted 41 and 8% of the organic, arable area in Europe. Barbieri et al., (2017) observed that nitrogen-fixing crops are more abundant in organic rotations because of more legumes included in temporary fodder crops, and more catch and undersown cover crops that contain more nitrogen-fixing species than in non-organic rotations, as well as higher frequency of cereal intercropping with legume crops.

3.2 Soil organic matter

Return of crop residues to the soil is standard practice in both organic and non-organic arable production; however, because of the more diverse crop rotations in stockless organic production systems (Barbieri et al., 2017), larger and more diverse inputs of herbage from green manures, leys, catch crops (CC) and intercropping are returned to soil than in non-organic systems (Gattinger et al., 2012). Other commonly used sources of organic inputs are animal manures and slurries, composts or biogas residues, organic fertilizers based on animal manure or municipal waste (Watson et al., In prep.).

Through the application of organic amendments and various crop residues from arable and forage crops, carbon (C) is applied to soil, and the content of soil organic matter (SOM) is often higher in organic than in non-organic arable crop rotations (Marriott and Wander, 2006; Marinari et al., 2007; Gomiero et al., 2011; Gattinger et al., 2012; Aguilera et al., 2013; Hu et al., 2018).

Earthworms, other soil fauna and soil microbes contribute directly to plant residue decomposition and mineralization and turnover of SOM. The quality of SOM differs between non-organic and the more diversified organic, arable crop rotation, with a higher share of labile SOM (Lynch, 2015) and thus easily degradable organic carbon in soils in organic crop rotations (Marinari et al., 2007; Marriott and Wander, 2006; Martyniuk et al., 2016). The higher content of labile SOM in organic crop rotations is valuable for maintaining soil fertility ~~in organic crop rotations~~ as it is a short-term pool for nutrients (Marriott and Wander, 2006; Martyniuk et al., 2016), ~~but it also enhances~~ SMN during periods of time when there is no or slow crop growth.

3.3 Soil biological activity

Addition of organic matter and a high SOM content provides substrate for soil fauna and microbes. Application of organic matter to soil commonly increases the growth of microbial communities, their enzyme activities and the microbial diversity compared to an unfertilised control or soil fertilized with only mineral fertilizer (Anderson and Domsch, 1989; Marinari et al., 2007; Thangarajan et al., 2013). Most of the available N forms produced by soil organisms are taken up by plants soon after release (Whalen et al., 1999). Higher biological activity has commonly been found in arable soils managed organically compared with non-organically (Mäder et al., 2002; Gomiero, 2013; Hartmann et al., 2015; Lori et al., 2017).

Certain groups of soil invertebrates, especially earthworms, may reach a high biomass and play an important role in organic matter turnover (Lubbers et al., 2013, Kuiper et al., 2013). Earthworms usually have higher frequency and biomass in organic rotations; their abundance can be twice as high as in non-organic systems (Pfiffner and Mader., 1997; Filser et al., 1999; Hansen and Engelstad, 1999; Riley et al., 2008). In the DOK-trial, they observed that the earthworm biomass in the organic treatment varied from 210 to 280 g m^{-2} and was 1.1 to 2.9 times higher than in the non-organic treatment also receiving animal manure depending on the crop where the earthworm population was investigated (calculation based on Pfiffner and Mäder, 1997). They attributed this to the chemicals used for plant protection. After 15 years Riley et al. (2008) observed an average earthworm biomass of 112 and 26 g m^{-2} with arable organic and non-organic crop rotations, respectively. They also attributed this to the to the chemicals used for plant protection and the inclusion of a year with grass clover every fourth year in the organic rotation. Higher biomass, abundance and species richness of earthworms have also been observed on organic farms compared with low-input farming without pesticides (ICM) (Pfiffner and Luka, 2007). They found an average biomass of around 100 and 160 g m^{-2} and an abundance of 140 and 220 earthworms m^{-2} in ICM and organic fields respectively when they compared the earthworm population in cereals at 6 farm pairs with similar crop rotations. Forty percent of the variation in earthworm populations was attributed to the farming system (Pfiffner and Luka, 2007). More abundant earthworm populations are found when large amounts of animal manure or green manure are applied to soil (Hansen and Engelstad, 1999; Frøseth et al., 2014), when autumn ploughing is avoided (Pfiffner and Luka, 2007) and in the absence of tractor traffic (Hansen and Engelstad, 1999).

3.4 N-supply

Crop N supply in organic farming relies on mineralisation of N in soil organic matter, N in organic amendments and BNF of legume-based crops (Gattinger et al., 2012; Lorenz and Lal, 2016; Watson et al., 2018). Despite substantial inputs of N from BNF (Kayser et al., 2010; Pandey et al., 2017) and from organic amendments (Watson et al., In prep.), the N-supply is often below optimum for plant growth in arable organic farming (Berry et al., 2002; Tuomisto et al., 2012,). BNF is important in determining the soil N dynamics during the season and in the following years through release of N from roots and aboveground residues. BNF may therefore be a larger and thus proportionally more important N source, than N from organic manures and fertilizers in some organic cropping systems.

Crops cultivated organically get most of their N supply from N mineralised through microbiological transformation of organic matter. Degradability, N contents and C/N-ratio vary strongly among different kinds of external amendments such as animal manures, composts or plant residues. The timing of N mineralisation and crop demand are controlled by a combination of soil moisture and temperature as well as soil management, the chemical characteristics of the incorporated residues and crop growth dynamics (Jarvis et al., 1996; Petersen et al., 2013, Watson et al., 2018). When plant residues are applied in spring, the major release of plant available N may occur within a period corresponding to the growing season (Gale et al., 2006). However, the mineralization process of the more stable N can continue over years to decades. Simulation modelling has shown that even over a 20-year period, only 10-15 % of organic N in applied manure may be taken up by crops, the rest being lost or retained in soil organic matter (Berntsen et al., 2007). The design of the rotation, as well as its management, influences the size of the potentially mineralizable N (PMN) pool. Working in three different organic arable systems, Spargo et al. (2011) showed that the PMN pool amounted on average to 315 kg N ha^{-1}. They showed that the more diversified the rotation was in terms of number of different crops, the higher concentration of PMN was measured. Poudel et al. (2002) reported 112 and 56% greater PMN pool in the organic system in comparison to the conventional and low-input systems, respectively. Moreover, the authors observed slower and more continuous release of mineral N in the organic systems compared to the more rapid release of mineral N from synthetic N fertilizers applied in non-organic systems. Moyo et al. (2016) reported higher PMN in soil under wheat following a cut and mulched red clover ley then after a ley where the residues had been removed indicating the importance of management. However, soil organic matter turnover rates vary with soil texture and climate, increasing when organic carbon is less protected from decomposer microbes (low clay content) and under wet and warm climates (Burke et al., 1989).

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Lori et al. (2017) found in their meta-analysis that when both organic and non-organic systems included legumes, the organic system displayed a higher microbial N content than the non-organic counterpart. In cases where only the organic systems contained legumes, the difference in microbial N between the two systems was even more pronounced. The high microbial activity and high content of organic matter affect N-cycling. This is exemplified by an incubation experiment with soil from a long-term field trial (DOK) where a higher potential for denitrification was observed in organic than in non-organic treatments (Krause 2017). Hu et al. (2018b) found a higher net N mineralisation of added organic matter in soils having a prehistory of use of catch crops, indicating positive legacy effects of catch crop use.

3.5 Soil acidity

Recommendations for liming soils based on pH measurements are targeted at individual crops and therefore pH is expected to be similar between organic and non/organic systems producing similar crops. Lori et al. (2017), however, found in their meta-analysis from different climatic zones an overall higher pH of approximately 0.15 pH units, in organic systems compared to non-organic systems. They observed, not surprisingly, that the actual pH at a given location is heavily dependent on the soil type and the rock type in the region. However, the regulation of soil acidity is influenced by the different crop choices and the ways that crop nutrients are supplied in these two modes of production. In a soil with high biological activity there will be a release of cations from minerals through microbial activity (Silverman, 1979) which will counteract soil acidification. Furthermore, the application of manures and composts will increase the pH (Cooper and Warman, 1997). In the long-term field trial in Switzerland (DOK) the pH was higher in the organic treatment than in the control treatment, although neither treatment was limed (Krause et al., 2017). Leguminous species are known to acidify soils with the magnitude of the effect dependent on species (Tang et al. 1998) and therefore in organic systems which tend to have a higher proportion of legumes in the rotation than non/organic systems, care is needed to maintain a desired pH. On non-organic farms use of ammonium-nitrate fertilizer will acidify the soil, and pH is normally regulated by liming. On soils with > 15 % clay, hydrated lime is used to improve soil aggregation by a rapid pH increase (Keiblinger et al., 2016). This is not allowed in organic production, where only natural occurring lime, with a slower influence on pH increase is allowed (Council of the European Union, 2007).

3.5 Soil structure

The activity of soil life and the quantity and quality of soil organic matter also influence soil structure (Bronick and Lal, 2005). Biopores that are formed by the activity of soil life contribute to air and water transport and can facilitate the acquisition of water and nutrients from the subsoil (Kautz, 2014). Marinari et al., (2000) observed that the addition of organic fertilisers improved several soil physical and biological properties. The increase in macropores, ranging from 50–500 µm, in soil treated with organic fertilisers was mainly due to an increase in elongated pores, which are considered very important both in soil–water–plant relationships and in maintaining a good soil structure. Also, the use of perennial leys has positive impacts on soil structure because of, among other reasons, dense and long root systems. From this, we should expect a better soil structure in organic than in non-organic crop rotations (Schjønning et al., 2007). It has been observed in long term comparative field trials that arable organic production generally has better soil structure than non/organic systems (Siegrist et al., 1998; Mäder et al., 2002; Riley et al., 2008). However, soil structure can easily be damaged by heavy traffic and intensive soil tillage in any farming system (Ball et al., 2007b).

3.6 Crop yields

Because of lower yields in organic arable production relative to non-organic systems, more land is needed per unit product (De Ponti et al., 2012). Meier et al. (2015) observed that 9 to 214% more land is needed to produce one arable crop unit by organic compared with non-organic production. Crop yields and resulting land use thus have a large impact on N_2O

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emissions and N leaching per unit produced. In the regulations of organic farming, there are strong restrictions on the use of herbicides, fungicides and insecticides, and an emphasis on using physical, mechanical, biological methods to control diseases, pests, and weeds (Lorenz and Lal, 2016). Commonly, organic farming has grater abundance of weeds and use of mechanical weeding and more frequent mouldboard ploughing to control annual and perennial weeds (Melander et al., 2016). This lack of efficient crop protection in organic farming negatively affects crop yields besides less N input, potentially enhancing N losses as a result of poor crop establishment and growth (Shah et al., 2017). These aspects are also important to include when mitigation strategies for organic arable crop rotations are discussed. Röös et al (2018) have recently reviewed options for increasing yields in organic production.

In summary 3, Characteristics of organic arable crop rotations: Organic rotations are diverse with frequent use of legumes, perennial leys, intercropping and organic fertilizers. The soil organic matter content and share of active organic matter, soil structure, microbial and faunal activity are higher, and yields lower, than in non-organic, arable crop rotations.

4 Sources and mechanisms underlying N_2O emissions and NO_3 leaching

4.1 N_2O

Many processes contribute to N_2O production in soils, but the ~~dominating~~ mechanisms for N_2O emission in terrestrial agricultural soils are microbial processes of nitrification, nitrifier denitrification (as a result of incomplete nitrification) and denitrification (Firestone and Davidson, 1989; Butterbach-Bahl et al., 2013). Nitrification and denitrification are both biological processes, thus the same mechanisms will cause N_2O emissions in organic as in non-organic farming systems. However, as fertilisation, crop and soil management are different in these two systems (section 3), the relative importance of the various triggers differ (section 6).

Nitrification is the microbial oxidation of NH_4+ to NO_2- and ultimately NO_3-, where N_2O ~~is~~ produced as by-product through some partially understood biotic and abiotic reactions (Anderson, 1964, Liu et al., 2017). Nitrifier denitrification occurs when NO_2^- produced during nitrification is reduced to N_2O (by denitrifying organisms) instead of being oxidized to NO_3^- under fluctuating oxic-anoxic conditions (Firestone and Davidson, 1989). Denitrification is the microbial anaerobic reduction of NO_3^- via NO_2^- to gaseous NO, N_2O and N_2, which are ultimately lost from soil to atmosphere. Denitrification is the main source of N_2O production in soils, as N_2O yield potential of denitrification is much higher (1-100%) than nitrification (0.1-1%) (e.g. Andersson et al., 1993, Jing and Bakken, 1993, Butterbach-Bahl et al., 2013). The ratio between the gaseous products of denitrification depends on NO_3^- availability, oxygen availability in the soil and/or microsites, amount of easily decomposable carbon as an energy source, soil pH and microbial community structure (Bakken et al., 2012). Oxygen availability depends on soil moisture content, soil texture, soil structure and microbial activity. Soil pH is suggested as the chief modifier for regional N_2O emissions in national inventories (Wang et al., 2017). Low soil pH inhibits the activity of N_2O reductase enzyme and thus N_2O:N_2 ratio increases (Liu et al., 2010) . At higher soil pH, the denitrification rate is higher, but the N_2O:N_2 ratio is lower as a greater part is completely denitrified to N_2. In a newly limed soil, however, the main N_2O source was observed to shift from denitrification to ammonia oxidation (Baggs et al., 2010). At low temperatures, nitrous oxide reductase is hampered (Holtan-Hartwig et al., 2002), but on the other hand, denitrification rates are also reduced (Butterbach-Bahl et al., 2013).

Increasing content of soil organic carbon (SOC) enhances the risk of N_2O emissions (Li et al., 2005). This is true whether the soil has a high content of SOC or the content is increased by additions of organic matter to the soil (Li et al., 2005), and is caused by the tight link between SOC and microbial production of N_2O (Sahrawat and Keeney, 1986). N_2O and N_2 production correlates with total organic C, water soluble C and mineralizable C in soil, but increased availability of C also decreases the ratio of N_2O/N_2 (Sahrawat and Keeney, 1986). The N_2O emission from SOM is often referred to as the

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background emission and will vary between years because of variations in temperature and precipitation (Hansen et al., 2014). Organic amendments added for improving soil fertility and enhancing crop productivity can lead to N_2O emissions by processes such as priming, nitrification, and denitrification (Thangarajan et al., 2013). Priming involves mineralization of SOM stimulated by microbial demands for certain elements by which CO_2 and mineral N may be released, (Fontaine et al., 2004; Frøseth et al., 2014), leading to SMN that is exposed to nitrification and denitrification.

Organic amendments and plant residues that provide easily decomposable carbon by microbes may enhance microbial growth and deplete soil oxygen through enhanced soil respiration. In addition, degradable carbon is an energy source for denitrifying bacteria. In accordance with this, Köster et al. (2011) concluded that bacterial denitrification was the main process for producing N_2O during the first three weeks after application of biogas residues, and high carbon availability was an important cause for this, and Li et al. (2016a) concluded that denitrification was the main cause for N_2O emission after addition of legumes. Several studies have shown higher rates of N loss through denitrification from soils treated with organic amendments such as manure, composts, and plant residues when compared to unamended or mineral N treated soils (Thangarajan et al., 2013). In line with this, incorporation of residues by tillage increases soil respiration and N_2O fluxes because of microbial stimulation (Krauss, 2017a).

Nitrifier denitrification may be a major source of N_2O originating from organic matter applied to soil under conditions when there is a low content of easily degradable carbon (Köster et al., 2011), because of ammonification of applied organic N (Paul and Clark, 1989), and thus enhanced risk of N_2O emissions from nitrifier denitrification.

4.2 NO_3 leaching

Nitrate leaching is an abiotic process driven by diffusion and convection (e.g. Johnsson et al., 1987). Nitrate is leached when it is washed out of the root zone. In addition to soil water content, soil texture and structure are important in determining leaching rates. Fine textured soils have slower infiltration rates than coarse textured soils, and porous sandy soils are most vulnerable to leaching (Askegaard et al., 2005). Due to its mobility in soil, nitrate can easily be lost from the agroecosystem by leaching during periods of high drainage. The potential losses depend on N applied as fertilizer or manure as well as soil and crop management (Di and Cameron, 2002). Sources ~~for~~, soil nitrate are mainly soil organic matter, plant residues ~~from tops and roots,~~ and fertilizers, including organic amendments as manure. In the same way as for N_2O emissions, added N not used by the plant is susceptible to leaching. The most efficient plant root uptake of nitrate occurs when other factors (nutrients, pH, water) are not limiting. A well-developed root system enhances nitrate uptake while a poor root system will not utilize all the nitrate available throughout the soil profile (Dunbabin et al., 2003). Nitrate remaining in the soil after the growing season, or mineralised subsequently, will greatly increase the risk of leaching loss.

4.3 Observed N_2O emissions and NO_3-leaching from organic versus non-organic arable crop production

There is a continued debate whether an organic mode of crop production enhances or reduces greenhouse gas (GHG) emissions and NO_3 leaching from agriculture (Lorenz and Lal, 2016; McGee, 2015). ~~Stockless organic crop rotations in particular have been suggested to have large emissions per unit product due to low productivity (Lorenz and Lal, 2016).~~ Lower area scaled, but slightly higher, similar or slightly lower yield scaled emissions are commonly observed for N_2O emissions (Gattinger et al., In preparation; Skinner et al., 2014; Tuomisto et al., 2012,) and NO_3 leaching (Aronsson et al., 2007; Benoit et al., 2014; Kirchmann and Bergström, 2001; Stopes et al., 2002; Tuomisto et al., 2012).

In summary 4, Sources: When not taken up by plants, NO_3-N is likely to be leached or denitrified, with leaching being the ~~dominating~~ process in freely draining soils and denitrification in soils with restricted aeration. Microbial access to easily degradable carbon will increase denitrification. Incomplete denitrification or nitrification will result in N_2O emissions. Area-

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scaled N_2O emissions and NO_3 leaching are generally lower in organic than in non-organic arable crop rotations, whereas yield-scaled losses show no consistent differences.

5 Dynamics of SMN in organic arable crop production

Table S1. [S1_Supplementary material 1_SMN]

Because of restricted N input in organic crop rotations, SMN is normally low during the crop growth period; however, under certain conditions, e.g. shortly after fertilization or termination of legume rich crops or green manures the concentration of SMN may be high (Watson et al., 1993; Chirinda et al., 2010; Nadeem et al., 2012; Brozyna et al., 2013; Frøseth et al., 2014; Peyrard et al., 2016; Krauss et al., 2017b). To get an understanding of the change in SMN content especially during winter, it is common to measure SMN in different soil layers in late autumn and in early spring. As shown in S1, there is a great variation in level of SMN in autumn as well as in early spring.

SMN is normally very low under organic grass-clover leys (Table S1, Watson et al., 1993; Nadeem et al., 2012; Brozyna et al., 2013; Frøseth et al., 2014; Krauss et al., 2017b), because in an N-limited grass-clover ley, grasses will quickly take up available NO_3 (Brophy et al., 1987). Frøseth et al. (2014) observed low levels of SMN irrespective of whether the green manure herbage was mulched or removed. However, after termination of a ley, the concentrations of SMN usually increase (Table S1, Ball et al., 2007a; Brozyna et al., 2013; Krauss et al., 2017b). Even in the year following termination of a ley, the content of SMN can still be high (Hansen et al. 2007; Jończyk and Martyniuk, 2017). Kayser et al. (2010) pointed out that N provided by spring ploughing of both 1-year grass-clover ley and 3-year grassland ley resulted in high concentrations of SMN (0-90 cm, 61 kg N ha^{-1} and 95 kg N ha^{-1}) in the following autumn after harvest of spring triticale. Much of this may not have been available for the crops ~~in~~ spring and is likely to have been mineralised after the crop maturity or ~~end of season~~. There might be a substantial time delay in mineralization of grass clover and low observed SMN after ploughing, depending on environmental conditions.

Frøseth et al. (2014) observed low concentrations of SMN in the topsoil (0-30 cm) and subsoil (30-80 cm) after spring ploughing of a 1-year grass-clover ley in four field trials in Norway, both in late spring and in autumn after harvest of a spring barley crop (Table S1) and in the year after (Frøseth, 2016). Płaza et al. (2015) found that CCs added between organically cultivated spring triticale and potato increased the amount of SMN in the topsoil (0-30 cm) in the spring by 53-80 kg N/ha. In the control plots without catch cropping this increase was only 8 kg N/ha. This can be explained by priming effect of incorporated biomass from a catch crop, but also by possible higher N leaching from bare soil on plots without catch cropping (Table S1).

Spargo et al. (2011) found that the pool of available N in organic arable fields increased with increasing frequency of manure application. The great diversity of N mineralisation patterns among the organic fertilizers and crop residues result in a large variation in how much N is mineralized. Some authors point out to the importance of the C:N ratio in the organic matter applied to soil. Bhogal et al. (2016) showed that for pig slurry and poultry layer manure with C:Norg of 9-12:1, up to 70% of the organic N was mineralized after five growing seasons, whereas in cattle slurry and straw-based farmyard manure with C:Norg of 10-21:1, only 10-30% of N was net mineralised. Pang and Letey (2000) observed with multi-year simulation based on published data that a crop with a very high maximum N-uptake rate, such as corn, would be difficult to fertilize with only organic N to meet peak demands without excessive N in the soil before and after crop growth.

In summary 5, SMN: There are small amounts of SMN under growing crops in organic arable farming, but considerable risks for accumulation of SMN after termination of legume-rich crops.

6 Possible triggers of N_2O emissions in organic arable crop rotations

Table S2. [S2_Supplementary material 2_N2O]

6.1 Legumes during plant growth

In general legumes have small N_2O emissions during growth, particularly when grown in mixtures with non-legumes. Low N_2O emission are found during growth in mixtures of grain legumes (Dusenbury et al., 2008; Jensen et al., 2012; Jeuffroy et al., 2013; Pappa et al., 2011; Rochette and Janzen, 2005), green manure crops and CCs (Baggs et al., 2000b; Brozyna et al., 2013; Peyrard et al., 2016; Li et al., 2015; Shelton et al., 2018) as well as for grass-clover leys (Baggs et al., 2000b; Ball et al., 2002; Brozyna et al., 2013; Gattinger et al., 2018; Krauss et al., 2017b; Nadeem et al., 2012). This is consistent with low SMN concentrations during growth (see section 5) and negligible N_2O emissions associated with BNF by the legume rhizobium symbioses (Rochette and Janzen, 2005; Carter and Ambus, 2006). However, when the legume growth is restricted, reactive N release from dying roots and nodules may lead to enhanced N_2O emission (Rochette and Janzen 2005). Enhanced N_2O emission correlated with clover content has been observed during thawing of a frozen grass-clover ley (Sturite et al., 2014) or during rewetting of a grass-clover ley after drought (Hansen et al., 2014). Under drought conditions the nitrification process prevails and N_2O is produced at very low rates. The application of irrigation to avoid drought enhances N_2O production providing the conditions favourable for denitrification. In Mediterranean climates, different N_2O emission factors are therefore proposed for rainfed (0.27%) and irrigated (0.63%) cropping systems (Cayuela et al., 2017). Similarly, to enhance water and N use efficiency with fertigation systems, localised irrigation would also reduce N_2O emissions by achieving drier average soil conditions compared to other irrigation systems with higher average soil wetness (Sanz-Cobena et al., 2017).

Mulching of harvested herbage could theoretically enhance N_2O emissions due to mineral N released from the herbage. However, several studies show that mulching of grass-clover herbage on the growing ley only causes a slight increase in N_2O emissions (Brozyna et al., 2013; Möller and Stinner, 2009; Nadeem et al., 2012). None of the abovementioned studies have measured ammonia volatilization from mulched herbage, which could have been a major loss of released N corresponding to the findings of Larsson et al. (1998). Volatilized NH_3 will be redeposited elsewhere and may result in increased N_2O formation downstream, as reported by IPCC (IPCC, 2006), 1% of volatilized NH_3-N is estimated to convert to N_2O-N. To estimate total N_2O emissions from crop rotations, indirect emissions from N lost through NH_3 volatilization and NO_3 leaching should also be included.

In summary 6.1, N_2O growing crop: N_2O emissions during active growth of leguminous crops are small and insignificant.

6.2 Plant residues after incorporation, frost or drought

As outlined in section 4, there is an enhanced risk for N_2O emission from agricultural soils when easily degradable carbon and N are simultaneously available, and denitrification is probably the main source for this. In line with increased content of SMN (section 5), many studies have reported increased N_2O emissions following incorporation of legume residues in field trials whether the residues is from grain legumes (Jeuffroy et al., 2013; Pappa et al., 2011), grass-clover (Baggs et al., 2000b; Ball et al., 2007a; Gattinger et al., 2018; Nadeem et al., 2012; Brozyna et al., 2013), intercropped clover (Pappa et al., 2011) or CCs (Baggs et al., 2000b; Peyrard et al., 2016, Pugesgaard et al., 2017). Enhanced N_2O fluxes were observed up to several days after destruction of N-rich CCs (egyptian clover, oat, vetch alone or in mixture with oat, mustard, phacelia,) in two extensive cropping systems in south-west France with the highest flux rates around 60 g N_2O-N $ha^{-1}day^{-1}$ (Peyrard et al., 2016). However, the contribution of such events to cumulative N_2O emissions remained negligible in their study. Shelton et al. (2018) observed only small peaks of N_2O fluxes after incorporation of green manure residues (max 15 g N_2O-N $ha^{-1}day^{-1}$.

In an organic crop rotation (spring barley, faba bean, potato, winter wheat), Pugesgaard et al. (2017) never observed any high peaks of N_2O after incorporation of regular crop residues except a small peak (20 g N_2O-N $ha^{-1}day^{-1}$) after manuring and incorporation of faba bean residues in the spring. The well drained nature of the soil and low WFPS during the N_2O measurement period (Table S2), together with good conditions when soil tillage was carried out, are likely to be contributory factors here.

N_2O emissions may also be associated with previous incorporation of plant residues. In accordance with this, Gattinger et al., (submitted) observed enhanced N_2O fluxes after a maize crop succeeding a grass clover ley. Measurement of N_2O fluxes shortly after incorporation of plant material, or measurements the following year, only tell part of the story. Enhanced content of various fractions of SOM derived from crop residues, ley and CC (section 3.2) are likely to increase the long-term potential background emissions of N_2O (section 4.1). In a ten-year-old field experiment with various content of legume rich CC in the crop rotation, Pugesgaard et al. (2017) concluded that crop residues were important source of N_2O, and that mineralizable C, rather than N input, was the main driver for N_2O emission. Contrary to this, Peyrard et al. (2016) observed in a three-year low input field trial that although N_2O fluxes increased for a few days after CC, the contribution of such events to cumulative N_2O emissions were negligible. In this study however the CC treatments started when the N_2O measurements started. More studies in long-term experiments with CC are needed to verify the actual impact of crop residues in a long-term perspective in various field situations because addition of plant material to soil, does not only influence the content of SOM, but also earthworm activity, soil structure etc (section 3).

Frost

Freezing/thawing of soil rich in organic matter and soil biota or covered with plant residues may result in a N_2O boost as easily degradable C and N is released from cells blasted by frost. Flessa et al. (1995) observed that 46% of total annual N_2O emissions from a sunflower crop, solely fertilized with farmyard manure (12 tonnes per ha) occurred during December and January mainly due to high N_2O peak fluxes (650 g N_2O-N $ha^{-1}day^{-1}$) after thawing of the first freezing period during winter. Correspondingly, Westphal et al, (2018) did not observe any enhanced N_2O fluxes after late summer incorporation of a ley dominated by alfalfa (0-10 g N_2O-N ha^{-1} day^{-1}), but fluxes were greatly enhanced during spring thaw in the following year (60 g N_2O-N $ha^{-1}day^{-1}$).

When CCs are killed by frost, the N_2O fluxes will increase during thawing of the soil because of release of easily degradable carbon and N in plant material. Li et al, (2015) observed significantly higher emissions from fodder radish than from other CCs (red clover (CL), grass-clover (GC), winter vetch (WV), perennial ryegrass (GR), S2). The fodder radish was frost-sensitive and rich in readily degradable carbon. Until onset of the frost, fluxes were low. Increased fluxes were observed after a frost period in December, and highest in mid-February (Table S2) after a new frost period. However, the winter emissions were even greater when plant growth was terminated in autumn (30^{th} of October) and the soil left bare (Table S2). The tops of fodder radish were harvested and removed, and a large part of the roots remained in soil. This suggests that N and C in roots of frost sensitive CCs can be an important source for N_2O emissions after frost.

C/N-ratio

The C/N ratio of incorporated herbage may affect N_2O emissions, with higher emissions expected from herbage having low C/N-ratio (Chen et al., 2013). From this one should expect higher N_2O emission from legume residues than from cereal or grasses (e.g. Rochette and Janzen, 2005). Larsson et al. (1998) observed the same N_2O-N EF (1% of applied-N) from mulched alfalfa (C/N-ratio 11) as from mulched grass with a C/N ratio of 21, but higher EF than from a mulched grass with a low N-content (C/N-ratio 36, EF = 0.1%). Jeuffroy et al. (2013) and Lemke et al. (2007) did not observe higher N_2O fluxes after incorporation of pea residues compared to cereals. This illustrates that N_2O emissions from legume residues are not always higher than from other residues. The N_2O fluxes might be high despite a high C/N- ratio when the carbon source is easily degradable as observed by Li et al. (2015) (Table S2). The high N_2O fluxes associated with the frost killed fodder radish are probably caused by denitrification driven by the easily available C and release of low molecular N compounds under low temperature conditions (Thomsen et al., 2016). These observations indicate that it is not only the C/N ratio that is valid, but how the C and N are bound in the herbage.

Soil factors influencing losses after crop residue incorporation

If the soil has restricted aeration because of high water content or low porosity, simultaneously with decaying incorporated herbage, then the probability of high N_2O peaks is enhanced (e.g. Li et al., 2016a). Krauss et al. (2017b) observed high N_2O fluxes some days after weeds and crop residues were superficially incorporated with a rotary harrow in a wet soil (WFPS 80 %) in late August (Table S2, highest observed peak in single plot 800 g N_2O-N $ha^{-1}day^{-1}$). Baggs et al. (2000a) observed high N_2O fluxes (peak of 67 g N_2O-N $ha^{-1}day^{-1}$) after incorporation of lettuce residues with 65% of the total emissions emitted during 14 days after herbage incorporation. They observed higher N_2O fluxes when the residues were incorporated by rotary harrow than by ploughing. Similarly, Peyrard et al. (2016) observed that N_2O fluxes were enhanced (max rates 60 g N_2O-N $ha^{-1}day^{-1}$) up to several days after crop destruction when crop residues (sunflower, wheat, faba bean) were mulched or placed near the soil surface, but not by ploughing or mechanical weeding. Restricted air diffusion is a likely explanation for the observed lower N_2O fluxes with deep incorporation of crop residues, where N_2O is reduced to N_2 and is in accordance with a general trend of a larger ratio of N_2O-N/(N_2O-N+N_2-N) close to the soil surface and smaller fluxes deeper in the soil profile (Sahrawat and Keeney, 1986). Kuntz et al. (2016) observed a decreased O_2 concentration at 8 cm soil depth and a corresponding reduction of N_2O to N_2, even with surface application of carbon rich material. Petersen et al. (2011) found that crop residues from CC of fodder radish, stimulated N_2O fluxes following spring cultivation and slurry application. In their case, the largest fluxes were observed when residues were incorporated by ploughing (100 versus 210 g N_2O-N $ha^{-1}day^{-1}$ for reduced tillage and ploughed residues respectively). A possible explanation for this could be that residues came directly into contact with the injected slurry after ploughing, thus fostering enhanced microbial turnover of C and N.

The time of ploughing crop residues also affects N_2O emissions. Ball et al. (2007a) concluded that early spring was the best time of the year to plough a grass-clover ley to minimize N_2O emissions as microbial activity is reduced at low soil temperatures. However, the soil must be friable, which can be a challenge for many soil types and climates in early spring.

In summary 6.2, N_2O crop residues: There are large risks for N_2O emissions when large amounts of plant herbage with easily degradable N and C are incorporated into soil or left on soil surface. Freezing / thawing, drying / rewetting, dense and/or wet soil, mixing with rotary harrow enhances the risk for N_2O emissions. It is not only the C/N ratio that influences the risk of N_2O emissions, but also the degradability of N and C. In the long-term incorporation of crop residues and other herbage may increase N_2O emissions because of enhanced SOM content.

6.3 Organic fertilizers

Organic fertilizers have a large variation in the content and types of N and C compounds. Their impact on N_2O emissions will therefore vary widely. Animal slurries contain more easily degradable N and C than solid manures and composts and are thus stronger triggers for rapid N_2O emissions shortly after application (Charles et al., 2017, section 3). In accordance with this, Krauss et al. (2017b) observed higher N_2O emissions shortly after application of cattle slurry than composted solid cattle manure. Correspondingly, in a field experiment with spring barley fertilized with various organic slurries, Baral et al. (2017) observed highest N_2O EF in the treatment with highest application of organic matter, and thus highest content of easily degradable C. Meijide et al. (2007) found that the C/N ratio of organic fertilizer was a good predictor of the observed denitrification losses.

Anaerobic digestion of slurries will reduce the amount of easily degradable C as this C is reduced to CH_4. In accordance with this, Meijide et al. (2007) found that the use of digested slurry compared to untreated pig slurry reduced soil N_2O emissions by 25% in an irrigated maize crop in a Mediterranean climate. However, Rivedal et al. (2012) observed slightly higher N_2O emissions after digested than untreated cattle slurry in well aerated grassland in Norway. The reasons for this discrepancy are probably that the main N_2O emissions are caused by different processes in these two cases. In the field trial conducted by Meijide et al. (2007), denitrification was the main trigger for N_2O emissions, whereas in Norway the higher NH_4-N content in the digested slurry likely led to enhanced nitrifier denitrification.

Because of the absence of synthetic fertilizers, organic fertilizers are likely to have a smaller short-term impact on N_2O emission in organic than in non-organic crop production as found by Charles et al. (2017). In a meta-analysis, they found that the N_2O EF was higher when soils received organic amendments in combination with synthetic fertilizers. They found EFs for liquid manures + synthetic fertilizers = 2.14 % (± 0.53), composts + synthetic fertilizers = 0.37 % (± 0.24), and the corresponding EFs without synthetic fertilizers equal to 1.12 % (±0 .18) and 0.00% (± 0.17).

The long-term impact of manures is not included in these EFs. In contrast to this short-term fertilizer effect, a long-term change of fertilization treatment may indirectly influence N_2O emissions. Chang et al. (1998) observed that annual N_2O emission increased with manure rate when different rates of solid feedlot manure and thus N-application were applied for 21 years. They concluded that the results probably reflected the accumulation of NO_3^- and organic matter from repeated manuring and suggested that the N_2O emissions from long-term manured soils may be underestimated by quantifying fluxes from short-term manuring studies. Their lowest manure rate was 60 Mg manure ha^{-1}, which equalled 557 kg N ha^{-1} yr^{-1} and gave an emission of 11 kg N_2O-N ha^{-1} yr^{-1} and an EF of 1.8 (Calculated from Chang et al., 1998, control= 0.7 kg N_2O-N). However, this manure rate is far from realistic for organic arable conditions, but the possibility for enhanced baseline N_2O emissions after long-term input of organic matter through manuring and application of crop residues should be considered. Krauss et al. (2017b) found that fertilization with slurry and manure compost, compared to sole slurry fertilization, increased annual N_2O emissions after more than ten years of differentiated management and related this to higher contents of SOC.

Although composts have a small impact on N_2O emissions when applied to soil, during composting there can be significant N_2O and NH_3 emissions (Chadwick et al., 2011; Webb et al., 2012, Pardo et al., 2015, Bernal et al., 2017). In their meta-analyses Pardo et al. (2015) observed the highest mean N_2O losses for turned compost with forced aeration (3.8 % of N added) and the highest NH_3 losses from turned compost (21% of N added). The emissions can be reduced by optimal management of C:N ratio and porosity (Jiang et al., 2011). Combining negative aeration static piles (NASP: Smith et al., 2016) and biofilters where the exhaust is passed through a biofilter before being released is a possible technology. It is a large risk however, that NH_3 trapped in the biofilter triggers N_2O production (Maia et al., 2011). To avoid N_2O production, and at the same time reduce NH_3 emission, homogeny biofilters and a correct balance in moisture content is needed. If the biofilter is to porous or dry, NH_3 is emitted, and if it is to dense or wet N_2O is produced (Maia et al., 2012). This is most challenging shortly after the start of composting when the NH_3 emissions are large (Bernal et al., 2017). Covering the heap with a dens layer may reduce NH_3 emissions, without increasing N_2O emissions (Pardo et al., 2015). N_2O emission during composting may also be reduced by addition of biochar (Li et al., 2016b) and other specific additives (Pardo et al., 2015).

In summary 6.3, Organic fertilizers: Per unit of total-N applied, we expect higher N_2O emissions shortly after application of organic fertilizers/amendments with high content of easily degradable N and C than if applied in less degradable form like compost, but smaller compared to when they are combined with synthetic fertilizers. Long-term manuring may enhance background emissions. N_2O and NH_3 emissions can be high during composting.

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6.4 Contribution of total N-input and high emission events on N_2O emissions

Skinner et al. (2014) concluded in their review that soil characteristics (N-content in soil) had a larger impact on N_2O emissions from organic production than the total-N input by fertilization. They have related this to the background emission and this is in accordance with the general observation of increased N_2O emission with increased content of SOM (section 4.1) This also corresponds to the more recent findings of Krauss et al. (2017b), Peyrard et al. (2016) and Pugesgaard et al. (2017). Pugesgaard et al. (2017) observed no significant correlation between N_2O emissions and N input in fertilizer/manure, for either annual emissions or spring emissions, but N_2O emissions were correlated with N input in residues from the previous main crop and CC (r = 0.56, p < 0.01). This is in accordance with the discussion in section 6.2 and with Bouwman et al. (2002), van Groenigen et al. (2010) and Peyrard et al. (2016). None of these studies observed any significant relationship between fertilizer N application rate and N_2O emissions when N fertilization was below optimum. As N-supply is normally below optimum in organic production (section 3.4) their findings can be related to organic production. When the N-supply is below optimum the available/applied N will be taken up quickly by growing plants. In accordance with this, Shcherbak et al. (2014), in their meta-analyses, found that at low fertilization rate, the fertilizer derived N_2O emissions were low, and that the EF were lower than the 1% suggested by IPCC.

A regression based on data from table S2 showed that the content of NO_3-N in soil and soil temperature had significant positive impacts on peak N_2O fluxes and this was also affected by site ($P_{NO3} < 0.01$, $P_{temperature} < 0.01$, $P_{site} < 0.001$, model 2 section 2). WFPS alone did not have a significant impact, but there was a significant interaction with NO_3-N ($P_{WFPS*NO3} < 0.01$), site ($P_{WFPS*site} < 0.001$) and soil temperature ($P_{WFPS*temp} < 0.001$, model 1 section 2). The content of NH_4-N in soil did not affect peak N_2O fluxes. These findings indicate that denitrification caused by simultaneous presence of easily available C and N during reducing conditions, is the main cause for high N_2O-flux rates in these investigations. In Frick (CH), Edinburgh (UK), Aberdeen (UK) and Ås (NO), the highest daily flux rates were 605, 211, 297 and 94 g N_2O-N $ha^{-1}day^{-1}$ respectively (Table S2). Because of the high flux rates, we could expect that high emission events could be responsible for a major part of the N_2O emissions from these systems. The single days with the highest fluxes correspond to 18% (65 days measurement period) in Frick, 2% in Edinburgh (161 days), 17 % in Aberdeen (38 days) and, 2% in Ås (218 days) of the cumulated N_2O emissions in the measurement periods. The five highest daily N_2O fluxes corresponded to 22, 7, 55 and 5% of the N_2O emission in the measurement periods in these investigations, respectively. In field trials conducted on well-structured sandy loams at either Foulum or Flakkebjerg in Denmark (Table S2), peak N_2O fluxes from one or five days, however, only constituted from <1- 8% and 5-14% of the total emission in the period, respectively. The highest daily flux rate in these trials was only 78 g N_2O-N $ha^{-1}day^{-1}$. This was in a treatment heavily fertilized with cattle slurry and digested sewage sludge (476 kg total N ha^{-1}, Table S2 (Baral et al., 2017)). The small peaks in the Danish field trials compared with the other sites reveals that well-drained light soils promote rapid water infiltration and good gas-diffusivity and in turn lower N_2O emissions.

Fitting the regression model in eq. 2 to the data gives R^2 = 69 %. From this we can conclude that when the conditions for high N_2O fluxes are met, there is a large chance for high N_2O emissions. In soils with good structure where the emissions are generally low, enhanced background emissions seem to be the main cause for the N_2O emissions.

In summary 6.4, total-N, SMN: There is no significant correlation between total N-input and N_2O emissions from organic arable crop rotations. The high emission events only constitute a minor part of the total N_2O emissions, particularly in soils with good gas-diffusivity and related to longer measurement periods, but at sites with high emission events of N_2O, there is a large chance of high total N_2O emissions.

6.5 Impacts of earthworms and pH

Abundant earthworm populations in organic crop rotations (section 3.3) are likely to influence N_2O fluxes as they significantly affect mineralization and reduction of N compounds to N_2O and N_2 (Prieto, 2011). On the other hand, they

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improve soil porosity and aggregate stability (Bronick and Lal, 2005) and thus gas-diffusivity and infiltration in soils, which will reduce N_2O emission. N_2O is emitted from intestinal microbes, but it is also released from nitrates emitted in body fluids as well as from casts, middens and burrows (Prieto, 2011). Epigeic species (living near surface and feeding on surface litter) and anecic species (deep burrowing) are well known to enhance N_2O production, because they feed directly on decomposing herbage (Evers et al., 2010; Nebert et al., 2011; Lubbers et al., 2011). Endogeic earthworms that feed on soil organic matter particles are most common in cultivated arable soils (Hansen and Engelstad, 1999), and do not increase denitrification (Postma-Blaauw et al., 2006). There are too few published field trials to robustly predict the impact of earthworms in arable organic crop rotations on N_2O emissions as this will depend on local climatic and edaphic conditions.

Although, N_2O reductase will be reduced by low pH, we do not know the overall impact of pH in organic production on N_2O-emissions as N_2O emissions are influenced by many factors (section 4.1). An incubation study from the DOK-trial (Krause et al., 2017) showed that with the same pH, the ratio of $N_2O/(N_2O+N_2)$ in gas fluxes from soil from the organic treatment was higher than from soil from the non-organic treatment, thus maintaining the functionality of microbial N_2O reduction in the long term and without further need for liming. This was likely to have been influenced by different fertilization history. Rapid soil pH increase by liming will induce many changes in soil including increased OM decomposition, higher microbial activity, higher respiration and microbial community change, which ultimately could lead to anoxia, higher denitrification and related N_2O emission potential. On the other hand, gradual pH increase caused by organic fertilization or by a careful liming (section 3.5) would avoid these circumstances and thus might reduce denitrification related transient N_2O flux peaks from soil observed after liming with rapid pH increase (Baggs et al., 2010).

In summary 6.5, Earthworms and pH: Earthworms have a large impact on decomposition of organic matter with corresponding associated denitrification, but earthworms also improve soil structure. The effect on N_2O is thus difficult to assess. Low pH will increase N_2O emissions also in organic crop production, but absence of rapid soil pH fluctuation caused by N-fertilization and liming is likely positive for mitigating N_2O emissions.

7 Possible triggers of NO_3 leaching in organic arable crop rotations

Table S3. [S3_Supplementary material 3_Leaching]

The design of crop rotation by choice of crop species and their cropping sequence influences the risk of N leaching from the cropping system (Kirchmann and Bergström, 2001). Typical triggers of nitrate leaching are situations when there is a large pool of soil mineralizable N and no or low uptake of the mineral N by a crop. This could happen outside the growing season, but also when there is poor crop establishment caused by unfavourable seedbed structure or from crop failure caused by diseases or pests (Stenberg et al., 2012). If a crop failure coincides with rainy weather, the risk for severe N leaching is large. This was observed by Torstensson et al. (2006) and De Notaris et al. (2018) where potato growth was restricted due to early crop termination following disease outbreaks. Torstensson et al. (2006) determined the annual leaching in the potato year to be 75 kg N ha^{-1} after green manure and 98 kg N ha^{-1} after pea/barley (Table S3). De Notaris et al. (2018) determined the annual leaching in the potato year to be 213 kg N ha^{-1} after green manure and 133 kg N ha^{-1} after grain legumes in a year with early occurring potato late blight. This was substantially higher than in previous years (140 and 78 kg N ha^{-1}, respectively), and could be reduced by growing CCs (see section 7.2). Because of the generally low content of soil mineral-N under organic cereals (see section 5), leaching under healthy cereal crops is expected to be low (Aronsson et al., 2007).

7.1 Legumes

In a crop rotation where N is added to the system by leguminous crops, N will to some extent be removed from the system by harvesting, but N will also be left in the soil in crop residues and green manures. Particularly substantial amounts of N derived from BNF are added to the soil by mulched green manures (Frøseth et al., 2014). In their review, Crews and Peoples (2005) found that when the N input was based on BNF the proportion of the N retained in the soil was higher (58% of legume N) than in the fertilized systems (31% of fertilizer N). The risk for N release outside the crop growing period may therefore be higher than in rotations without legumes. However, with good management the risk can be highly reduced (section 5). In their meta-analyses of crop yield and N dynamics as influenced by CCs, Tonitto et al., (2006) concluded that on average, nitrate leaching was reduced by 40% in legume-based systems relative to conventional fertilizer-based systems. The reason for this is probably the large difference in N input between legume-based systems relative to conventional fertilizer-based systems. The response of N leaching to N input in fertilizer, manure and residues may also differ between sites due to soil type and precipitation (Pandey et al. 2018).

Grain legumes

In general, low nitrate leaching is reported from crop residues of grain legumes. Highest values are found when grain legumes are grown in monoculture rather than in mixtures with e.g. cereals, and when CCs are not used (Plaza-Bonilla et al. 2015). Stenberg et al. (2012) observed that nitrate leaching tended to peak after faba bean compared to after non-leguminous crops. On a clay soil in Sweden, they observed an average leaching of 20 kg N ha^{-1} yr^{-1} which was twice as high as for spring cereals. On average over three years on loamy sand in Denmark, De Notaris et al. (2018) observed 50 kg N ha^{-1} yr^{-1} (38-64 kg N ha^{-1} yr^{-1}) leached in spring wheat following grain legumes. In a sandy soil in northwest Germany, Kayser et al. (2010) observed that 83 kg N ha^{-1} was leached in triticale following field bean. In a worst-case situation, Askegaard et al. (2011) observed annual nitrate leaching of 270 kg N ha^{-1} during and after a lupin crop on a course sandy soil in a situation where the lupin crop did not ripen leaving a large amount of N in crop residues (same experiment as De Notaris et al. 2018). Pappa et al. (2008) observed very low N-leaching during and after a barley/pea intercrop, but they observed a significant effect of the pea cultivar in the autumn and winter period after harvest. The difference between the two cultivars Nitouche and Zero was small but significant at 4 kg NO_3-N ha^{-1}.

Forage legumes

Many authors (Kayser et al., 2010; Neumann et al., 2011; Stalenga and Jończyk, 2008) emphasize that one of the most critical times for nitrate leaching in organic crop rotations is after the incorporation of grass-clover ley. N leaching was low during the growing period of grass-clover leys (Kayser et al., 2010), but because of the large amounts of mineral N released to soil after termination of green-manure or forage ley, the risk of N-leaching is large for one to two years after termination of these crops (Berntsen et al., 2005). The leaching may occur shortly after ley termination, during winter, or during the succeeding seasons, depending on time of incorporation, quality of the herbage, the weather and the crop sequence. Stenberg et al. (2012) observed higher N leaching following termination of a grass-clover ley than following faba bean, but values were still low (4 kg N ha^{-1} higher in average). They found the highest leaching when the grass-clover ley lasted for two years (up to 40 kg N leached ha^{-1} yr^{-1}). This corresponds to the finding of Kayser et al., (2010), who observed greater N leaching the winter after spring incorporation of a three-year ley than after a one-year ley (121 versus 83 kg N ha^{-1}). However, the crop yield of triticale was much better after the three-year ley than after the one-year ley. The share of clover (0-5, 30 and 50%) did not influence the amount leached after ley termination, neither the crop yield. In contrast, Eriksen et al. (2008) measured leaching after 1 to 8 year old grass/clover leys but found that the length of the ley had no effect on nitrate leaching. Stenberg et al. (2012) observed that cereals succeeding grass-clover ley had nearly double yearly N leaching compared to cereals with no legume pre-crop. The highest N leaching occurred after cultivation of a winter rye (48 kg N ha^{-1} yr^{-1}). De Notaris et al. (2018) observed that the leaching during cultivation of spring wheat was about 50 kg N ha^{-1} higher when the spring wheat succeeded a two-year green manure crop (alfalfa or ryegrass and clover) than when it succeeded a grain legume (107 versus 50 kg N ha^{-1}). Similarly, Askegaard et al. (2011) observed peaks in N leaching in autumn and winter after ploughing-in grass-clover ley. However, at crop rotation level, neither inclusion of grass-clover on 25% of the area nor the time of termination of it (spring or autumn) influenced N leaching.

Forage legumes may also be undersown as intercrops to increase soil fertility in organic crop rotations. Pappa et al. (2008) found that clover intercropped in spring barley resulted in a significantly increased N leaching during the cultivation year and in oats the year after. However, the amounts leached were very small, 1 kg NO_3-N ha^{-1} in barley and 2 kg NO_3-N ha^{-1} in oats.

Summing up 7.1, Leguminous: Normally, the leaching during cultivation of legumes are small, but the leaching may be substantial after legume cultivation. In general, higher leaching is observed after forage legumes than grain legumes.

7.2 Catch crops

Catch crops (CC) are grown between main crops to minimize nitrate leaching by plant N uptake in periods when no main crop is grown. Many field trials have shown reduced leaching using CC (among others Rasse et al., 2000; Torstensson and Aronsson, 2000; Constantin et al., 2010; Valkama et al., 2015). This is also the case for organic crop rotations (Tonitto et al., 2006; Askegaard et al., 2011; Tosti et al., 2014; Tosti et al., 2016; De Notaris et al., 2018). The reduction in N leaching can be substantial. Studies in Nordic countries report reductions of 50-60% in N leaching (Askegaard et al., 2011; De Notaris et al., 2018; Torstensson and Aronsson, 2000). If the cash crop fails, the effect of CCs on can be even higher. In a year with crop failure in potato because of potato blight, the CCs reduced N-leaching by 95% when the potato succeeded a grain legume (from 133 to 6 kg N ha^{-1} leached), and by 92% when the potato succeeded a green manure ley (from 213 to 17 kg N ha^{-1} leached) (calculated from Table S3, De Notaris et al., 2018).

De Notaris et al. (2018) concluded that the use of CCs had a larger impact on leaching than a substantial variation in N surplus between alternative cropping systems. In three long-term field trials (13-17 years) in Northern France, Constantin et al. (2010) observed that CCs were the most efficient measure to decrease N leaching (from 36 to 62%) and remained efficient in the long term. Good establishment and growth of the CC is essential to obtain sufficient uptake of SMN and thus reduce N leaching. Stenberg et al. (1999) did not get any significant reduced nitrate leaching during winter from a ryegrass CC that was undersown in spring. They explained this with poor establishment of the CC. De Notaris et al. (2018) also observed occasions with very small impact of CCs on nitrate leaching. They related this to CC growth in early November and identified threshold values in CC above-ground biomass, above which N leaching was reduced to a low stable level. N leaching from spring wheat averaged 15 (sd=8) kg N ha^{-1} yr^{-1} with CC biomass above 0.9 Mg ha^{-1}, and 41 (sd=29) kg N ha^{-1} yr^{-1} with CC biomass below 0.9 Mg ha^{-1}. In potatoes, the average N leaching was 11 kg N ha^{-1} yr^{-1} (sd=6) with CC biomass above 1.5 Mg ha^{-1}, and 80 kg N ha^{-1} yr^{-1} (sd=36) below.

Including legumes in CCs mixtures does not seem to reduce the ability of CCs to reduce N leaching (Tonitto et al., 2006; Tosti et al., 2014; De Notaris et al., 2018; Shelton et al., 2018). In a field trial with barley, hairy vetch and a 50:50 mixture of both species as CC, Tosti et al. (2014) found that, in all years, the barley/vetch mixture decreased N leaching at the same level of pure barley, both during its own growing cycle and after CC incorporation into the soil. De Notaris et al. (2018) concluded that the same degree of reduced N leaching was obtained with legume-based CCs as with non-legume CCs. The CC was either undersown in spring or after harvest of the main crop. The undersown legumes were white clover and red clover, and winter vetch was used in the mixture sown after harvest. Shelton et al. (2018) found greater N leaching from intercropped hairy vetch than from simultaneously grown wheat and wheat/hairy vetch mixture. When CC constitute legumes in pure stand, the CC does not necessarily reduce N leaching (Tosti et al., 2014; Valkama et al., 2015; Shelton et al., 2018). Tosti et al. (2014) concluded that hairy vetch sown as pure crop in autumn showed a high BNF, but no NO_3-N leaching mitigation effect as compared to bare soil. Valkama et al. (2015) found in their meta-analysis of Nordic studies of under sown CCs that legumes (white and red clovers) in pure stand did not diminish the risk for N leaching.

Summing up 7.2, Catch crops: Well established catch crops have a significant ability to reduce N leaching. Including legumes in the mixtures does not reduce the ability of CCs to reduce N leaching, but pure legume crops have not been shown to reduce leaching.

7.3 Tillage: time of the year and method

Tillage stimulates mineralization, at least in the short term. Timing of tillage is therefore crucial for the N use efficiency of the following crops, and thereby the risk of N leaching when crop residues, green manures or CCs are incorporated into the soil. In general, incorporation should consider soil type, climate conditions and type of herbage (C/N ratio). Thorup-Kristensen and Dresbøll (2010) suggest a late incorporation of CCs in high rainfall areas on sandy soils, and earlier in low rainfall areas on nitrate retentive soils. Field studies have shown rapid N mineralization from N-rich plant material, even at low temperatures (Breland, 1994; Thorup-Kristensen and Dresbøll, 2010). Spring incorporation has therefore been recommended to increase N recovery by subsequent crops. However, under Scandinavian conditions, there may still be a deficit in crop-available N, even after spring incorporation of a green manure ley (Frøseth et al. 2014; Känkänen et al., 1998). Under such conditions, Torsteinsson and Aronsson (2000) suggest that late autumn incorporation of CCs, instead of spring incorporation, will be preferable with respect to N availability for the subsequent crop and will not increase N leaching. Under Mediterranean climate conditions, characterized by mild rainy winters and warm to hot dry summers, there is a risk of N leaching if organic matter is incorporated prior to the wet season. No studies were found that measured N leaching in relation to timing of tillage in organic arable farming under these conditions.

In organic crop production, the timing of mechanical cultivation for control of perennial weeds may conflict with the aims of high N use efficiency (Melander et al., 2016). Askegaard et al. (2011) found, on sandy soils in Denmark, that the management of crop and soil during autumn was the main determinant of N leaching. Stubble harrowing in autumn for controlling perennial weeds, followed by bare soil during winter, led to an average of 25 kg N ha^{-1} more leached than for soils left untouched with a cover of weeds/volunteers. N leaching increased with increasing number of autumn soil cultivations.

Compared to conventional tillage, reduced tillage may reduce N leaching, but its suitability over time depends on the establishment and growth of the succeeding crop (Känkänen et al., 1998). In their meta-analysis comparing different reduced tillage intensities in organic farming, Cooper et al. (2016) found that using inversion tillage to only a shallow depth (<25 cm) relative to deep inversion (≥25 cm) resulted in minimal reductions in yield, but significantly higher soil carbon stocks in topsoil and better weed control. N leaching was not a part of this study but may be related to yields and need for weed management. They found that weeds were consistently higher, by about 50 %, when tillage intensity was reduced, although this did not always lower yields.

Bare fallow has traditionally been a method to control perennial weeds by repeated tillage of superficial or deeper top soil layers. In organic farming in practice, a bare fallow can sometimes be used before or after the main crop if conditions have promoted perennial weeds. However, if carried out in the growing season, soil temperature and moisture conditions favour soil microbial activity and therefore the build-up of SMN, and therefore increases the risk of N leaching (Borgen et al., 2012).

Summing up 7.3, Tillage: Incorporation of N rich plant residues or mechanical weeding followed by bare soil leaves the soil exposed to N leaching. N leaching caused by tillage is strongly related to soil type and climate.

7.4 Soil type and climate

The soil type and climate have a large impact on when and how much N is leached with the greatest risk in sandy soils, and in areas with heavy rainfall (Di and Cameron, 2002). The risk of N leaching on sandy soils is enhanced if shallow rooted crops are grown. That also enhances N leaching risk during wet spring and summer periods. This is no different from non-organic cropping systems. The impact of soil type was clearly demonstrated in Denmark. Askegaard et al. (2011) found that, depending on soil type (coarse sand>loamy sand>sandy loam) and precipitation, 20-100 kg N ha^{-1} yr^{-1} was leached on average for the crop rotations. In this study, the location on coarse sand had 200-300 more mm rainfall per year than the other locations. The leaching was higher than in the Swedish clay soils (20 kg N ha^{-1} yr^{-1}, Stenberg et al. 2012).
Extreme rainfall events and/or periods with drought can significantly affect leaching for a variety of reasons. A field experiment over 13-years in the UK showed that N leaching in winter from fertilized grass (non-organic) was highly correlated with the preceding summer's soil moisture deficit, with the highest losses following dry summers (Tyson et al., 1997). Tosti et al. (2016) found, under Mediterranean rainfed conditions, that the risk of N leaching was mainly at the onset of drainage due to rainfall, i.e., at the initial stage of growth, and being typically variable among years depending on timing of heavy rains. Thus, amendments applied at pre-crop stage would be a risky practice for N leaching. Most leaching studies in organic farming in Mediterranean environments are focused on row and vegetables crops e.g .Campanelli and Campali (2012) because these systems are most demanding in N inputs and thus higher N applications and potential leaching than in arable crops are common.

Summing up 7.4 Soil type and climate: Sandy soils and heavy rainfall increase the likelihood of leaching losses

7.5 Effect of earthworms on NO_3 leaching

The effect of earthworms on nitrate leaching depends on several factors: availability of organic matter, density of earthworm burrows and rainfall intensity. Burrows of the anecic species *Lumbricus terrestris* can reach 1-2 m in the soil and may be significantly transport routes for water and N compounds to the groundwater (Domínguez et al., 2004). A high density of individual anecic earthworms can significantly affect N elution (Edwards et al., 1989), but also increase water infiltration, reduce water runoff and soil erosion (Kautz, 2015) and thus reduce losses. In arable crop rotations, endogeic species dominate, but perennial ley will increase the number of anecic earthworms. Because earthworm channels are important pathways for root elongation, they can also facilitate the retrieval of nutrients from the subsoil (Kautz, 2015) and thus prevent further leaching. Earthworm activity may enhance physical protection of SOM in aggregates which prevent N from mineralization (Angst et al., 2017; Bronick and Lal, 2005; Ketterings et al., 1997).

Summing up 7.5, Earthworms: Earthworms channels may increase leaching, but they also facilitate root elongation to subsoil and stabilization of SOM.

8 Suggested strategies to mitigate N_2O emissions and NO_3 leaching

The main strategy to mitigate N_2O emissions and NO_3 leaching and simultaneously enhance yields in organic crop rotations is to efficiently recycle N in the system, until it can be utilized by crops. Strategies for increased N efficiency in organic cropping systems is comprehensively reviewed by Watson et al. (in prep.). Because weeds, pests and nutritional deficiencies other than N are also important reasons for yield limitations in organic crop rotations, measures that improve these are important to mitigate N_2O emissions and NO_3 leaching. Such measures are discussed in many advisory books for organic

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farming and are too comprehensive to discuss here. See for instance Köpke (2018), Vacante et al. (2017) and Younie, (2012).
In the present paper, we will therefore concentrate on some key points for farmers to reduce N_2O emission and NO_3 leaching from organic arable crop rotations based on the findings in the previous sections.

8.1 Strategies that simultaneously reduce N_2O emissions and NO_3 leaching

One of the main strategies is the avoidance of large quantities of herbage applied to soil through mulching, ley herbage or crop residues. After decomposition large quantities of herbage creates hotspots as well as hot moments for N_2O emissions and NO_3 leaching. N-rich residues may instead be moved within the farm to fields deficient in N. The N use efficiency of the residues can be enhanced by various treatments such as digestion or composting (Watson et al., In prep.).
It is important to create a rotation design that retains N within the systems, so that accessible N is taken up and utilized by the following crop. A succeeding crop or CC with high NO_3 uptake initiated early after establishment, as for instance mustard, is a way to do this. When soil conditions allow, early spring is the best time of the year to terminate and incorporate catch crops and leys. By the application of crop residues, other herbage and organic fertilizers and/or the use of catch crops, the amount of labile organic matter in soil are increased. On occasions with bare soil, the C and N in the labile organic matter is rapidly decomposed with large potentials for denitrification and N leaching losses.
Maintaining labile organic matter in soil through input of plant material therefore requires continued use of CCs, and bare soil conditions should be avoided. This requires new approaches for controlling perennial weeds such as couch grass (Rasmussen et al., 2014) and thistles (Melander et al., 2016). Soil water content is a key issue in controlling both denitrification and leaching and good soil structure is imperative for maintaining adequate drainage (to prevent flooding) but also sufficient water holding capacity to enable crop growth in dry conditions.

8.2 Strategies for mitigating N_2O emissions

To reduce stimulation of denitrification, it is important to avoid conditions under which high concentrations of degradable C and N occur especially in combination with moist and warm soil conditions (sections 4.1 and 6.2). Thus, we recommend that residues from crops comprising easily decomposable tissue like clover and Brassica are removed from fields, and composted or used in a biogas plant before redistributed to soil. To minimise N_2O and other greenhouse gas emissions during composting of organic material, practical steps such as optimal C:N ratio and porosity covering the compost heap can be taken as outlined in section 6.3. Optimal composting is however, challenging and more research is needed to effectively reduce the risk of high N_2O emissions during composting.
Because of the large impact of poorly aerated soil on N_2O emissions (sections 4.1, 6.2), measures should be taken to improve and maintain a good soil structure. In organic production, soil fauna, microorganisms and soil structure, are supported by crop rotations that include legumes or grass clover leys, use of CCs and application of organic fertilizers. However, despite this, traffic and tillage under wet soil conditions are damaging, and should be avoided. Tilling moist soil will particularly increase risk for N_2O emission, because crop residues are crushed, herbage and soil are mixed and soil structure is destroyed. Controlled traffic and other strategies that reduce soil compaction are recommended. In soil that is not freely draining, good drainage systems must be ensured. In case of low pH, careful liming should be done to enhance pH to above 6.

8.3 Strategies for specifically mitigating NO_3 leaching

The choice of crops in the cropping system, both in time and space, is the central strategy for specifically mitigating NO_3 leaching in organic systems. The knowledge about the rooting pattern of different crop species can be used as a tool for designing crop rotations that achieve higher N use efficiency and thereby reduces the risk of NO_3 leaching. Deep-rooted

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crops, especially tap rooted ones, can recover NO_3 from deeper soil layers before and after more shallow-rooted cash crops, such as leek (Thorup-Kristensen, 2007). As shown by Fan et al. (2016), the root distribution and rooting depth may differ between varieties although plant breeders do not normally select crops based on the root system. In addition to the rotation of the main crops, including CC has great potential for reducing NO_3 leaching, whether the CC is legume-based or not (De Notaris et al., 2018). The choice of CC must be adapted to local conditions so that frost tolerant and drought tolerant varieties are used where appropriate. A mixture of legumes and non-legumes (for instance grasses or cereals) are just as efficient for reducing N leaching as sole non-legume CCs, whereas sole legumes are not recommended CC (section 7.2).

For the choice of crop, species and varieties should be well-adapted to the climate conditions on the farm and the soil fertility level. Crops in good conditions are also more able to compete against weeds. This decreases the need for soil management to achieve weed control, and thereby reduces the risk of N leaching. Timing of release of N from residues and amendments and crop uptake are crucial for minimizing the risk for NO_3 leaching. This can be achieved by timing of soil tillage and incorporation of residues. In any case, the effect of mitigation strategy is highly dependent on soil type and precipitation.

10 Conclusions

Maintenance and improvement of soil fertility is paramount for maintaining good yields in arable organic systems. At the same time, enhanced fertility and thus nitrogen status increases the potential for N_2O emissions and NO_3-leaching when labile N is not taken up by the crop. SMN pools are generally small under growing crops in organic arable farming, and the largest risks for accumulation of SMN are after crop termination or crop harvest when crop residues are left in soil.

Mineralization of organic matter derived from plant residues, organic amendments or SOM are the main sources for SMN. The risk for high N_2O fluxes is increased when large amounts of plant herbage or organic fertilizers with easily degradable C and N are incorporated into soil or left on the soil surface. Freezing/thawing, drying/wetting, dense and/or wet soil and mixing with rotary harrow enhances the risk high N_2O fluxes. At sites with high emission events of N_2O, there is a large chance for high total N_2O emissions. However, single high N_2O fluxes have limited impact on total N_2O emissions in soils with good gas-diffusivity. There is no clear correlation between total N-input and N_2O emissions from organic arable crop rotations, which is consistent with the findings from non-organic crop rotations with sub-optimal N-supply.

The highest risk for leaching is after incorporation of N-rich plant residue or mechanical weeding followed by bare fallow or crop failure which in both cases leaves the soil exposed to N leaching. Reduced tillage may reduce N leaching if crop growth is maintained.

Collecting and targeted treatment and use of herbage from green manures, crop residues and catch crops will increase N use efficiency and reduce N_2O emissions and NO_3 leaching. Continued use of catch crops has a proven ability to reduce NO_3 leaching from organic arable crop rotations. A mixture of legumes and non-legumes (for instance grasses or cereals) are just as efficient catch crops as sole non-legumes and have a better impact on soil fertility than non-legumes. Crop rotations where deep-rooted crops succeed crops leaving a high content of SMN, will correspondingly keep the N in the system and reduce leaching.

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Doltra: Content of the MS, mainly from Mediterranean perspective; Shahid Nadeem: Content of the MS, mainly N_2O, complementary data from Norwegian field trial in Table S2, Torfinn Torp; Statistical analyses on cause of N_2O fluxes based on Table S2; Valentini Pappa; Complementary data from field trials in Edinburgh and Aberdeen in Table S2, Christine Watson: Overall development and content of the MS.

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References

Aguilera, E., Lassaletta, L., Gattinger, A., and Gimeno, B. S.: Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis, Agric. Ecosyst. Environ., 168, 25–36, doi:10.1016/j.agee.2013.02.003, 2013.

Anderson, J. H.: The metabolism of hydroxylamine to nitrite by Nitrosomonas, Biochem. J., 91, 8–17, 1964.

Anderson, T.-H., and Domsch, K. H.: Ratios of microbial biomass carbon to total organic carbon in arable soils, Soil Biol. Biochem., 21(4), 471–479, doi:10.1016/0038-0717(89)90117-X, 1989.

Anderson, I.C., Poth, M., Homstead, J., and Burdige, D.: A comparison of NO and N2O production by the autotrophic nitrifier Nitrosomonas europaea and the heterotrophic nitrifier Alcaligenes faecalis, Appl. Environ. Microbiol., 59: 3525–3533, 1993.

Angst, Š., Mueller, C. W., Cajthaml, T., Angst, G., Lhotáková, Z., Bartuška, M., Špaldoňová, A., and Frouz, J.: Stabilization of soil organic matter by earthworms is connected with physical protection rather than with chemical changes of organic matter, Geoderma, 289, 29–35, doi:10.1016/j.geoderma.2016.11.017, 2017.

Aronsson, H., Torstensson, G., and Bergstrom, L.: Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil, Soil Use Manag., 23(1), 71–81, 2007.

Askegaard, M., Olesen, J. E., and Kristensen, K.: Nitrate leaching from organic arable crop rotations: effects of location, manure and catch crop, Soil Use Manag., 21(2), 181–188 [online] Available from: isi:000230816100003, 2005.

Askegaard, M., Olesen, J. E., Rasmussen, I. A., and Kristensen, K.: Nitrate leaching from organic arable crop rotations is mostly determined by autumn field management, Agric. Ecosyst. Environ., 142(3–4), 149–160, doi:10.1016/j.agee.2011.04.014, 2011.

Baggs, E. M., Rees, R. M., Smith, K. A., and Vinten, A. J. A.: Nitrous oxide emission from soils after incorporating crop residues, Soil Use Manag., 16, 82–87, 2000a.

Baggs, E. M., Watson, C. A., and Rees, R. M.: The fate of nitrogen from incorporated cover crop and green manure residues, Nutr. Cycl. Agroecosys., 56(2), 153–163 [online] Available from: wos:000086647600008, 2000b.

Baggs, E.M., Smales, C.L., and Bateman, E.J.: Changing pH shifts microbial source as well as magnitude of N_2O emission from soil. Biol. Fert. Soil, 46:793-805, 2010.

Bakken, L. R., Bergaust, L., Liu, B., and Frostegård, A.: Regulation of denitrification at the cellular level: a clue to the understanding of N2O emissions from soils., Philos. Trans. R. Soc. Lond. B. Biol. Sci., 367(1593), 1226–34, doi:10.1098/rstb.2011.0321, 2012.

Ball, B. C., Mctaggart, I. P., and Watson, C. A.: Influence of organic ley-arable management and afforestation in sandy loam to clay loam soils on fluxes of N2O and CH4 in Scotland, Agric. Ecosyst. Environ., 90(3), 305–317 [online] Available from: isi:000177795300008, 2002.

Ball, B. C., Watson, C. A., and Crichton, I.: Nitrous oxide emissions, cereal growth, N recovery and soil nitrogen status after ploughing organically managed grass/clover swards, Soil Use Manag., 23(2), 145–155, doi:10.1111/j.1475-2743.2006.00072.x, 2007a.

Ball, B. C., Watson, C. A., and Baddeley, J. A.: Soil physical fertility, soil structure and rooting conditions after ploughing organically managed grass/clover swards, Soil Use Manag., 23(1), 20–27 [online] Available from: isi:000245080800003, 2007b.

Baral, K. R., Labouriau, R., Olesen, J. E., and Petersen, S. O.: Nitrous oxide emissions and nitrogen use efficiency of manure and digestates applied to spring barley, Agric. Ecosyst. Environ., 239, 188–198, doi:10.1016/j.agee.2017.01.012, 2017.

Bernal, M.P., Sommer, S.G., Chadwick, D., Qing,C., Guoxue,L., and Michel, F.C.: Current Approaches and Future Trends in Compost Quality Criteria for Agronomic, Environmental, and Human Health Benefits. Adv. Agron., 144:143-233. doi:10.1016/BS.AGRON.2017.03.002, 2017.

Benoit, M., Garnier, J., Anglade, J., and Billen, G.: Nitrate leaching from organic and conventional arable crop farms in the Seine Basin (France), Nutr. Cycl. Agroecosys, 100(3), 285–299, 2014.

Berntsen, J., Grant, R., Olesen, J. E., Kristensen, I. S., Vinther, F. P., Mølgaard, J. P., and Petersen, B. M.: Nitrogen cycling in organic farming systems with rotational grass–clover and arable crops. Soil Use Manag., 22(2), 197-208, 2006.

Berntsen, J., Petersen, B. M., Olesen, J. E., Eriksen, J. E., and Soegaard, K.: Simulation of residual effects and nitrate leaching after incorporation of different ley types, Eur. J. Agron., 23(3), 290–304, [online] Available from: isi:000233029100007, 2005.

Berntsen, J., Petersen, B. M., Sørensen, P., and Olesen, J. E.: Simulating Residual Effects of Animal Manures Using N-15 Isotopes, Plant Soil, 290, 173–87, 2007.

Berry, B. M., Sylvester-Bradley, R., Philipp, L., Hatch, D. J., Cuttle, S. P., Rayns, F. W., and Gosling, P.: Is the productivity of organic farms restricted by the supply of available nitrogen? Soil Use Manag., 18(3), 248–255, https://doi.org/10.1079/SUM2002129, 2002.

Bhogal, A., Williams, J.R., Nicholson, F.A., Chadwick D.R., Chambers K.H., and Chambers B.J.: Mineralization of organic nitrogen from farm manure applications, Soil Use Manag., 32, 32-43, 2016.

Borgen, S. K., Lunde, H. W., Bakken, L. R., Bleken, M. A., and Breland, T. A.: Nitrogen dynamics in stockless organic clover-grass and cereal rotations, Nutr. Cycl. Agroecosys., 92(3), 363–378 [online] Available from: wos:000302576100009, 2012.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Modeling global annual N2O and NO emissions from fertilized fields, Global Biogeochem. Cycles, 16(4) [online] Available from: isi:000180874100028, 2002.

Breland, T. A.: Measured and predicted mineralization of clover green manure at low temperatures at different depths in two soils, Plant Soil, 166(1), 13–20, 1994.

Bronick, C. J., and Lal, R.: Soil structure and management: A review, Geoderma, 124(1–2), 3–22, doi:10.1016/j.geoderma.2004.03.005, 2005.

Brophy, L.S., Heichel, G. H., and Russelle, M. P.: Nitrogen transfer from forage legumes to grass in a systematic planting design, Crop Sci., 27, 753–758, 1987.

Brozyna, M. A., Petersen, S. O., Chirinda, N., and Olesen, J. E.: Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation, Agric. Ecosyst. Environ., 181, 115–126, doi:10.1016/j.agee.2013.09.013, 2013.

Burke, I. C., Yonker, C. M., Parton, W. J., Cole, C. V., Flach, K., and Schimel, D. S.: Texture, Climate, and Cultivation Effects on Soil Organic Matter Content in U.S. Grassland Soils, Soil Sci. Sos. Am. J., 53(i), 800–805, 1989.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philos. Trans. R. Soc. Lond. B. Biol. Sci., 368(1621), 20130122, doi:10.1098/rstb.2013.0122, 2013.

Campanelli, G., and Canali, S.: Crop production and environmental effects in conventional and organic vegetable farming systems: The case of a long-term experiment in Mediterranean conditions (Central Italy). J. Sust. Agric., 36(6), 599-619, 2012.

Campiglia, E., Mancinelli, R., Radicetti, E., and Marinari, S.: Legume cover crops and mulches: Effects on nitrate leaching and nitrogen input in a pepper crop (Capsicum annuum L.), Nutr. Cycl. Agroecosys., 89(3), 399–412, doi:10.1007/s10705-010-9404-2, 2011.

Cayuela, M. L., Aguilera, E., Sanz-Cobena, A., Adams, D. C., Abalos, D., Barton, L., Ryals, R., Silver, W. L., Alfaro, M. A., Pappa, V. A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., and Lassaletta, L.: Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data, Agric. Ecosyst. Environ., 238, 25–35, doi:10.1016/j.agee.2016.10.006, 2017.

Carter, M. S. and Ambus, P.: Biologically fixed N_2 as a source for N_2O production in a grass-clover mixture, measured by N-^{15}, Nutr. Cycl. Agroecosys., 74 (1), 13–26, wos:000235949200002, 2006.

Chadwick, D.: Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering, Atmos. Environ., 39(4), 787–799, doi:10.1016/j.atmosenv.2004.10.012, 2005.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., and Misselbrook, T.: Manure management: Implications for greenhouse gas emissions, Anim. Feed Sci. Technol., 166–167, 514–531, 2011.

Chang, C., Cho, C. M., and Janzen, H. H.: Nitrous oxide emission from long-term manured soils, Soil Sci. Soc. Am. J., 62(3), 677–682, 1998.

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., and Bertrand, N.: Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis, Agric. Ecosyst. Environ., 236(3), 88–98, doi:10.1016/j.agee.2016.11.021, 2017.

Chen, H. H., Li, X. C., Hu, F., and Shi, W.: Soil nitrous oxide emissions following crop residue addition: a meta-analysis, Glob. Chang. Biol., 19(10), 2956–2964, doi:10.1111/gcb.12274, 2013.

Chirinda, N., Carter, M. S., Albert, K. R., Ambus, P., Olesen, J. E., Porter, J. R., and Petersen, S. O.: Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types, Agric. Ecosyst. Environ., 136(3–4), 199–208 [online] Available from: isi:000276275400003, 2010.

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., and Beaudoin, N.: Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments, Agric. Ecosyst. Environ., 135(4), 268–278, doi:10.1016/j.agee.2009.10.005, 2010.

Cooper, J. M., and Warman, P. R.: Effects of three fertility amendments on soil dehydrogenase activity, organic C and pH, Can. J. Soil Sci., 77(2), 281–283, doi:10.4141/S96-023, 1997.

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Döring, T. F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden, M. G. A., Willekens, K., Wittwer, R., and Mäder, P.: Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis, Agron. Sustain. Dev., 36(1), doi:10.1007/s13593-016-0354-1, 2016.

Council of the European Union.: Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91, Official Journal of the European Union, L 189/1, 2007. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007R0834&from=EN

Crews, T. E., and Peoples, M. B.: Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review, Nutr. Cycl. Agroecosys., 72(2), 101–120, doi:10.1007/s10705-004-6480-1, 2005.

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B., Kronvang, B., Olesen, J.E., Schjørring, J., Termansen, M., and Vejre, H.: Policies for agricultural nitrogen management - trends, challenges and prospects for improved efficiency in Denmark, Environ. Res. Lett., 9, 115002, 2014.

De Ponti, T., Rijk, B., and Van Ittersum, M. K.: The crop yield gap between organic and conventional agriculture. Agricultural Systems, 108, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004, 2012.

Di, H. J., and Cameron, K. C.: Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies, Nutr. Cycl. Agroecosys., 64(3), 237–256 [online] Available from: isi:000179746500004, 2002.

Domínguez, J., Bohlen, P. J., and Parmelee, R. W.: Earthworms increase nitrogen leaching to greater soil depths in row crop agroecosystems. Ecosyst., 7(6), 672-685, 2004.

Dunbabin, V., Diggle, A., and Rengel, Z.: Is there an optimal root architecture for nitrate capture in leaching environments?, Plant. Cell. Environ., 26(6), pp.835-844, 2003.

Edwards, W. M., Shipitalo, M. J., Owens, L. B., and Norton, L. D.: Water and nitrate movement in earthworm burrows within long-term no-till cornfields, J. Soil. Water. Conserv., 44(3), 240-243, 1989.

Eriksen, J., Askegaard, M., and Søegaard, K.: Residual effect and nitrate leaching in grass-arable rotations: effect of grassland proportion, sward type and fertilizer history. Soil Use Manag., 24, 373–382, 2008.

Evers A. K., Demers T. A., Gordon A. M., and Thevathasan N. V.: The effect of earthworm (Lumbricus terrestris L.) population density and soil water content interactions on nitrous oxide emissions from agricultural soils, Appl. Environ. Soil Sci., doi:10.1155/2010/737096, 2010.

Fan, J., McConkey, B., Wang, H., and Janzen, H.: Root distribution by depth for temperate agricultural crops, F. Crop. Res., 189, 68–74, doi:10.1016/j.fcr.2016.02.013, 2016.

Filser J., Dette A., Fromm H., Lang A., Munch J.C., Winter K., and Beese F.: Reactions of soil organisms in site-specific management. The first long-term study at the landscape scale, Ecosyst. Suppl., 28, 139–147, 1999.

Firestone, M., and Davidson, E.: Microbiological basis of NO and N_2O production and consumption in soil, in Exchange of trace gases between terrestrial ecosystems and the atmosphere., edited by M. O. Andreac and D. S. Schimel, pp. 7–21, John Wiley & Sons Ltd., 1989.

Flessa, H., Dörsch, P., and Beese, F.: Seasonal variation of N_20 and CH_4 fluxes in differently managed arable soils in southern Germany, J. Geophys. Res., 100(23), 115–124, 1995.

Fontaine, S., Bardoux, G., Abbadie, L., and Mariotti, A.: Carbon input to soil may decrease soil carbon content, Ecol. Lett., 7(4), 314–320, doi:10.1111/j.1461-0248.2004.00579.x, 2004.

Frøseth, R. B.: Nitrogen dynamics in an organic green manure – cereal rotation and mineralization of clover leaves at low temperature. Philosophiae Doctor (PhD) Thesis 2016:25. Norwegian University of Life Sciences, Ås, pp 58, 2016.

Frøseth, R. B., Bakken, A. K., Bleken, M. A., Riley, H., Pommeresche, R., Thorup-Kristensen, K., and Hansen, S.: Effects of green manure herbage management and its digestate from biogas production on barley yield, N recovery, soil structure and earthworm populations, Eur. J. Agron., 52, doi:10.1016/j.eja.2013.10.006, 2014.

Gale E.S., Sullivan D.M., Cogger C.G., Bary A.I., Hemphill D.D., Myhre E.A: Estimating plant-available nitrogen release from manures, composts, and specialty products, J. Environ. Qual, 35, 2321–2332, http://dx.doi.org/10.2134/jeq2006.0062, 2006.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N. E.-H., and Niggli, U.: Enhanced top soil carbon stocks under organic farming., Proc. Natl. Acad. Sci. U. S. A., 109(44), 18226–18231, doi:10.1073/pnas.1209429109, 2012.

Gattinger, A., Skinner, C., Krauss, M., Mayer, J., van der Heijden, M., and Mäder, P.: Lower area-scaled and equal yield-scaled nitrous oxid emissions in organically than in non-organically managed soils under identical crop rotations, Scientific Reports, Submitted.

Gomiero, T.: Alternative Land Management Strategies and Their Impact on Soil Conservation, Agriculture, 3(3), 464–483, doi:10.3390/agriculture3030464, 2013.

Gomiero, T., Pimentel, D., and Paoletti, M.: Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture, CRC. Crit. Rev. Plant Sci., 30(1–2), 95–124, doi:10.1080/07352689.2011.554355, 2011.

Jiang, Q. Q., and Bakken, L. R.: Nitrous oxide production and methane oxidation by different ammonia -oxidizing bacteria. Appl. Environ. Microbiol. 65: 2679–2684, 1999.

Jiang, T., Schuchardt, F., Li, G., Guo, R., and Zhao, Y.: Effect of C/N ratio, aeration rate and moisture content on ammonia and greenhouse gas emission during the composting, J. Environ. Sci., 23(10), 1754-1760, 2011.

Van Groenigen, J. W., Velthof, G. L., Oenema, O., Van Groenigen, K. J., and Van Kessel, C.: Towards an agronomic assessment of N2O emissions: A case study for arable crops, Eur. J. Soil Sci., 61(6), 903–913, doi:10.1111/j.1365-2389.2009.01217.x, 2010.

Hansen, E. M., Eriksen, J., and Vinther, F. P., 2007. Catch crop strategy and nitrate leaching following grazed grass-clover. Soil Use Manag., 23(4), pp.348-358.

Hansen, S., and Engelstad, F.: Earthworm populations in a cool and wet district as affected by tractor traffic and fertilisation, Appl. Soil Ecol., 13(3), doi:10.1016/S0929-1393(99)00037-2, 1999.

Hansen, S., Bernard, M.-E., Rochette, P., Whalen, J. K., and Dörsch, P.: Nitrous oxide emissions from a fertile grassland in Western Norway following the application of inorganic and organic fertilizers, Nutr. Cycl. Agroecosys., 98(1), 71–85, doi:10.1007/s10705-014-9597-x, 2014.

Hartmann, M., Frey, B., Mayer, J., Mäder, P., and Widmer, F.: Distinct soil microbial diversity under long-term organic and conventional farming, ISME J., 9(5), 1177–1194, doi:10.1038/ismej.2014.210, 2015.

Holtan-Hartwig, L., Dorsch, P., and Bakken, L. R.: Low temperature control of soil denitrifying communities: kinetics of N2O production and reduction, Soil Biol. Biochem., 34(11), 1797–1806 [online] Available from: isi:000179996900029, 2002.

Hu, T., Sørensen, P., and Olesen, J .E.: Soil carbon varies between different organic and conventional management schemes in arable agriculture, Eur. J. Agron., 94, 79-88, 2018a.

Hu, T., Olesen, J.E., Christensen, B.T. & Sørensen, P.: Release of C and N from fodder radish (Raphanus sativus) shoots and roots incubated in soils of different management history. Acta Agriculturae Scandinavica, Plant Soil (in press), 2018b.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Agriculture, Forestry and Other Land Use., International Panel oif Climate Change, http://www.ipcc-nggip.iges.or.jp/public/2006gl/index. [online] Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, 2006.

Jarvis, S. C., Stockdale, E. A., Shepherd, M. A., and Powlson, D.S.: Nitrogen mineralization in temperate agricultural soils: processes and measurement, Adv. Agron., 57, 187–235, 1996.

Johnsson, H., Bergström, L., Jansson, P.-E., and Paustian, K.: Simulated nitrogen dynamics and losses in a layered agricultural soil. Agric. Ecosyst. Environ., 18, 333-356, 1987.

Jończyk, K., and Martyniuk, S.: Productivity of crop rotations and selected indicators of soil fertility in different types of ecological farms, J. Res. Appl. Agric. Eng., 62(3), 153-157, 2017.

Kayser, M., Müller, J., and Isselstein, J.: Nitrogen management in organic farming: Comparison of crop rotation residual effects on yields, N leaching and soil conditions, Nutr. Cycl. Agroecosys., 87(1), 21–31, doi:10.1007/s10705-009-9309-0, 2010.

Keiblinger, K. M., Bauer, L. M., Deltedesco, E., Holawe, F., Unterfrauner, H., Zehetner, F., and Peticzka, R.: Quicklime application instantly increases soil aggregate stability, Int. Agrophysics, 30(1), 123–128, doi:10.1515/intag-2015-0068, 2016.

Ketterings, Q. M., Blair, J. M., and Marinissen, J. C. Y.: Effects of earthworms on soil aggregate stability and carbon and nitrogen storage in a legume cover crop agroecosystem, Soil Biol. Biochem., 29(3–4), 401–408, doi:10.1016/S0038-0717(96)00102-2, 1997.

Kirchmann, H. and Bergström, L.: Do organic farming practices reduce nitrate leaching?, Commun. Soil Sci. Plant Anal., 32(7–8), 997–1028 [online] Available from: isi:000170101800005, 2001.

Krauss, M., Krause, H. M., Spangler, S., Kandeler, E., Behrens, S., Kappler, A., Mäder, P., and Gattinger, A.: Tillage system affects fertilizer-induced nitrous oxide emissions. Biol. Fert. Soils, 53(1), 49–59., doi.org/10.1007/s00374-016-1152-2, 2017a.

Krauss, M., Ruser, R., Müller, T., Hansen, S., Mäder, P., and Gattinger, A.: Impact of reduced tillage on greenhouse gas emissions and soil carbon stocks in an organic grass-clover ley - winter wheat cropping sequence, Agric. Ecosyst. Environ., 239, 324–333, doi:10.1016/j.agee.2017.01.029, 2017b.

Kuiper, I., Deyn G. B., Thakur M. P., and Groenigen J. W.: Soil invertebrate fauna affect N2O emissions from soil, Glob. Chang. Biol., 19(9): 2814-2825, 2013.

Kuntz, M., Morely, N. J., Hallett, P. D., Watson, C., and Baggs, E. M.: Residue-C effects on dinitrification vary with soil depth, Soil Biol. Biochem., 103, 365–375, 2016.

Köpke, U.: Improving Organic Crop Cultivation, Burleigh Dodds Science Publishing Limited, 2018.

Köster, J. R., Cárdenas, L., Senbayram, M., Bol, R., Well, R., Butler, M., Mühling, K. H., and Dittert, K.: Rapid shift from denitrification to nitrification in soil after biogas residue application as indicated by nitrous oxide isotopomers, Soil Biol. Biochem., 43(8), 1671–1677, doi:10.1016/j.soilbio.2011.04.004, 2011.

Känkänen, H., Kangas, A., Mela, T., Nikunen, U., Tuuri, H., and Vuorinen, M.: Timing incorporation of different green manure crops to minimize the risk of nitrogen leaching, Agric. Food Sci. Finl., 7(5–6), 553–567, 1998.

Larsson, L., Ferm, M., Kasimir-Klemedtsson, A., and Klemedtsson, L.: Ammonia and nitrous oxide emissions from grass and alfalfa mulches, Nutr. Cycl. Agroecosys., 51(1), 41–46, 1998.

Li, C. S., Frolking, S., and Butterbach-Bahl, K.: Carbon Sequestration in Arable Soils Is Likely to Increase Nitrous Oxide Emissions, Offsetting Reductions in Climate Radiative Forcing, Climatic Change, 72, 321–38, 2005.

Li, X., Petersen, S. O., Sørensen, P., and Olesen, J. E.: Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system, Agric. Ecosyst. Environ., 199, 382–393, doi:10.1016/j.agee.2014.10.016, 2015.

Li, X., Sørensen, P., Olesen, J. E., and Petersen, S. O.: Evidence for denitrification as main source of N_2O emission from residue-amended soil, Soil Biol. Biochem., 92, 153–160, doi:10.1016/j.soilbio.2015.10.008, 2016a.

Li, S., Song, L., Jin, Y., Liu, S., Shen, Q., and Zou, J.: Linking N_2O emission from biochar-amended composting process to the abundance of denitrify (nirK and nosZ) bacteria community. AMB Express, 6 (1). doi:10.1186/s13568-016-0208-x, 2016b.

Liu, B., Mørkved, P. T., Frostegård, Å., and Bakken, L. R.: Denitrification gene pools, transcription and kinetics of NO, N_2O and N_2 production as affected by soil pH, FEMS Microbiol. Ecol., 72(3), 407–417, doi:10.1111/j.1574-6941.2010.00856.x, 2010.

Liu, S., Han, P., Hink, L., Prosser, J., Wagner M., and Brüggemann N.: Abiotic conversion of extracellular NH_2OH contributes to N_2O emission during ammonia oxidation. Environ. Sci. Technol., 51, 13122-13132. DOI:10.1021/acs.est.7b02360, 2017.

Lorenz, K., and Lal, R.: Environmental Impact of Organic Agriculture, Elsevier Inc., 2016.

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., Gattinger, A., and Dentener, F.: Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression, PLoS One, 12(7), 1–25, doi:10.1371/journal.pone.0180442, 2017.

Lubbers, I. M., Brussaard, L., Otten, W., and Van Groenigen, J. W.: Earthworm induced N mineralization in fertilized grassland increases both N2O emission and crop N uptake, Eur. J. Soil Sci., 62(1), 152-161, 2011.

Lubbers I. M., Van Groenigen K. J., Fonte S. J., Six J., Brussaard L., and Van Groenigen J. W.: Greenhouse-gas emissions from soils increased by earthworms, Nat. Clim. Chang., 3(3), 187-194, 2013.

Lynch, D. H.: Nutrient Cycling and Soil Health in Organic Cropping Systems - Importance of Management Strategies and Soil Resilience, Sustain. Agric. Res., 4(3), 80, doi:10.5539/sar.v4n3p80, 2015.

Maia, G. D. N., Day V. G. B., Gates, R. S., and Taraba, J. L. Ammonia biofiltration and nitrous oxide generation during the start-up of gas-phase compost biofilters. Atmos. Environ., 46, 659-664. doi:10.1016/j.atmosenv.2011.10.019, 2011.

Maia G, D. N., Day V. G. B., Gates, R.S., Taraba, J.L., and Coyne, M.: Moisture effects on greenhouse gases generation in nitrifying gas-phase compost biofilters. Water Res. 46, 3023-3031. https://www.sciencedirect.com/science/article/pii/S0043135412001704, 2012.

Marinari, S., Masciandaro, G., Ceccanti, B., and Grego, S.: Influence of organic and mineral fertilisers on soil biological and physical properties, Bioresour. Technol., 72(1), 9–17, doi:10.1016/S0960-8524(99)00094-2, 2000.

Marinari, S., Masciandaro, G., Ceccanti, B., and Grego, S.: Evolution of soil organic matter changes using pyrolysis and metabolic indices: A comparison between organic and mineral fertilization, Bioresour. Technol., 98(13), 2495–2502, doi:10.1016/j.biortech.2006.09.001, 2007.

Marriott, E. E., and Wander, M. M.: Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems, Soil Sci. Soc. Am. J., 70(3), 950, doi:10.2136/sssaj2005.0241, 2006.

Martyniuk, S., Koziel, M., Stalenga, J., and Jonczyk, K.: Labile factions of soil organic matter and microbial characteristics of soil under organic and conventional crop management systems, Biol. Agric. Hort. 32, 1–6, doi:10.1080/01448765.2015.1015054, 2016.

McGee, J. A.: Does certified organic farming reduce greenhouse gas emissions from agricultural production?, Agric. Hum. Values, 32(2), 255–263, doi:10.1007/s10460-014-9543-1, 2015.

Meier, M. S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., and Stolze, M.: Environmental impacts of organic and conventional agricultural products - Are the differences captured by life cycle assessment?, J. Environ. Manag., 149, 193–208, doi:10.1016/j.jenvman.2014.10.006, 2015.

Meijide, A., Díez, J. A., Sánchez-Martín, L., López-Fernández, S., and Vallejo, A.: Nitrogen oxide emissions from an irrigated maize crop amended with treated pig slurries and composts in a Mediterranean climate, Agric. Ecosyst. Environ., 121(4), 383–394, doi:10.1016/j.agee.2006.11.020, 2007.

Melander, B., Rasmussen, I.A., and Olesen, J.E.: Incompatibility between fertility building methods and the management of perennial weeds in organic cropping systems, Agric. Ecosyst. Environ, 220, 184-192, 2016.

Migliorini, P., Moschini, V., Tittarelli, F., Ciaccia, C., Benedettelli, S., Vazzana, C., and Canali, S.: Agronomic performance, carbon storage and nitrogen utilisation of long-term organic and conventional stockless arable systems in Mediterranean area. Eur. J. Agron., 52, 138-145, 2014.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U.: Soil fertility and biodiversity in organic farming., Science, 296(5573), 1694–7, doi:10.1126/science.1071148, 2002.

Moyo, H., Davies, W. P., Cannon, N. D., and Conway, J. S.: Influences of two year red clover-grass ley management on nitrogen economy and following wheat performance, Biol. Agric. Hort., 32:2, 98-109, DOI: 10.1080/01448765.2015.1057865, 2016.

Möller, K., and Stinner, W.: Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides), Eur. J. Agron., 30(1), 1–16, doi:10.1016/j.eja.2008.06.003, 2009.

Nadeem, S., Hansen, S., Bleken, M. A., and Dörsch, P.: N_2O emission from organic barley cultivation as affected by green manure management, Biogeosciences, 9(7), doi:10.5194/bg-9-2747-2012, 2012.

Nebert L. D., Bloem J., Lubbers I. M., and van Groenigen J. W.: Association of earthworm-denitrifier interactions with increased emission of nitrous oxide from soil mesocosms amended with crop residue, Appl. Environ. Microbiol., 77(12), 4097-4104, 2011.

De Notaris, C., Rasmussen, J., Sørensen, P., and Olesen, J. E.: Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops, Agric. Ecosyst. Environ., 255, 1–11, doi:10.1016/J.AGEE.2017.12.009, 2018.

Neumann, A., Torstensson, G. and Aronsson, H.: Losses of nitrogen and phosphorus via the drainage system from organic crop rotations with and without livestock on a clay soil in southwest Sweden, Org. Agric., 1(4), 217–229, doi:10.1007/s13165-011-0017-0, 2011.

Pandey, A., Li, F., Askegaard, M., and Olesen, J. E.: Biological nitrogen fixation in organic and conventional arable crop rotations in Denmark, Eur. J. Agr, 90, 87-95, 2017.

Pandey, A., Li, F., Askegaard, M., Rasmussen, I.A., and Olesen, J.E.: Nitrogen balances in organic and conventional arable crop rotations and their relations to nitrogen yield and leaching losses. (accepted). Agric. Ecosyst. Environ.

Pang, X. P., and Letey, J.: Organic farming: Challenge of timing nitrogen availability to crop nitrogen requirements, Soil Sci. Soc. Am. J., 64(1), 247–253 [online] Available from: isi:000089446000034, 2000.

Pappa, V. A., Rees, R. M., Walker, W. A., and Baddely, J. A.: Intercropping can reduce environmental impacts, Agric. Environ. VII L. Manag. a Chang. Environ. Proc. SAC SEPA Bienn. Conf., 287–290, 2008.

Pappa, V. A., Rees, R. M., Walker, R. L., Baddeley, J. A., and Watson, C. A.: Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop, Agric. Ecosyst. Environ., 141(1–2), 153–161, doi:10.1016/j.agee.2011.02.025, 2011.

Pardo, G., Moral, R., Aguilera, E., and del Prado, A.: Gaseous emissions from management of solid waste: A systematic review. Glob. Chang. Biol.; 21(3):1313-1327. doi:10.1111/gcb.12806, 2015.

Paul, E. A., and Clark, F. E.: Soil microbiology and biochemistry. Academic Press Inc., San Diego, 1989.

Petersen, S. O., Mutegi, J. K., Hansen, E. M., and Munkholm, L. J.: Tillage effects on N_2O emissions as influenced by a winter cover crop, Soil Biol. Biochem., 43(7), 1509–1517, doi:10.1016/j.soilbio.2011.03.028, 2011.

Petersen, S.O., Schjonning, P., Olesen, J.E., Christensen, S., and Christensen, B.T.: Sources of Nitrogen for Winter Wheat in Organic Cropping Systems, Soil Sci. Soc. Am. J., 77(1), 155-165, 2013.

Peyrard, C., Mary, B., Perrin, P., Vericel, G., Grehan, E., Justes, E., and Leonard, J.: N_2O emissions of low input cropping systems as affected by legume and cover crops use, Agric. Ecosyst. Environ., 224, 145–156, doi:10.1016/j.agee.2016.03.028, 2016.

Pfiffner L., Mäder P.: Effects of biodynamic, organic and conventional production systems on earthworm populations, Biol. Agric. Hortic, 15:1-4, 2–10, DOI: 10.1080/01448765.1997.9755177, 1997.

Pfiffner, L., Luka, H.: Earthworm Populations in Two Low-Input Cereal Farming Systems. Appl. Soil Ecol., 37, 184–91, doi:10.1016/j.apsoil.2007.06.005, 2007.

Płaza, A., Makarewicz, A., and Gąsiorowska, B.: Influence of undersown catch crops on mineral nitrogen content determined in the soil profile in autumn and spring in conventional and organic farming systems, Fresenius Envir. Bull., 24, 3315-3319, 2015.

Plaza-Bonilla, D., Nolot, J.M., Raffaillac, D., and Justes, E.: Cover crops mitigate nitrate leaching in cropping systems including grain legumes: field evidence and model simulations, Agric. Ecosyst. Environ., 212,1-12, 2015.

Postma-Blaauw, M. B., Bloem, J., Faber, J. H., Van Groenigen, J. W., De Goede, R. G., and Brussaard, L.: Earthworm species composition affects the soil bacterial community and net nitrogen mineralization, Pedobiologia, 50(3), 243-256, 2006.

Poudel D.D., Horwath W.R., Lanini W.T., Temple S.R., Van Bruggen A.H.C.: Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California, Agric. Ecosyst. Environ., 90,125–137, 2002.

Prieto, R. A.: The role of earthworms in nitrous oxide emissions from forage agroecosystems, In Masters Abstracts International, (Vol. 50, No. 02), 2011.

Pugesgaard, S., Petersen, S. O., Chirinda, N., and Olesen, J. E.: Crop residues as driver for N_2O emissions from a sandy loam soil, Agric. For. Meteorol., 233, 45–54, doi:10.1016/j.agrformet.2016.11.007, 2017.

Rasmussen, I. A., Melander, B., Askegaard, M., Kristensen, K., and Olesen, J.E.: Ely-trigia repens population dynamics under different management schemes in organic crop-ping systems on coarse sand, Eur. J. Agr., 58, 18-27, 2014

Rasse, D., Ritchie, J., Peterson, W., Wei, J., and Smucker, A.: Rye cover crop and nitrogen fertilization effects on nitrate leaching in inbred maize fields, J. Environ. Qual., 29, 298–304, doi:10.2134/jeq2000.00472425002900010037x, 2000.

Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century, Science 326, 123–125, doi:10.1126/science.1176985, 2009.

Riley, H., Pommeresche, R., Eltun, R., Hansen, S., and Korsaeth, A.: Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use, Agric. Ecosyst. Environ., 124(3–4), 275–284 [online] Available from: isi:000254944900016, 2008.

Rivedal, S., Hansen, S., Løes, A.-K., and Dörsch, P.: Utslepp av lystgass frå moldrik jord på Vestlandet, Bioforsk Fokus, 8(2), 366–368, 2012.

Robertson, G. P., and Vitousek, P. M.: Nitrogen in Agriculture: Balancing the Cost of an Essential Resource, Annu. Rev. Environ. Resour., 34(1), 97–125, doi:10.1146/annurev.environ.032108.105046, 2009.

Rochette, P., and Janzen, H. H.: Towards a revised coefficient for estimating N2O emissions from legumes, Nutr. Cycl. Agroecosys., 73(2–3), 171–179 [online] Available from: wos:000233363200006, 2005.

Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., Wallenbeck, A., Hoffmann, R., Nilsson, U., Sundberg, S., and Watson, C.A.: Risks and opportunities of increasing yields in organic farming. A review, Agron. Sust. Dev., 38, 14. https://doi.org/10.1007/s13593-018-0489-3, 2018.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., del Prado, A., Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., Álvaro-Fuentes, J., Gilsanz, C., Báez, D., Doltra, J., González-Ubierna, S., Cayuela, M. L., Menéndez, S., Díaz-Pinés, E., Le-Noë, J., Quemada, M., Estellés, F., Calvet, S., van Grinsven, H. J. M., Westhoek, H., Sanz, M. J., Gimeno, B. S., Vallejo, A., and Smith, P.: Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review, Agric. Ecosyst. Environ., 238, 5–24, doi:10.1016/j.agee.2016.09.038, 2017.

Sahrawat, K. L., and Keeney, D.R.: Nitrous Oxide Emissions from Soils, Adv. Soil Sci., 4, 103–47, 1986.

Schjønning, P., Munkholm, L. J., Elmholt, S., and Olesen, J. E.: Organic matter and soil tilth: Management makes a difference within 5-6 years, Agric. Ecosyst. Environ., 122, 157-172, 2007.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen, P. Natl. Acad. Sci. USA, 111(25), 9199–9204, doi:10.1073/pnas.1322434111, 2014.

Shah, A., Askegaard, M., Rasmussen, I.A., Jimenez, I. M. C., and Olesen, J. E.: Productivity of organic and conventional arable cropping systems in Denmark, Eur. J. Agron., 90, 12-22, 2017.

Shelton, R. E., Jacobsen, K. L., and McCulley, R. L.: Cover Crops and Fertilization Alter Nitrogen Loss in Organic and Conventional Conservation Agriculture Systems, Front. Plant Sci., 8, 1–14, doi:10.3389/fpls.2017.02260, 2018.

Siegrist, S., Schaub, D., Pfiffner, L., and Mäder, P.: Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland, Agric. Ecosyst. Environ., 69, 253–264, 1998.

Silverman, M. P.: Biological and organic chemical decomposition of silicates, in: Trudinger, P.A., and Swaine, D. J. (eds.) Biogeochemical cycling of mineral-forming elements. Elsevier, Amsterdam, 445-465, 1979.

Skinner, C., Gattinger, A., Muller, A., Mäder, P., Flieβbach, A., Stolze, M., Ruser, R., and Niggli, U.: Greenhouse gas fluxes from agricultural soils under organic and non-organic management — A global meta-analysis, Sci. Total Environ., 468–469, 553–563, doi:http://dx.doi.org/10.1016/j.scitotenv.2013.08.098, 2014.

Smith, M.M., Aber, J. D., and Rynk, R.: Heat Recovery from Composting: A Comprehensive Review of System Design, Recovery Rate, and Utilization, Compost Sci. Util., pp.1–12, https://www.tandfonline.com/doi/full/10.1080/1065657X.2016.1233082, 2016.

Spargo, J. T., Cavigelli, M. A., Mirsky, S. B., Maul, J. E., and Meisinger, J. J. Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems, Nutr. Cycl. Agroecosys., 90, 253–266, 2011.

Stalenga, J., and Jończyk, K.: Nutrient management and soil organic matter balance in the organic crop production system evaluated by NDICEA model, J. Res. Appl. Agric. Eng., 53(4), 78-84, 2008.

Stehfest, E., and Bouwman, L.: N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions, Nutr. Cycl. Agroecosys., 74(3), 207–228 [online] Available from: isi:000240619700001, 2006.

Stenberg, M., Aronsson, H., Linden, B., Rydberg, T., and Gustafson, A.: Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop, Soil Tillage Res., 50(2), 115–125, doi:10.1016/S0167-1987(98)00197-4, 1999.

Stenberg, M., Ulén, B., Söderström, M., Roland, B., Delin, K., and Helander, C. A.: Tile drain losses of nitrogen and phosphorus from fields under integrated and organic crop rotations. A four-year study on a clay soil in southwest Sweden, Sci. Total Environ., 434, 79–89, doi:10.1016/j.scitotenv.2011.12.039, 2012.

Stockdale, E. A., Lampkin, N. H., Hovi, M. Keatinge, R., Lennartsson, E. K. M., MacDonald, D. W., Padel, S., Tattersall, F. H., Wolfe, M. S. and Watson, C. A.: Agronomic and Environmental Implications of Organic Farming Systems, Adv. Agron. 70, 261-327, 2001.

Stopes, C., Lord, E. I., Philipps, L., and Woodward, L.: Nitrate leaching from organic farms and conventional farms following best practice, Soil Use Manag., 18, 256–263 [online] Available from: isi:000178455700004, 2002.

Sturite, I., Rivedal, S., and Dörsch, P.: Nitrous oxide emissions from clover rich leys during the long Northern winter., in Cordovil C.M.d.S.(Ed.), Proceedings of the 18th Nitrogen Workshop – The nitrogen challenge: building a blueprint for nitrogen use efficiency and food security, 30th June – 3rd July 2014, Lisboa, Portugal, pp. 517–518., 2014.

Tang, C., Barton, L., and Raphael, C., 1998. Pasture legume species differ in their capacity to acidify soil. Austr. J. Agric. Res., 49(1), 53-58.

Thangarajan, R., Bolan, N. S., Tian, G. L., Naidu, R., and Kunhikrishnan, A.: Role of organic amendment application on greenhouse gas emission from soil, Sci. Total Environ., 465, 72–96, doi:10.1016/j.scitotenv.2013.01.031, 2013.

Thomsen, I. K., Elsgaard, L., and Olesen, J. E: Nitrogen release from differently aged cover crops (Raphanus sativus L.) during mineralization at autumn temperatures. Soil Use Manag., 32, 183-191, 2016

Thorup-Kristensen, K.: Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations, Plant Soil, 288(1–2), 233–248 [online] Available from: isi:000243001400018, 2006.

Thorup-Kristensen, K., and Dresbøll, D. B.: Incorporation time of nitrogen catch crops influences the N effect for the succeeding crop, Soil Use Manag., 26(1), 27–35 [online] Available from: wos:000274666500005, 2010.

Tonitto, C., David, M. B., and Drinkwater, L.: Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics, Agr. Ecosyst. Environ., 112, 58–72, doi:10.1007/s10705-010-9354-8, 2006.

Torstensson, G., and Aronsson, H.: Nitrogen leaching and crop availability in manured catch crop systems in Sweden, Nutr. Cycl. Agroecosys., 56(2), 139–152, doi:10.1023/A:1009821519042, 2000.

Torstensson, G., Aronsson, H., and Bergstrom, L.: Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden, Agron. J., 98(3), 603–615 [online] Available from: isi:000237867600023, 2006.

Tosti, G., Benincasa, P., Farneselli, M., Tei, F., and Guiducci, M.: Barley–hairy vetch mixture as cover crop for green manuring and the mitigation of N leaching risk, Eur. J. Agron., 54, 34–39, doi:10.1016/J.EJA.2013.11.012, 2014.

Tosti, G., Farneselli, M., Benincasa, P., and Guiducci, M.: Nitrogen fertilization strategies for organic wheat production: Crop yield and nitrate leaching, Agron. J., 108(2), 770–781, doi:10.2134/agronj2015.0464, 2016.

Tuomisto, H. L., Hodge, I. D., Riordan, P., and Macdonald, D. W.: Does organic farming reduce environmental impacts? - A meta-analysis of European research, J. Environ. Manage., 112(834), 309–320, doi:10.1016/j.jenvman.2012.08.018, 2012.

Tyson, K. C., Scholefield, D., Jarvis, S. C., and Stone, A. C.: A comparison of animal output and nitrogen leaching losses recorded from drained fertilized grass and grass/clover pasture. J. Agric. Sci., 129(3), 315-323, 1997.

Ussiri, D., and Lal, R.: Global Sources of Nitrous Oxide, in Soil Emission of Nitrous Oxide and its Mitigation, pp. 131–175, Springer Netherlands, Dordrecht., 2013.

Vacante, V., and Kreiter, S.: Handbook of pest management in organic farming, CABI, Boston MA, 576 pp. 2017

Valkama, E., Lemola, R., Känkänen, H., and Turtola, E.: Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries, Agric. Ecosyst. Environ., 203, 93–101, doi:10.1016/j.agee.2015.01.023, 2015.

Watson, C.A., Fowler, S.M., and Wilman, D.: Soil inorganic-N and nitrate leaching on organic farms, J. Agric. Sci., 120(3), 361-369, 1993.

Watson, C., et.al.: Managing crop residues to increase crop yield in stockless organic systems through improved use of nitrogen – field, farm and landscape level solutions, In preparation.

Wang, Y., Guo, J., Vogt, R. D., Mulder, J., Wang, J., and Zhang, X.: Soil pH as the chief modifier for regional nitrous oxide emissions: New evidence and implications for global estimates and mitigation, Glob. Chang. Biol., 24, 1–10, doi:10.1111/gcb.13966, 2017.

Webb, J., Sommer, S. G., Kupper, T., Groenestein, K., Hutchings, N. J., Eurich-Menden, B., Rodhe, L., Misselbrook, T. H., and Amon, B.: Emissions of Ammonia, Nitrous Oxide and Methane during the Management of Solid Manures, Sust. Agric. Rev., 8, 67 – 107, 2012.

Wells, K. C., Millet, D. B, Bousserez, N., Henze, D. K., Griffis, T. J., Chaliyakunnel, S., Dlugokencky, E. J., Saikawa, E., Xiang, G., Prinn, R. G., O'Doherty, S., Young, D., Weiss, R. F., Dutton, G. S., Elkins, J. W., Krummel, P. B., Langenfelds R., and Steele L. P.: Top-down constraints on global N2O emissions at optimal resolution: application of a new dimension reduction technique, Atmos. Chem. Phys., 18(2), 735-756, 2018.

Westphal, M., Tenuta, M., and Entz, M. H.: Nitrous oxide emissions with organic crop production depends on fall soil moisture, Agric. Ecosyst. Environ., 254, 41–49, doi:10.1016/j.agee.2017.11.005, 2018.

Whalen, J. K., Parmelee R. W., McCartney D.A., and Vanarsdale J.L.: Movement of N from decomposing earthworm tissue to soil, microbial and plant N pools, Soil Biol. Biochem., 31, 487-492, 1999.

Willer, H., Schaack, D., and Lernoud, J.: Organic farming and market development in Europe and the European Union. In: Willer, H. and Lernoud, J. (Eds.): The World of Organic Agriculture. Statistics and Emerging Trends 2018. Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM – Organics International, Bonn, p 218 – 255, 2018.

Willer, H. and Lernoud, J. (Eds.): The World of Organic Agriculture. Statistics and Emerging Trends 2018. Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM – Organics International, Bonn, 2018.

Younie, D., Grassland Management for Organic Farmers. Crowood Press, 2012

Captions supplementary material

S1. Soil mineral nitrogen (SMN) contents in soil profiles in organic field trials in Norway and Poland as influenced by crop rotation, soil tillage and N fertilization.

S2. N_2O emission and the five highest daily N_2O flux rates in the given measurement periods for organic field trials in Switzerland, Denmark, Scotland and Norway. WFPS, soil temperature and soil mineral-N at 0-20 cm depth are given for the day with highest flux rate. Abbreviations: CS = Cattle Slurry, CCM = composted cattle manure, PS = Pig slurry, P=ploughing, H = Harrowing, CCinc= Cover crop incorporated, CCs= Cover Crop under sown, CCh = cover crop harvested

S3. Annual N leaching (total N or nitrate N) reported from organic field trials in Europe, as influenced by crops, soil type and N applied as organic fertilizers.