Klaus Sieling

Improved N transfer by growing catch crops – a challenge

Verbesserter N-Transfer durch Zwischenfrüchte – eine Herausforderung

Abstract

Based on the literature amended by some unpublished data and data compilations from the literature, this review identifies the mechanisms of nitrogen (N) losses from arable land and explores the potential of growing catch crops to mitigate N loss risks from the soil-plant system. The nitrate pool in the soil can be regarded as starting point of most of the N losses via gaseous losses and/or leaching from the soil-plant system. Depleting this pool, especially in autumn, lowers the risk of losses and related impairments of the environment. The input into the nitrate pool can be reduced by adjusting the N fertilization to the N demand of the preceding crop, thus decreasing the N surplus. Less intensive soil tillage after the harvest of the preceding crop may lessen N release from the soil organic matter and the crop residues. On the other hand, cover or catch crops and, to a lesser extent, main crops can take up considerable N amounts in autumn and prevent it from being lost. However, in order to reduce N fertilization of the subsequent crop due to an improved N transfer, the big challenge is to harmonize the N demand of the subsequent main crop and the N release from the catch crop residues. Since the latter depends on several factors like accumulated N amount, C:N ratio of the residues, incorporation date and weather conditions, it can hardly be estimated. Another crucial point is the choice of a suitable cover crop because it should not propagate pests or diseases of the main crops.

Key words: Catch crop, N transfer, soil nitrate pool, crop residues

Zusammenfassung

Diese Literaturübersicht in Kombination mit unveröffentlichten Daten zeigt verschiedene Verlustursachen von Stickstoff (N) aus ackerbaulich genutzten Böden auf und diskutiert, inwieweit der Anbau von Zwischenfrüchten helfen kann, N-Verluste aus dem System Boden-Pflanze zu vermindern. Der Pool an Nitratstickstoff im Boden im Herbst kann als Ausgangspunkt für verschiedene Verlustpfade von N (gasförmige Verluste, Auswaschung) aus dem System Boden-Pflanze angesehen werden. Eine Verkleinerung des Bodennitratpools verringert die Verlustrisiken und die damit verbundene Belastung der Umwelt. Der Input zum Nitratpool kann durch eine optimierte N-Düngung der Vorfrucht und eine damit einhergehende Reduzierung der N-Überschüsse vermindert werden. Zudem kann eine reduzierte Bodenbearbeitung einer verstärkten N-Freisetzung nach der Ernte der Vorfrucht entgegenwirken. Zwischenfrüchte und teilweise auch Hauptfrüchte können bereits vor Winter erhebliche N-Mengen in ihrer Biomasse akkumulieren und somit vor einer Verlagerung in tiefere Bodenschichten bewahren. Voraussetzung für eine nachhaltige Verbesserung der N-Ausnutzung ist jedoch, dass der aus den Residuen der Zwischenfrucht freiwerdende Stickstoff von der/den nachfolgenden Hauptfrucht/-früchten für ihre Ertragsbildung genutzt wird; andernfalls wird das Problem nur um ein Jahr verschoben. Da Umfang und Zeitpunkt der N-Mineralisation unter anderem von der N-Menge im Zwischenfruchtbestand, dem C:N-Verhältnis der Residuen, Einarbeitungstermin der Residuen und der nachfolgenden Witterung abhängt, ist eine präzise Voraussage

Affiliation
Kiel University, Institute of Crop Science and Plant Breeding, Kiel, Germany

Correspondence
PD Dr. Klaus Sieling, Institute of Crop Science and Plant Breeding, Kiel University, Hermann-Rodewald-Str. 9, 24118 Kiel, Germany, e-mail: sieling@pflanzenbau.uni-kiel.de

Accepted
26 April 2019

des N-Transfers in die Folgefrucht schwierig. Darüber hinaus muss bei der Wahl der geeigneten Zwischenfrucht (-mischungen) darauf geachtet werden, dass keine Schaderreger vermehrt werden, die auch die Nachfrüchte infizieren können.

Stichwörter: Zwischenfrucht, N-Transfer, Bodennitratpool, Ernterückstände

Introduction

Nitrogen (N) is an ambivalent plant nutrient. On the one hand, plants require an appropriate N amount for optimal growth and yield. Otherwise, if leaving the plant-soil system, N can impair the environment due to the pollution of the groundwater with nitrate, the eutrophication of natural ecosystems as consequence of ammonia volatilization or the emission of the greenhouse gas N_2O.

In order to increase the crop N use efficiency, N losses from the plant-soil system have to be minimized. In humid climates, N losses from the soil mainly occur as nitrate via N leaching or as nitrous N or N_2 via denitrification. Gaseous N losses from the canopy and ammonia volatilization from ammonium (NH_4^+) containing fertilizers (e.g. urea, slurry, biogas digestate) are not considered in this review. Thus, starting point of most of the losses is the nitrate (NO_3^-) pool in the soil. Nitrate is very mobile in the soil since the anion cannot be adsorbed by clay minerals and, therefore is at risk to be lost from the system via leaching during the percolation period when rainfall exceeds evapotranspiration (mainly during autumn and winter) (Hooker et al., 2008). In addition, under reducing conditions (high soil water content and high amount of water filled pores) soil microorganisms can use nitrate as O_2 source in the course of denitrification increasing gaseous losses as N_2O or N_2. Therefore, the soil nitrate pool should be kept as small as possible during autumn/winter, when crop N requirement is low or non-existent.

Focusing on arable farming in temperate climates, this review identifies the inputs to the soil nitrate pool during autumn/winter (e.g. N fertilization of the preceding crop, mineralization of N from the soil organic matter and/or crop residues) and highlights possibilities to mitigate the risks resulting from a high soil mineral N content at the beginning of/during the percolation period (e.g. autumn N uptake of a main crop or a catch crop, application of organic matter with a wide C:N ratio). Reducing N losses increases the amount of N remaining in the plant-soil system and an improved N transfer into the subsequent crop allows reducing its N fertilizer requirement or, under N limited conditions, improving grain yield and/or protein concentration. However, the amount of successfully transferred N then largely depends on the synchronism of N release and N requirement of the subsequent crop. Therefore, the entire crop rotation has to be considered (Doltra et al., 2014) because a problem caused by the preceding crop, e.g. large N residues may be solved by the subsequent crop due to its large autumnal N uptake (Benincasa et al., 2010) or a high root depth penetration rate (Dresbøll and Thorup-Kristensen, 2014).

Inputs to the soil nitrate pool

The soil mineral N content (SMN; NO_3-N plus NH_4-N), which can easily be determined, described well the size of the soil nitrate pool (Myrbeck and Stenberg, 2014a), since the ammonium share is generally small compared to the nitrate one, because the nitrification (conversion from ammonium to nitrate) normally proceeds faster than the ammonification (degradation of organic matter to ammonium) (Metzger, 2002).

N fertilization of the preceding crop

Initially, the preceding crop and its management affect soil N dynamics via N fertilization and N offtake by the harvest products. N fertilization exceeding the crop requirement as well as inadequate timing increases N surplus (N input minus N offtake by the harvest products), soil mineral N content after harvest and the risk of N losses (Lafond and Pageau, 2008; Constantin et al., 2010; Heumann et al., 2013; Zhou and Butterbach-Bahl, 2014; Durand et al., 2015; Rasmussen et al., 2015; Shepherd and Newell-Price, 2016; De Notaris et al., 2018; Pandey et al., 2018). However, Hansen et al. (2015) were not able to significantly correlate N balances calculated for each growing season and N leaching in the subsequent percolation period. Unrealistic yield expectation by the farmers leads to an overestimated crop N requirement and, in consequence, overestimated N fertilization. On the other hand, unfavorable weather conditions (e.g. reduced radiation during grain filling, drought stress) or diseases may reduce N offtake; however, if these shortcomings occur after all N has been applied, a correction of the N amount is no longer possible (Sieling et al., 2005; Bingham et al., 2007a; Serrago and Miralles, 2014; Martre et al., 2015). As shown by Beaudoin et al. (2005) a reduction in N fertilization below the recommended rate often failed to further reduce N leaching losses.

Nitrogen use efficiency (kg grain per kg N; NUE) of organic fertilizers like slurries or residues from biogas plants is generally lower than that of mineral N fertilizers (Bergström and Kirchmann, 2006). It can be improved if the timing of application clearly depends on crop nutrient demand (and not on soil trafficability), e.g. in spring instead of autumn, and if the applied N amount is taken into account when calculating the additional mineral fertilization. It can be roughly assumed that in cereals and oilseed rape (OSR), NUE of ammoniacal N from organic fertilizers is similar to that of mineral fertilizers (Sieling, 2004; Sieling et al., 2014; Shepherd and Newell-Price, 2016).

The N surplus at field scale or in larger areas e.g. catchment areas is often used to estimate the leaching risk (Doluschitz et al., 1992; Lord et al., 2002; Jansons et al., 2003; Sacco et al., 2003; Sieling and Kage, 2006). It can give an indication of the risk of unwanted effects which are associated with specific farming practices, especially in the wider environment e.g. landscapes and if integrated over a relatively long period of several years or decades (Öborn et al., 2003; Wick et al., 2012; Bechmann et al., 2014; Blicher-Mathiesen et al., 2014). However, in the short-term (e.g. one growth period), fertilizer use (except excessive amounts) and nitrate in the (ground) water seem to be not very directly linked, since a nutrient surplus in itself may not be sufficient to quantitatively determine the amount of nutrient lost via various pathways, due to the interaction with other environmental parameters. For example, the large reserve of organic N in soils and vegetation will inevitably contribute nitrate to leaching once the land is tilled (Macdonald et al., 1989; Sylvester-Bradley and Chambers, 1992; Hansen et al., 2015). If N fertilization meets plant N requirement of the preceding crop in time and rate, only small amounts of unused fertilizer contribute to the autumn nitrate pool (Glendining et al., 1996; Lafond and Pageau, 2008; Engström et al., 2011; Rasmussen et al., 2015). Therefore, N leached from arable soils in northern Europe mainly originates from the mineralization of soil organic matter and/or crop residues in late summer and autumn, when soils being still warm from the summer become moist and plant demand is still low or non-existent (Jenkinson, 1986; Macdonald et al., 1989; Chaney, 1990; Webb et al., 1997).

Mineralization of soil organic matter and crop residues during autumn

The weather is the main factor influencing N mineralization. Adequate water availability assumed, increasing soil temperatures enhance N release, whereas water limitation impairs soil microorganism's activity.

Long-term application of N fertilization increases total soil N amount compared to unfertilized plots (Glendining and Powlson, 1995). Organic fertilizers as slurry or farmyard manure raise soil organic matter per unit of N input more than mineral fertilizers (Ciardi et al., 1988; Uhlen, 1991; Jenkinson et al., 1994; Nardi et al., 2004). Even if timing and amount meet the need of the crop, mineral N fertilizer may increase mineralizable soil N and SMN content by increasing both the amount of crop residues and their N concentration (Glendining and Powlson, 1995; Silgram and Chambers, 2002).

In their review, Chen et al. (2014) identified four pathways how crop residues may influence the soil N dynamics: biotic immobilization–remineralization, abiotic immobilization, soil organic N mineralization and organic N mineralization of the plant residues. Adequate environmental conditions (mainly soil temperature and soil moisture) for the soil microorganism's activity provided, N release from soil organic matter and crop residues mostly depend on their C:N ratio and consequently on their N content (Trinsoutrot et al., 2000; Redin et al., 2014).

Crop residues can return large amounts of N back to the soil after harvest. Maidl et al. (1991) found 121 kg N ha^{-1} in grain pea residues, 148 kg N ha^{-1} in field bean residues and 44 kg N ha^{-1} in wheat straw. Due to the narrow C:N ratio of 21 and 27, N release from the grain legume residues happened quicker and to a larger extent than from wheat straw with a C:N ratio of 84; consequently, grain legume residues considerably increase soil mineral N content during autumn. Also incorporation of sugar beet tops in early autumn can enhance N leaching (Thomsen and Christensen, 1998). In addition, plant components dropped before harvest, e.g. petals or leaves, have to be kept in mind. In an experiment with OSR, Malagoli et al. (2005) observed N losses from the crop of up to 45 kg N ha^{-1} due to leaf losses between stem elongation and harvest. Mitchell et al. (2001) and Arcand et al. (2013; 2014) highlighted that beside the aboveground residues also the roots have to be taken into account when investigating soil N dynamics.

A wide C:N ratio (> 30) of the residues as occurring in e.g. wheat straw (60–80) decreases the decomposition of and delays N release from the crop residues because the carbon-rich substrates are not able to satisfy the N demand of the microorganisms (Mary et al., 1996; Garnier et al., 2003; Peltre et al., 2016). An improved N availability can enhance N mineralization in such situations. However, in a 4-year field trial, Catt et al. (1998) compared burning and incorporation of wheat straw and observed a significant decrease in N leaching only during the first percolation period, whereas in later winters the effects were smaller or even reversed. Also incorporation of OSR residues which show a wide C:N ratio of about 70 (Kaul, 2004) reduce availability of mineral N in the soil and, in consequence, the risk of nitrate leaching (Justes et al., 1999; Engström and Lindén, 2012). As shown in Fig. 1 OSR straw clearly decreased soil mineral N content during autumn. On the other hand, dry matter (DM) accumulation and N uptake of the following early sown winter wheat crop were impaired by OSR straw, both at the end of autumn growth and at the beginning of spring growth (Table 1; Henke, unpublished data). In addition, further chemical components may potentially cause the nitrogen to become unavailable, e.g. tannic acid or phenolic lignin from the residues (De Neve et al., 2004; Olk et al., 2006).

Soil tillage stimulates mineralization of crop residues and soil organic matter (Goss et al., 1993; Silgram and Shepherd, 1999) and reduces N uptake by volunteers and weeds, thus increases SMN and the risk of N leaching (Møller Hansen and Djurhuus, 1997; Stenberg et al., 1999; Goulding, 2000; Myrbeck et al., 2014b). Therefore, SMN accumulation in autumn can be lessened by omitting or at least delaying stubble cultivation after harvest and/or soil tillage in autumn (Stenberg et al., 1999).

In intensive cropping systems in high-yielding regions, farmers apply organic and, to a lesser extent, mineral N fertilizers in autumn in order to enhance straw decomposition and to ensure crop growth before the end of autumn growth. In OSR, application of 20–50 kg N ha^{-1} is usual in minimum tillage systems or if sowing date is delayed, e.g. following wheat as preceding crop. How-

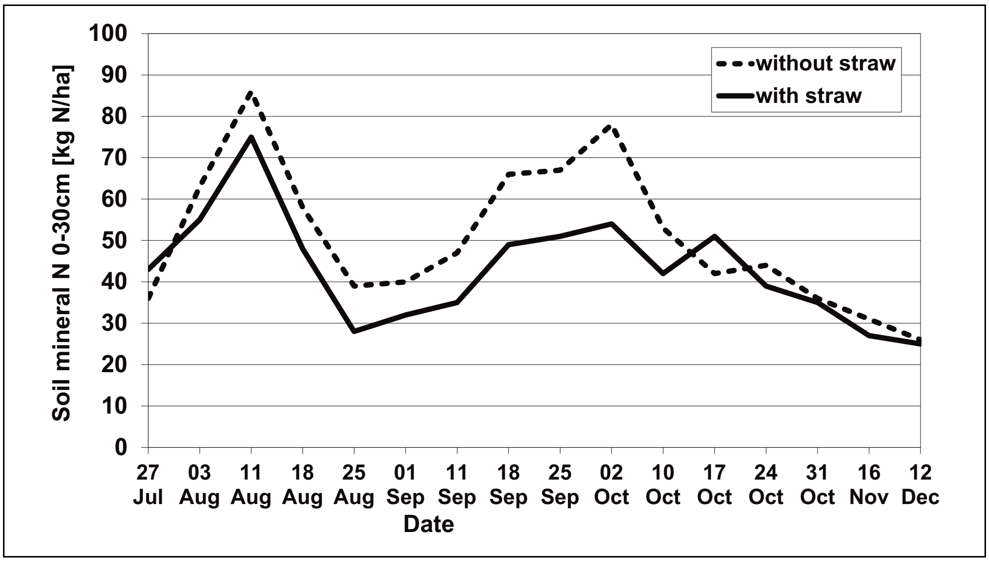

Fig. 1. Effect of incorporation of oilseed rape straw (26 July) on soil mineral N in 0–30 cm during autumn 2006 (Henke, unpublished data).

Table 1. Effect of incorporation of oilseed rape (OSR) straw (26 Jul 2006) on dry matter accumulation and N uptake of a subsequent winter wheat crop sown on 12 Sep 2006 (Henke, unpublished data)

	Without OSR straw	With OSR straw
End of autumn growth (16 Nov 2006)		
Dry matter [g m^{-2}]	80.8[a#]	50.2[b]
N uptake [kg N ha^{-1}]	37.5[a]	23.8[b]
Beginning of spring growth (27 Feb 2007)		
Dry matter [g m^{-2}]	90.3[a]	77.6[b]
N uptake [kg N ha^{-1}]	36.7[a]	31.9[b]

[#] – Means with the same letter within a row do not differ significantly at P = 0.05.

ever, the effect on seed yield is not consistent. In most of the cases, seed yield gains were negligible (Ogilvy and Bastiman, 1992; Colnenne et al., 2002; Sieling and Kage, 2010; Engström et al., 2011), whereas in some cases substantial yield increases occurred, even if the unfertilized treatment showed a sufficient crop growth in terms of above-ground DM and N accumulation (Sieling et al., 2017b); however, the underlying pathways remain unclear. Although OSR can take up large amounts of N during autumn growth thus preventing it from leaching in the short-term, the risk of N losses increases in the subsequent year(s) if the applied N will not remove from the system via the harvest products (seed yield). Cereals, e.g. winter barley or winter wheat, receive autumnal N only if following cereals, however, autumn fertilizer N applied in the seed bed seems not to significantly increase yield above applying the entire N after winter (Table 2; Kendall et al., 2017). Due to the later application in cereals compared to OSR, less N will immobilized during straw decomposition thus directly increasing the soil nitrate pool. In consequence, against the background of the small or non-existent yield relevance, autumn N application at least in cereals should be avoided.

Reducing the soil nitrate pool

Crop N uptake reduces SMN content and thereby the risk of N losses via leaching during the subsequent percolation period. Additionally, crops utilize water, thus delaying the beginning of drainage and reducing the amount of percolation (Tribouillois et al., 2018). However, according to Yeo et al. (2014), this effect seems to be negligible. To deplete the soil nitrate pool, main crops can be established in autumn e.g. winter OSR or winter cereals, allowing the N taken up to be used for yield formation without an additional N transfer into another crop. Furthermore, crops can be grown solely aimed to take up as much N as possible before winter, so-called catch crops. In general, if water availability does not limit crop growth, the thermal time in autumn and, therefore the duration of autumn growth, positively correlates with the

Table 2. Effect of autumn N application on the grain yield of a third wheat (2000 – 2011) (unpublished data)

Treatment	Grain yield ($t\ ha^{-1}$)	Amount of autumn N remaining in the system ($kg\ N\ ha^{-1}$)
Unfertilized control	8.47^{ns}	–
40 kg N ha^{-1} on the stubble of the preceding crop	8.46^{ns}	39
40 kg N ha^{-1} at sowing	8.62^{ns}	37
40 kg N ha^{-1} on the stubble of the preceding crop + 40 kg N ha^{-1} at sowing	8.54^{ns}	78

Spring N application:
Beginning of spring growth:100 kg N ha^{-1}
Stem elongation:80 kg N ha^{-1}
Ear emergence:60 kg N ha^{-1}

DM accumulation and amount of crop N uptake (Allison et al., 1998a; De Waele et al., 2017).

Main crops

Winter OSR is known to be able to take up large N amounts (> 100 kg N ha^{-1}) during autumn (Barraclough, 1989; Reau et al., 1994; Dejoux et al., 2003). In contrast, N uptake of cereals at the end of autumn growth rarely exceeds 30 kg N ha^{-1} under the growing conditions of northern or central Europe (Myrbeck et al., 2012a; Wahlström et al., 2015).

These ‚crop' effects interact with the sowing date. Delaying sowing of winter OSR markedly decreases autumnal growth and N uptake and increases SMN (Henke et al., 2009; Sieling et al., 2017a). In addition, the time span between soil tillage and sowing affects the duration of soil N mineralization and N translocation down the soil profile (Engström and Delin, 2016). Several studies have indicated that earlier sowing of winter wheat may be an alternative tool for reducing nitrate leaching (Thorup-Kristensen et al., 2009; Myrbeck et al., 2012a,b) which is also supported by simulation studies of Peltre et al. (2016) using the *Daisy* model in continuous winter wheat in Denmark. These studies showed that advancing sowing of winter wheat increased the N uptake during autumn and reduced the amounts of leachable soil N more effectively than normal or late sowing. This is well in line with studies of the effect of catch crop sowing time on N uptake and soil nitrate depletion (Sørensen, 1992; Vos and van der Putten, 1997; Thorup-Kristensen et al., 2003). In addition, Rasmussen and Thorup-Kristensen (2016) concluded that an early sown wheat crop showed an increased rooting depth and increased total root density at the end of autumn growth, which in combination with a higher N uptake resulted in soil N reductions of up to 20 kg nitrate N ha^{-1} compared to a late sown one. These differences persisted throughout the growing season in next spring, although late sown wheat continued to increase its rooting depth after anthesis. An improved rooting depth up to 1.8–2.0 m enabled the wheat crop to take up N from deeper soil layers reducing SMN content in the subsoil. Earlier sowing can therefore be an important tool to reduce nitrate leaching loss. Unfortunately, the authors did not test the potential to save N fertilizers in spring. In contrast, despite similar root growth rates, growing spring wheat has only little potential to reduce N leaching. Firstly, maximum N leaching mostly occurs during winter before spring wheat establishment (Herrera et al., 2016). Secondly, compared to spring wheat, winter wheat develops a deeper root system due to a longer growth period allowing taking up nitrate from deeper soil layers (Thorup-Kristensen and Nielsen, 1998; Thorup-Kristensen et al., 2009).

Catch crops

An appropriate time span between harvest of one main crop and sowing of the subsequent main crop (usually established in spring) allows growing autumn-sown cover crops for different ecosystem services (for review see Blanco-Canqui et al., 2015), such as accumulation of soil organic matter (Sapkota et al., 2012; Plaza-Bonilla et al., 2016), weed and pest control (Brust et al., 2014; Björkman et al., 2015; Rueda-Ayala et al., 2015), water retention, affecting soil thermal properties (Haruna et al., 2017), increasing the sunlight reflected back to space by an increased average albedo (Carrer et al., 2018), improving soil structure (Blanco-Canqui et al., 2015), preventing soil erosion (Bodner et al., 2010; Dabney et al., 2010), and reducing losses of other nutrients than N (e.g. P) (Liu et al., 2015; Øgaard, 2015; Aronsson et al., 2016). However, this review focusses on the N dynamic and the above-mentioned aspects will not be further considered. If the time span is too short e.g. due to late harvest of the preceding crop (maize) or to an early end of autumn growth (northern countries), undersowing into the previous crop is an appropriate method allowing catch crops to grow adequately before winter (for review: see Aronsson et al., 2016; but also: Bergkvist et al., 2011; Arlauskienė and Maikštėnienė, 2012; Tuulos et al., 2015;

Valkama et al., 2015). Results of Snapp et al. (2008) suggest that seed priming can improve germination and emergence of some cover crops under suboptimal conditions as in compacted soils.

Depending on the purpose of the green manure, different species of crops or their mixtures should be used (Ramírez-García et al., 2015a, b). In low input systems and/or in less fertile environments, introducing additional N into the system might be desirable by growing legumes as pure stands or in combination with grasses due to the biological N fixation (Tonitto et al., 2006; Olesen et al., 2007; Askegaard and Eriksen, 2008; Hansen et al., 2010; Büchi et al., 2015). On the other hand in high intensive cropping systems, the main aim of cover (catch) crops is to take up as much N as possible before the end of autumn growth in order to deplete soil N and thus to minimize N leaching. Non-legume species like grasses, OSR or radish are mainly used to trap N.

A lot of literature is available describing the positive effects of growing catch crops on soil mineral N (SMN) content in autumn and N leaching during the following percolation period in autumn and winter as well as on yield and N uptake of the subsequent crop (examples given in Table 3; for reviews see also: Thorup-Kristensen et al., 2003; Valkama et al., 2015; Aronsson et al., 2016).

Briefly, the reduction of the nitrate pool positively correlates with the DM accumulation and N uptake of the catch crop. Since the below-ground N uptake often is neglected (due to difficulties in correctly determining root biomass), the positive effects are frequently underestimated (Kristensen and Thorup-Kristensen, 2004; Munkholm and Hansen, 2012; Li et al., 2015a; Komainda et al., 2016). Komainda et al. (2016) suggested using allometric relationships to overcome this shortcoming. Furthermore, fine roots are decomposed and released faster than coarse roots (Jani et al., 2015).

Overall, aside the cover crop species, the length of the growth period (preferably expressed as thermal time) or, more precisely, the amount of intercepted photosynthetically active radiation (PAR) determines the potential DM accumulation and N uptake before the end of autumn growth (Brant et al., 2011; Hashemi et al., 2013; Agneessens et al., 2014; Yeo et al., 2014; Büchi et al., 2015; Stobart et al., 2015; White et al., 2016b; Koch et al., 2017; De Notaris et al., 2018). Vos and van der Putten (1997) derived the potential of DM accumulation and N uptake from the number of days after sowing. They identified the leaf expansion as key process and estimated a light use efficiency of 1.12 g dry matter accumulated per MJ intercepted global radiation being lower than that for main crops as e.g. wheat (Sieling et al., 2016), presumably due to the decreasing temperature during autumn growth.

Several authors discussed the impact of the characteristics of the catch crop root system (depth, architecture) on soil N depletion (Thorup-Kristensen, 2001; Dunbabin et al., 2003; Wahlström et al., 2015) and the factors which it depends on like soil tillage (Munkholm and Hansen, 2012). For instance, Wendling et al. (2016) found five nutrient acquisition strategies depending on the root system of the different species: 1. 'biomass' group (high root and shoot biomass, dense tissue, large diameter and high root area; 2. 'length' group (high root length density (RLD) and high root and leaf area); 3. 'intermediate' group with characteristics of group 1 and 2 (high root and shoot mass, high RLD and high root and leaf area); 4. 'diameter' group (large root diameter, high leaf dry matter content); 5. 'SLA' group (high specific root length, high specific leaf area (SLA), low root tissue density, low root mass, low RLD, low root area). Species specific parameters of the rooting system as a high rooting depth and a high root growth rate (rapid root establishment), which depends mainly on temperature sum, positively correlate with the ability to deplete soil nitrate (Thorup-Kristensen, 1994, 2001; Kristensen and Thorup-Kristensen, 2004; Herrera et al., 2010). In addition, kinetic parameters of nitrate uptake, e.g. Michaelis-Menten constant and maximum uptake rate, may differ between the catch crop species (Lainé et al., 1993).

The soil nitrate pool is the starting point not only for nitrate leaching losses, but also a main source for N_2O emissions due to denitrification. Therefore, N once taken up by a catch crop is saved to get lost until catch crop residues are decomposed and bounded N is remineralized (Delgado et al., 2010). Results on denitrification losses during or following catch cropping are not consistent. Some authors reported of no or only small changes in N_2O emissions due to catch crops (Sanz-Cobena et al., 2014; Peyrard et al., 2016). Simulating scenarios of cover crop introduction in southern France revealed a reduction of greenhouse gas emissions compared to bare soils, mainly due to an increase in carbon storage in the soil, although N_2O emissions slightly increased (Tribouillois et al., 2018). On the other hand, the risk of N_2O emissions during winter increases if residues are already incorporated in autumn. Additionally, higher emissions can occur during the growth of the succeeding main crop, especially if residues show a narrow C:N ratio (Baggs et al., 2000; Rosecrance et al., 2000; Li et al., 2015b, 2016; Pimentel et al., 2015), which, however, can be compensated by adapting N fertilization of the subsequent crop to the estimated N release (Guardia et al., 2016).

Application of C-rich substrates

As mentioned above, incorporation of crop residues with a wide C:N ratio (e.g. wheat straw) can reduce the soil mineral N pool in autumn as a result of microbial immobilization (Catt et al., 1998; Silgram and Chambers, 2002; Garnier et al., 2003; Beaudoin et al., 2005). Accordingly, the application of substrates with large C:N ratios e.g. biochar or hydrochar (products of the carbonization of biomass in different conversion processes) is discussed in order to induce and/or to intensify N immobilization beside of other effects like improving soil structure, soil field capacity or bioavailability of key nutrients (Atkinson et al., 2010).

Results from pot, lysimeter and field experiments suggest that application of biochar has the potential to miti-

Table 3. Examples for DM yield and N uptake of cover crops and their effects of soil mineral N before winter and N leaching

Reference	Region	Year(s)	Cover crop(s)	Cover crop DM yield [t/ha]	Cover crop N uptake [kg N/ha]	Soil mineral N reduction before winter [% of the control before winter]	N leaching reduction [kg N/ha]
Allison et al., 1998a,b	UK	1989/90 – 1992/93	cereals, oilseed rape	1.6 (0.92 – 2.98)	35 (4 – 136)	30	nr[#]
Arlauskienė and Maikštėnienė, 2012	Lithuania	2004/05	undersown clover, ryegrass and mustard	0.75 – 2.41	29.2 – 60.4	3 – 8	nr
Askegaard and Eriksen, 2008	Denmark	2001/02 + 2002/03	clover, ryegrass	0.8 – 1.8	16 – 56	nr	65 – 86
Bergkvist et al., 2011	Sweden	2003/04 – 2004/05	under-sown clover +/- ryegrass	nr	15 – 75	nr	nr
Constantin et al., 2010, 2011	France	1990 – 2007	white mustard, radish, Italian ryegrass	1.07 – 2.32	29 – 37	50	9 – 32
Gabriel et al., 2016	Spain	2012/13 – 2013/14	barley, vetch	0.5 – 3.4	11 – 97	no differences	nr
Garwood et al., 1999	Eastern England	1989/90 – 1994/95	winter rye	0.6 – 1.4	15 – 34	5 – 70	2 – 58
Hansen et al., 2010	Denmark	2002/03 + 2004/05	undersown fodder radish	nr	nr	nr	33 – 40
Hashemi et al., 2013	USA	2004 – 2006	oat, rye	1.0 – 3.5	3 – 119	20 – 67	nr
Komainda et al.,. 2016	Germany	2012/13 + 2013/14	rye, ryegrass	0.1 – 1.2	2 – 52	nr	nr
Kramberger et al., 2014	Slovenia	2008/09 + 2009/10	crimson clover, ryegrass	nr	51–135	nr	nr
Munkholm and Hansen, 2012	Denmark	2008 – 2010	different species	0.9 – 1.8	27 – 65	60 – 67	nr
Plaza-Bonilla et al., 2015	France	2004 – 2010	different legumes	0.6 – 3.1	16 – 83	52 – 62	7 – 34
Premrov et al., 2014	Ireland	2006/07 – 2008/09	mustard	nr	nr	nr	19.4 – 52.3
Schröder et al., 1996	The Netherlands	1988 – 1994	rye, undersown ryegrass	nr	36 – 46	nr	35 – 100
Shepherd, 1999	UK	1988–1996	forage rape, winter rye, white turnip	0.3 – 2.4	10 – 53	nr	9–59
Thorup-Kristensen, 1994	Denmark	1990/91 + 1991/92	different species	2.0 – 5.7	75 – 167	41 – 85	nr
Tribouillois et al., 2016a	France	2012	legumes, non-legumes and their mixtures	nr	30 – 200	16 – 78	16 – 29
Tuulos et al., 2015	Finland	2009/10 + 2010/11	winter turnip rape	2.4 – 3.2	57 – 74	28 – 52	nr
Vos and van der Putten, 1997, 2001	The Netherlands	1991/92 + 1995/96	diverse	0.1 – 4.0	3 – 141	no differences	nr

[#] nr – not reported

gate N leaching losses (Bargmann et al., 2014; Hüppi et al., 2016, Libutti et al., 2016). However, the (short-term) effects on crop productivity are not consistent. In a meta-analysis of literature data, Liu et al. (2013) estimated an increase of 11% across a wide range of experimental conditions with greater responses in pot experiments, for dry land crops and in acid, poor-structured soils. In contrast, Gajić and Koch (2012), Nelissen et al. (2015) and Hüppi et al. (2016) did not identify any increases in yield, nutrient uptake or N use efficiency. The main problem is an adequate remineralization of immobilized N by the start of the following spring (Chaves et al., 2007; Gajić and Koch, 2012). From a practical point of view, the availability (application of 10–30 t ha^{-1} are assumed) and the associated high costs of biochar currently oppose to a broad use (Liu et al., 2013; BUND, 2015).

Nitrogen utilization by the succeeding crop

It is evident that growing catch crops is suitable to reduce the soil nitrate pool in autumn and, in consequence, the risk of nitrate leaching losses, resulting in larger N amount retained in the plant-soil system (Tonitto et al., 2006; Pedersen et al., 2009; Plaza-Bonilla et al., 2015;). However, the challenge is to transfer as much as possible of the nitrogen bounded in the catch crop biomass into the subsequent crop(s) reducing its N fertilizer demand. This requires a timed coincidence of the N release from the catch crop residues and the N demand of the following main crop. If the N mineralization occurs before the main crop is able to utilize this nitrogen (e.g. due to incorporation in autumn or early freezing off, narrow C:N ratio), large nitrate leaching losses can occur during a mild and wet winter and spring (Bergkvist et al., 2011). Delayed incorporation of green manure residues has the potential to reduce the susceptibility of mineral N to leaching and yields more N available to a subsequent crop (Lahti and Kuikman, 2003). On the other hand, N released too late to meet the N requirement of the subsequent crop (Cicek et al., 2015) shifts the nitrate problem into the next percolation period.

The amount of the N fixed or captured by the cover crop can be utilized by the subsequent main crop largely varies and depends on several factors (Table 4 and White et al., 2016a for some examples). When assessing NUE of cover crop N by the subsequent crop, it has to be distinguished between an N limited system (mostly in organic agriculture) and an intensive (conventional) system. If the succeeding main crop remains unfertilized or receives only small N fertilizer amounts, NUE is generally higher compared to adequate N supply (Berntsen et al., 2006; Olesen et al., 2007; Askegaard and Eriksen, 2008; Doltra and Olesen, 2013). However, the challenge is to quantify the seasonal soil N availability patterns in order to adjust the actual N fertilization on the basis of the N requirements of the main crop following cover cropping (Vaughan et al., 2000; Cherr et al., 2006; Tonitto et al., 2006; Heumann et al., 2013; Dresbøll and Thorup-Kristensen, 2014).

Decomposition of catch crops residues in order to provide the nitrogen bounded with the subsequent main crop mainly depends on the soil temperature, concomitant the date of incorporation or freezing off of the catch crop biomass (Lahti and Kuikman, 2003; Thorup-Kristensen and Dresbøll, 2010). The higher the temperature sum or the earlier the incorporation, the higher is the rate of N release. Thönnissen et al. (2000) and Mansoer et al. (1997) suggested that incorporation of plant residues may speed up decomposition and N release by buffering temperature and water regimes relative to the surface. In addition, residues with a narrow C:N ratio and/or high N content e.g. from legumes decompose faster than e.g. grass residues (Ranells and Wagger, 1996, 1997; Vos and van der Putten, 2001; Justes et al., 2009; Pantoja et al., 2015, 2016; Sievers and Cook, 2018). In an incubation experiment with radish residues of different age as well as with those of white mustard and perennial ryegrass, Thomsen et al. (2016) found a linear correlation between net N release and residue C:N ratio respectively N concentration. Consequently, green manure consisting of legumes as pure stands or as mixtures are able to provide more N at early growth stages than non-legumes (Brennan et al., 2013; Kramberger et al., 2014; Li et al., 2015a; Finney et al., 2016; Tribouillois et al., 2016a; St. Luce et al., 2016). In contrast, high lignin and polyphenol contents impair N mineralization (Seneviratne, 2000).

Wagger (1989) and Benincasa et al. (2010) pointed out a contradiction: If the incorporation of catch crop biomass is delayed, the catch crop can accumulate more biomass and take up more soil mineral N; however, the time span for the soil microorganisms to decompose the incorporated residues is reduced before the establishment of the subsequent crop (Garwood et al., 1999). A longer growth period increases residue C:N ratio which may additionally delay N release. On the other hand, main crops like OSR and cereals require high N amounts early in spring when soil temperatures are low impairing decomposition of catch crop residues. Due to a harvest in summer, those crops are not able to utilize N released during summer and early autumn. Therefore, in crops like sugar beet or maize with a long growing period N demand coincides better with N mineralization.

So far, it was assumed that N not take up by a (catch) crop will be lost mainly due to nitrate leaching during the percolation period over winter. This is more or less the case in environments where the water balance exceeds the retention capacity of the soil. However, under some conditions where no or low N leaching losses (low rainfall and/or high field capacity of the soil), depletion of the soil nitrate pool due to catch crop N uptake can exceed N release from the catch crop residues thus reducing the N supply for the succeeding crop. Thorup-Kristensen et al. (2003) termed this occurrence ‘pre-emptive competition’. Removal of catch crop above-ground biomass e.g. for biogas feedstock production, delayed incorporation or growing catch crops with a wide C:N ratio additionally decrease N availability (Thorup-Kristensen and Dresbøll, 2010; Alonso-Ayuso et al., 2014; Li et al., 2015a; Gabriel et al., 2016).

Repeated cover cropping in the crop rotation increases in the capacity of the soil to provide N presumably due to a positive N input to the system (Constantin et al., 2011; Gabriel et al., 2016). While Constantin et al. (2010, 2011) did not observe any reduction in the potential to reduce N leaching, Garwood et al. (1999) reported on elevated nitrate concentrations in drainage water with the number of years under cover cropping. Based on

Table 4. Examples for the effects of cover crops on the N uptake of the succeeding crop.

Reference	Region	Year(s)	Cover crop(s)	Cover crop N uptake [kg N/ha]	Succeeding crop	Fertilization [kg N/ha]	Cover crop N use by the succeeding crop [kg N/ha]
Berntsen et al., 2006	Denmark	1968 – 1992	Italian/perennial rye-grass	38	spring cere-als	70, 110 or 150	+24
Collins et al., 2007	USA	2001 – 2004	mustard	92 – 142	potatoes	112, 263	+27 – +41
Doltra and Olesen, 2013	Denmark	1997 – 2008	grass clover	24 – 59	spring oat	40	+1 – +39
Doltra et al., 2014	Denmark	1998 – 2008	grass clover	25 – 59	spring barley	50	+10 – +27
Garwood et al., 1999	England	1989/90 – 1994/95	winter rye	15 – 34	spring crops	optimum N rates	−9 – +10
Kramberger et al., 2014	Slovenia	2008/09 – 2011/12	crimson clover, Italian ryegrass	51 – 135	maize	120	−60 – +17
Lahti and Kuikman, 2003	Finland	1992/93	common vetch	173	spring wheat	0, 50	+27
Li et al., 2015a	Denmark	2012/13	red clover, winter vetch, clover-grass mixture	153 – 226	spring barley	0	+20 – +23
Olesen et al., 2007	Denmark	1997 – 2004	grass-clover	21 – 37	spring barley	0, 50	+4 – +6
Pantoja et al., 2016	USA	2010 – 2011	winter rye	27	corn	0 – 225	+14
Plaza-Bonilla et al., 2015	France	2005 – 2010	vetch, vetch + oats, mustard	23 – 79	durum wheat, sor-ghum, sun-flower	optimum N rates	+2
Rinnofner et al., 2008	Austria	2002/03 – 2004/05	different legumes and non-legumes	17 – 141	potatoes, winter rye, spring barley	nr	−5 – +28
Sainju and Ssingh, 2001	USA	1997/98 – 1998/99	hairy vetch	169 – 189	corn	0	+21 – +39
Thorup-Kristensen, 1994	Denmark	1990/91 – 1991–92	different legumes and non-legumes	75 – 167	spring barley	0	+13 – +67
Thorup-Kristensen and Dresbøll, 2010	Denmark	1993/94 – 1995/96	winter rye	56 – 140	spring barley	0	−130 – +60
Tosti et al., 2012	Italy	2005/06 + 2006/07	barley, hairy vetch	30 – 200	maize	0	−5 – +105
Vaughan et al., 2000	USA	1994/95 + 1995/96	rye, wheat, hairy vetch	30 – 245	corn	0 – 300	−40 – +72
Vos and van der Putten, 2001	The Nether-lands	1991/92	winter rye forage rape	42 – 123	potatoes	0 125	−3 – +36 -27 – +36

nr – not reported

observations and FASSET simulations, Berntsen et al. (2006) also estimated an increase in nitrate leaching if cover crops are grown each year.

Knowledge of the amount of cover crop N uptake and the subsequent N release is required to adjust N fertilization of the succeeding crop(s). Since environmental conditions (e.g. weather, soil) can vary largely, the use of crop growth model(s) and of decomposition model(s) can provide useful information. Cover crops normally remain in vegetative stages, thus DM accumulation and N uptake mainly depend on radiation, temperature sum, water and nutrient availability, whereas photoperiod and vernalization are negligible (Habekotté, 1997; Vos and van der Putten, 1997; Qi et al., 1999; Constantin et al., 2015; Tribouillois et al., 2016b). No translocation processes into harvest organs have to be considered. Under adequate soil temperature and soil moisture conditions (Ruffo and Bollero, 2003), N mineralization from cover crop residues is mainly affected by N concentration and C:N ratio (Justes et al., 2009; Finney et al., 2016; Thomsen et al., 2016). Other approaches subdivide crop residues (and soil organic matter) into 2–6 pools, defined by their respective composition and rate of C turnover (Jenkinson et al., 1990; Mueller et al., 1997; Henke et al., 2008). However, the proportions of the respective pools as well as the estimates of their decay rates remain difficult to determine.

Challenges and outlook

In temperate climates, growing catch crops in autumn is a very efficient management measure to prevent nitrate from leaching or denitrification; however, it is not *per se* sustainable. This nitrogen has to be transferred into the succeeding crop(s) allowing a reduction of its fertilizer N demand, and to be exported from the system by the harvest products. Otherwise, leaching and denitrification risks may be postponed but not solved.

Although main crops like winter OSR or, to a lesser extent, early sown winter cereals, are able to accumulate some N before winter, an additional N uptake in autumn may lead to excessive crop growth hindering optimal canopy management in spring. This does not inevitably ensure improved yield formation or higher N offtake with the harvest products (Sieling and Kage, 2010). In addition, an early sowing date improving root growth and N uptake likely goes along with a higher pressure in weeds, pests and diseases. On the other hand, a delay in soil tillage can reduce N mineralization in autumn. However, if leading also to a postponed sowing date, yield may be impaired due to a lower ability to compete with weeds (Stenberg et al., 1999).

Catch crops have to be wisely integrated into a crop rotation, which is difficult to realize in intensive production systems with only winter crops like winter OSR, winter wheat and winter barley, since no adequate growing period can be provided to accumulate appreciable N amounts. Especially growing winter wheat after OSR rape or grain legumes regularly results in high N leaching losses due to a high N release between OSR harvest (end of July) and wheat establishment (mid to end of September) and to the poor N uptake before winter (Sieling and Kage, 2006). In order to avoid secondary dormancy, it is currently recommended to delay tillage, thus to allow OSR seeds lost during harvest to germinate (Pekrun et al., 2006; Thöle and Dietz-Pfeilstetter, 2012; Huang et al., 2018). After 3–4 weeks, growth of rapeseed volunteers has to be ceased by herbicides or soil tillage to prevent pathogens e.g. club root (caused by *Plasmodiophora brassicae*) or nematodes from propagation. However, since the use of herbicides comes more and more under criticism, the mandatory soil tillage additionally enhances N release from soil organic matter and crop residues, which, in turn, cannot completely be utilized by the succeeding wheat crop, thus enhancing the risk of N leaching. Although some species (e.g. *Avena strigosa*) may be able to overgrow and thus to suppress rapeseed volunteers, the risk remains that some rapeseed volunteers survive being a host for club root allowing it to form a new generation. Additionally, the germination rate of OSR seeds decreases due to unfavorable conditions in a fast growing catch crop canopy, thus increasing the OSR seed bank in the soil (Soltani et al., 2017). An establishment of a catch crop after the destroying rapeseed volunteers requires a delay of winter wheat sowing in order to ensure sufficient N uptake by the catch crop. From a practical point of view, farmers will not like late sowing dates of wheat since this decreases the likelihood of suitable sowing conditions (e.g. due to increasing rainfall in late autumn).

Another crucial point is the choice of a suitable catch crop species in order to avoid a further increase of pathogens. Generally, catch crops can act as a 'green bridge' providing a permanent food source for e.g. aphids or free-living nematodes or representing a pool for viruses which can be easily broadcasted by aphids into adjacently growing new crops. The latter becomes more and more a problem as increasing temperatures in autumn due to the climate change extend the period of aphid activity, thus increasing the risk of virus infections (e.g. Barley Yellow Dwarf Virus). In addition, the catch crop itself can be a host for pathogens, thus increasing the inoculum in the succeeding main crop. For example, no crucifers should be grown in OSR based rotations due to the club root disease. Phacelia can contribute to the spread of *Verticillium* spp.. Cereals such as rye or barley are hosts for take all (caused by *Gaeumannomyces graminis*) (De Cara et al., 2011).

A successful improvement of the N dynamic requires that the succeeding crop utilizes the N recovered by the catch crop as much as possible, thus allowing to reduce its N fertilizer demand adequately. Therefore, crop N demand has to coincide with the N release from the catch crop residues (White et al., 2016a). Often, the crop rotation has to be adapted accordingly, which may reduce the economic return. Winter crops are less suitable because their optimal sowing dates interfere with the catch crop N uptake in autumn. Since in temperate climates the slow increase of soil temperature delays residue decomposition during spring, spring cereals can only partly use N mineralized from catch crops (Cicek et al., 2015) while the early harvest in July/August hampers the utilization of N released during summer and autumn. Therefore, crops with a late harvest in autumn like sugar beet or maize are more suitable; however, farmers have to have the possibility to utilize them, e.g. as substrates for biogas plants.

An early incorporation of catch crop residues, especially with a narrow C:N ratio can lead to a precipitate N release thus increasing N leaching (Thomsen, 2005; Thorup-Kristensen and Dresbøll, 2010). On the other hand, residues with a wide C:N ratio or a high lignin concentration (grasses) may not be completely decomposed during the growing period after incorporation (Pantoja et al., 2015), thus again increasing the risk of N losses in the subsequent percolation period. Therefore, the effects of catch crop growing have to be considered over more than one cropping period (Thomsen and Christensen, 1998; Baggs et al., 2000). In their simulation study of genotype × environment × management interactions, Dresbøll and Thorup-Kristensen (2014) highlighted the need to consider the fate of N within the whole cropping system in order to optimize its N use efficiency instead of regarding only at a single crop. For example, an N surplus of a crop or N rich residues (e.g. of grain legumes) must not inevitably increase N leaching losses if the succeeding crop (OSR or catch crops) is able to take up this N before winter. As long as the nutrients are not lost from the field, they may be used by later crops. However, Doltra et al. (2014) believed that the currently used catch crop management does not sufficiently control the risk of N losses and reminded to develop more efficient strategies in the future. In intensive cropping systems with a high proportion of OSR and winter wheat, this will demand a change of the crop rotation, e.g. to reduce the occurrence of OSR or grain legumes as preceding crop before winter wheat since this sequence does not offer any wise possibility to handle the N problem. Crop growth and N mineralization models would be useful to estimate autumn N uptake and N release in the succeeding crop(s) allowing the farmer to adjust the N fertilization.

References

Agneessens, L., J. de Waele, S. de Neve, 2014: Review of alternative management options of vegetable crop residues to reduce nitrate leaching in intensive vegetable rotations. Agronomy **4**, 529-555, DOI: 10.3390/agronomy4040529.

Allison, M.F., M.J. Armstrong, K.W. Jaggard, A.D. Todd, 1998a: Integration of nitrate cover crops into sugarbeet (*Beta vulgaris*) rotations. I. Management and effectiveness of nitrate cover crops. Journal of Agricultural Science **130**, 53-60.

Allison, M.F., M.J. Armstrong, K.W. Jaggard, A.D. Todd, 1998b: Integration of nitrate cover crops into sugarbeet (*Beta vulgaris*) rotations. II. Effect of cover crops on growth, yield and N requirement of sugarbeet. Journal of Agricultural Science **130**, 61-67.

Alonso-Ayuso, M., J.L. Gabriel, M. Quemada, 2014: The kill date as a management tool for cover cropping success. Plos One **9**, e109587, DOI: 10.1371/journal.pone.0109587.

Arcand, M.M., J.D. Knight, R.E. Farrell, 2013: Estimating belowground nitrogen inputs of pea and canola and their contribution to soil inorganic N pools using ^{15}N labeling. Plant and Soil **371**, 67-80, DOI: 10.1007/s11104-013-1626-z.

Arcand, M.M., J.D. Knight, R.E., Farrell, 2014: Differentiating between the supply of N to wheat from above and belowground residues of preceding crops of pea and canola. Biology and Fertility of Soils **50**, 563-570, DOI: 10.1007/s00374-013-0877-4.

Arlauskienė, A., S. Maikštėnienė, 2012: Mineral nitrogen dynamics and nitrate leaching in a catch crop and straw management system. Journal of Food Agriculture and Environment **10**, 1188-1193, DOI: 10.1234/4.2012.3627.

Aronsson, H., E.M. Hansen, I.K. Thomsen, J. Liu, A.F. Øgaard, H. Känkänen, B. Ulén, 2016: The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. Journal of Soil and Water Conservation **71**, 41-55, DOI: 10.2489/jswc.71.1.41.

Askegaard, M., J. Eriksen, 2008: Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on a coarse sand. Agriculture, Ecosystems and Environment **123**, 99-108, DOI: 10.1016/j.agee.2007.05.008.

Atkinson, C.J., J.D. Fitzgerald, N.A. Hipps, 2010: Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil **337**, 1-18, DOI: 10.1007/s11104-010-0464-5.

Baggs. E.M., C.A. Watson, R.M. Rees, 2000: The fate of nitrogen from incorporated cover crop and green manure residues. Nutrient Cycling in Agroecosystems **56**, 153–163, DOI: 10.1023/A:1009825606341.

Bargmann, I., R. Martens, M.C. Rillig, A. Kruse, M. Kücke, 2014: Hydrochar amendment promotes microbial immobilization of mineral nitrogen. Journal of Plant Nutrition and Soil Science **177**, 59–67, DOI: 10.1002/jpln.201300154.

Barraclough, P.B., 1989: Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop. Plant and Soil **119**, 59-70, DOI: 10.1007/BF02370269.

Beaudoin, N., J.K. Saad, C. Van Laethem, J.M. Machet, J. Maucorps, B. Mary, 2005: Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. Agriculture, Ecosystems and Environment **111**, 292-310, DOI: 10.1016/j.agee.2005.06.006.

Bechmann, M., G. Blicher-Mathiesen, K. Kyllmar, A. Lital, A. Lagzdins, T. Salo, 2014: Nitrogen application, balances and their effect on water quality in small catchments in the Nordic–Baltic countries. Agriculture, Ecosystems and Environment **198**, 104-113, DOI: 10.1016/j.agee.2014.04.004.

Benincasa, P., G. Tosti, F. Tei, M. Guiducci, 2010: Actual N availability from winter catch crops used for green manuring in maize cultivation. Journal of Sustainable Agriculture **34**, 705-723, DOI: 10.1080/10440046.2010.507452.

Bergkvist, G., M. Stenberg, J. Wetterlind, B. Båth, S. Elfstrand, 2011: Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley - Effect of N dose and companion grass. Field Crops Research **120**, 292-298, DOI: 10.1016/j.fcr.2010.11.001.

Bergström, L., H. Kirchmann, 2006: Leaching and crop uptake of nitrogen and phosphorus from pig slurry as affected by different application rates. Journal of Environmental Quality **35**, 1803-1811, DOI: 10.2134/jeq2006.0003.

Berntsen, J., J.E. Olesen, B.M. Petersen, E.M. Hansen, 2006: Long-term fate of nitrogen uptake in catch crops. European Journal of Agronomy **25**, 383-390, DOI: 10.1016/j.eja.2006.07.00.

Bingham, I.J., J. Blake, M.J. Foulkes, J. Spink, 2007: Is barley yield in the UK sink limited? I. Post-anthesis radiation interception, radiation-use efficiency and source–sink balance. Field Crops Research **101**, 198-211, DOI: 10.1016/j.fcr.2006.11.005.

Björkman. T., C. Lowry, J.W. Shail jr., D.C. Brainard, D.S. Anderson, J.B. Masinuas, 2015: Mustard cover crops for biomass production and weed suppression in the Great Lakes region. Agronomy Journal **107**, 1235–1249, DOI: 10.2134/agronj14.0461.

Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, G.W. Hergert, 2015: Cover crops and ecosystem services: insights from studies in temperate soils. Agronomy Journal **107**, 2449–2474, DOI: 10.2134/agronj15.0086.

Blicher-Mathiesen, G., H.E. Andersen, S.E. Larsen, 2014: Nitrogen field balances and suction cup-measured N leaching in Danish catchments. Agriculture, Ecosystems and Environment **196**, 69-75, DOI: 10.1016/j.agee.2014.06.022.

Bodner, G., M. Himmelbauer, W. Loiskandl, H.P. Kaul, 2010: Improved evaluation of cover crop species by growth and root factors. Agronomy of Sustainable Development **30**, 455–464, DOI: 0.1051/agro/2009029.

Brant, V., J. Pivec, P. Fuksa, K. Neckář, D. Kocourková, V. Venclová, 2011: Biomass and energy production of catch crops in areas with deficiency of precipitation during summer period in central Bohemia. Biomass and Bioenergy **35**, 1286-1294, DOI: 10.1016/j.biombioe.2010.12.034.

Bremer, E., C. van Kessel, 1992: Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. Soil Science Society of America Journal **56**, 1155-1160, 10.2136/sssaj1992.03615995005600040025x.

Brennan, E.B., N.S. Boyd, R.F. Smith, 2013: Winter cover crop seeding rate and variety effects during eight years of organic vegetables: III. Cover crop residue quality and nitrogen mineralization. Agronomy Journal **105**, 171–182, DOI: 10.2134/agronj2012.0258.

Brust, J., W. Claupein, R. Gerhards, 2014: Growth and weed suppression ability of common and new cover crops in Germany. Crop Protection **63**, 1-8, DOI: 10.1016/j.cropro.2014.04.022.

Büchi, L., C.-A. Gebhard, F. Liebisch, S. Sinaj, H. Ramseier, R. Charles, 2015: Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. Plant and Soil **393**, 163-175, DOI: 10.1007/s11104-015-2476-7.

BUND, 2015: Terra Preta/Pyrolysekohle - BUND-Einschätzung ihrer Umweltrelevanz.

Carrer, D., G. Pique, M. Ferlicoq, X. Ceamanos, E. Ceschia, 2018: What is the potential of cropland albedo management in the fight against global warming? A case study based on the use of cover crops. Environmental Research Letters **13**, 044030, DOI: 10.1088/1748-9326/aab650.

Catt, J.A., K.R. Howse, D.G. Christian, P.W. Lane, G.L. Harris, M.J. Goss, 1998: Strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK, 1988-93: the effect of straw incorporation. Journal of Agricultural Science **131**, 309-319.

Chaney, K., 1990: Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. Journal of Agricultural Science **114**, 171-176.

Chaves, B., S. de Neve, P. Boeckx, O. van Cleemput, G. Hofman, 2007: Manipulating nitrogen release from nitrogen-rich crop residues using organic wastes under field conditions. Soil Science Society of America Journal **71**, 1240-1250, DOI: 10.2136/sssaj2005.0379.

Chen, B., E. Liu, Q. Tian, C. Yan, Y. Zhang, 2014: Soil nitrogen dynamics and crop residues. A review. Agronomy of Sustainable Development **34**, 429-442, DOI: 10.1007/s13593-014-0207-8.

Cherr, C.M., J.M.S. Scholberg, R. McSorley, 2006: Green manure approaches to crop production: a synthesis. Agronomy Journal **98**, 302–319, DOI: 10.2134/agronj2005.0035.

Ciardi, C., P. Nannipieri, G. Toderi, G. Giordani, 1988: The effect of past fertilization history on plant uptake and microbial immobilization of urea-N applied to a two course rotation. In: *Nitrogen efficiency in agricultural soils.* Eds.: Jenkinson, D.S., Smith, K.A.; Elsevier Applied Science, 95-109.

Cicek, H., J.R. Thiessen Martens, K.C. Bamford, M.H. Entz, 2015: Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand. Agriculture, Ecosystems and Environment **202**, 31-41, DOI: 0.1016/j.agee.2014.12.007.

Collins, H.P., J.A. Delgado, A.K. Alva, R.F. Follett, 2007: Use of nitrogen-15 isotopic techniques to estimate nitrogen cycling from a mustard cover crop to potatoes. Agronomy Journal **99**, 27-35, DOI: 10.2134/agronj2005.0357.

Colnenne, C., J.-M. Meynard, R. Roche, R. Reau, 2002: Effects of nitrogen deficiencies on autumnal growth of oilseed rape. European Journal of Agronomy **17**, 11–28, DOI: 10.1016/S1161-0301(01)00140-X.

Constantin, J., B. Bary, F. Laurent, G. Aubrion, A. Fontaine, P. Kerveillant, N. Beaudoin, 2010: Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agriculture, Ecosystems Environment **135**, 268-278, DOI: 10.1016/j.agee.2009.10.005.

Constantin, J., N. Beaudoin, F. Laurant, J.-P. Cohan, F. Duyme, B. Mary, 2011: Cumulative effects of catch crops on nitrogen uptake, leaching and net mineralization. Plant and Soil **341**, 137–154, DOI: 10.1007/s11104-010-0630-9.

Constantin, J., C. Dürr, H. Tribouillois, E. Justes, 2015: Catch crop emergence success depends on weather and soil seed bedconditions in interaction with sowing date: A simulation study using the SIMPLE emergence model. Field Crops Research **176**, 22-33, DOI: 10.1016/j.fcr.2015.02.017.

Dabney, S.M., J.A. Delgado, J.J. Meisinger, H.H. Schomberg, M.A. Liebig, T. Kaspar, J. Mitchell, W. Reeves, 2010: Using Cover crops and cropping systems for nitrogen management. In *Advances in Nitrogen Management for Water Quality*, eds. J.A. Delgado, R.F. Follett, 230-281. Ankeny, IA: Soil and Water Conservation Society.

De Cara, S., F. Jacquet, A. Reynaud, G. Goulevant, M.-H. Jeuffroy, F. Montfort, P. Lucas, 2011: Economic analysis of summer fallow management to reduce take-all disease and N leaching in a wheat crop rotation. Environmental Modeling and Assessment **16**, 91–105, DOI: 10.1007/s10666-010-9234-2.

Dejoux, J.-F., J.-M. Meynard, R. Reau, R. Roche, P. Saulas, 2003: Evaluation of environmentally-friendly crop management systems based on very early sowing dates for winter oilseed rape in France. Agronomie **23**, 725-736, DOI: 10.1051/agro:2003050.

Delgado, J.A., S.J. del Grosso, S.M. Ogle, 2010: ^{15}N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated. Nutrient Cycling in Agroecosystems **86**, 383–390, DOI: 10.1007/s10705-009-9300-9.

De Neve, S., S. Gaona Sáez, B. Chaves Daguilar, S. Sleutel, G. Hofman, 2004: Manipulating N mineralization from high N crop residues using on- and off-farm organic materials. Soil Biology and Biochemistry **36**, 127–134, DOI: 10.1016/j.soilbio.2003.08.023.

De Notaris, C., J. Rasmussen, P. Sørensen, J.E. Olesen, 2018: Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agriculture, Ecosystems and Environment **255**, 1-11, DOI: 10.1016/j.agee.2017.12.009.

De Waele, J., K. D'Haene, J. Salomez, G. Hofman, S. De Neve, 2017: Simulating the environmental performance of post-harvest management measures to comply with the EU Nitrates Directive. Journal of Environmental Management **187**, 513-526, DOI: 10.1016/j.jenvman.2016.10.048.

Doltra, J., M. Lægdsmand, J.E. Olesen, 2014: Impacts of projected climate change on productivity and nitrogen leaching of crop rotations in arable and pig farming systems in Denmark. Journal of Agricultural Science **152**, 75-92, DOI: 10.1017/S0021859612000846.

Doltra, J., J.E. Olesen, 2013: The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. European Journal of Agronomy **44**, 98-108, DOI: 10.1016/j.eja.2012.03.006.

Doluschitz, R., H. Welck, J. Zeddies, 1992: Stickstoffbilanzen landwirtschaftlicher Betriebe – Einstieg in die ökologische Buchführung? Berichte über Landwirtschaft **70**, 551-565.

Dresbøll, D.B., K. Thorup-Kristensen, 2014: Will breeding for nitrogen use efficient crops lead to nitrogen use efficient cropping systems?: a simulation study of GxExM interactions. Euphytica **199**, 97–117, DOI: 10.1007/s10681-014-1199-9.

Dunbabin, V., A. Diggle, Z. Rengel, 2003: Is there an optimal root architecture for nitrate capture in leaching environments? Plant, Cell and Environment **26**, 835–844, DOI: 10.1046/j.1365-3040.2003.01015.x.

Durand, P., P. Moreau, J. Salmon-Monviola, L. Ruiz, F. Vertes, C. Gascuel-Odoux, 2015: Modelling the interplay between nitrogen cycling processes and mitigation options in farming catchments. Journal of Agricultural Science **153**, 959-974, DOI: 10.1017/S0021859615000258.

Engström, L., S. Delin, 2016: Nitrage leaching under winter oilseed rape as affected by sowing date and early incorporation of slurry. In: *Abstracts of the 19th Nitrogen Workshop 'Efficient use of different sources of nitrogen in agriculture – from theory to practice'*, 27 – 29 June 2016, Skåra, Sweden, 317-318.

Engström, L., B. Lindén, 2012: Temporal course of net N mineralization and immobilization in topsoil following incorporation of crop residues of winter oilseed rape, peas and oats in a northern climate. Soil Use and Management **28**, 436-447, DOI: 10.1111/sum.12004.

Engström, L., M. Stenberg, H. Aronsson, B. Lindén, 2011: Reducing nitrate leaching after winter oilseed rape and peas in mild and cold winters. Agronomy of Sustainable Development **31,** 337-347, DOI: 10.1051/agro/2010035.

Finney, D.M., C.M. White, J.P. Kaye, 2016: Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agronomy Journal **108**, 39-52, DOI: 10.2134/agronj15.0182.

Gabriel, J.L., M. Alonso-Ayuso, I. García-González, C. Hontoria, M. Quemada, 2016: Nitrogen use efficiency and fertiliser fate in a long-term experiment with winter cover crops. European Journal of Agronomy **79**, 14-22, DOI: 10.1016/j.eja.2016.04.015.

Gajić, A., H.-J. Koch, 2012: Sugar beet (*Beta vulgaris* L.) growth reduction caused by Hydrochar is related to nitrogen supply. Journal of Environmental Quality **41**, 1067-1075, DOI: 10.2134/jeq2011.0237.

Garnier, P., C. Néel, C. Aita, S. Recous, F. Lafolie, B. Bary, 2003: Modelling carbon and nitrogen dynamics in a bare soil with and without straw incorporation. European. Journal of Soil Science **54**, 555-568, DOI: 10.1046/j.1365-2389.2003.00499.x.

Garwood, T.W.D, D.B. Davies, A.R. Hartley, 1999: The effect of winter cover crops on yield of the following spring crops and nitrogen balance in a calcareous loam. Journal of Agricultural Science **132**, 1-11.

Glendining, M.J., D.S. Powlson, 1995: The effects of long continued applications of inorganic nitrogen fertilizer on soil organic nitrogen – a review. In: *Soil management: Experimental basis for sustainability and environmental quality*. Eds.: R. Lal, B.A. Steward, Advances in Soil Science, Lewis Publishers, 385-446.

Glendining, M.J., D.S. Powlson, P.R. Poulton, N.J. Bradbury, D. Palazzo, X. Li, 1996: The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment. Journal of Agricultural Science **127**, 347-363.

Goss, M.J., K.R. Howse, P.W. Lane, D.G. Christian, G.L. Harris, 1993: Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing. Journal of Soil Science **44**, 35-48, DOI: 10.1111/j.1365-2389.1993.tb00432.x.

Goulding, K., 2000: Nitrogen leaching from arable and horticultural land. Soil Use and Management **16**, 145–151, DOI: 10.1111/j.1475-2743.2000.tb00218.x.

Guardia, G., D. Abalos, S. García-Marco, M. Quemada, M. Alonso-Ayuso, L.M. Cárdenas, E.R. Dixon, A. Vallejo, 2016: Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management. Biogeosciences **13**, 5245-5257, DOI: 10.5194/bg-13-5245-2016.

Habekotté, B., 1997: Evaluation of seed yield determining factors of winter oilseed rape (*Brassica napus* L.) by means of crop growth modelling. Field Crops Research **54**, 137-151, DOI: 10.1016/S0378-4290(97)00044-0.

Hansen, E.M., L.J. Munkholm, J.E. Olesen, B. Melander, 2015: Nitrate leaching, yields and carbon sequestration after noninversion tillage, catch crops, and straw retention. Journal of Environmental Quality **44**, 868–881, DOI: 10.2134/jeq2014.11.0482.

Hansen, E.M., L.J. Munkholm, B. Melander, J.E. Olesen, 2010: Can non-inversion tillage and straw retainment reduce N leaching in cereal-based crop rotations? Soil and Tillage Research **109**, 1-8, DOI: 10.1016/j.still.2010.04.001.

Haruna, S.I., S.H. Anderson, N.V. Nkongolo, T. Reinbott, S. Zaibon, 2017: Soil thermal properties influenced by perennial biofuel and cover crop management. Soil Science Society of America Journal **81**, 1147–1156, doiDOI: 10.2136/sssaj2016.10.0345.

Hashemi, M., A. Farsad, A. Sadeghpour, S.A. Weis, S.J. Herbert, 2013: Cover-crop seeding-date influence on fall nitrogen recovery. Journal of Plant Nutrition and Soil Science **176**, 69-75, DOI: 10.1002/jpln.201200062.

Henke, J., U. Böttcher, D. Neukam, K. Sieling, H. Kage, 2008: Evaluation of different agronomic strategies to reduce nitrate leaching after winter oilseed rape (*Brassica napus* L.) using a simulation model. Nutrient Cycling in Agroecosystems **82**, 299-314, DOI: 10.1007/s10705-008-9192-0.

Henke, J., K. Sieling, W. Sauermann, H. Kage, 2009: Analysing soil and canopy factors affecting optimum nitrogen fertilization rates of oilseed rape (*Brassica napus*). Journal of Agricultural Science **147**, 1-8, DOI: 10.1017/S0021859608008162.

Herrera, J.M., B. Feil, P. Stamp, M. Liedgens, 2010: Root growth and nitrate-nitrogen leaching of catch crops following spring wheat. Journal of Environmental Quality **39**, 845–854, DOI: 10.2134/jeq2009.0306.

Herrera, J.M., C. Noulas, P. Stamp, D. Pellet, 2016: Little potential of spring wheat genotypes as a strategy to reduce nitrogen leaching in Central Europe. Agronomy **6**, 29; DOI: 10.3390/agronomy6020029.

Heumann, S., A. Fier, M. Haßdenteufel, H. Höper, W. Schäfer, T. Eiler, J. Böttcher, 2013: Minimizing nitrate leaching while maintaining crop yields: insights by simulating net N mineralization. Nutrient Cycling in Agroecosystems **95**, 395-408, DOI: 10.1007/s10705-013-9572-y.

Hooker, K.V., C.E. Coxon, R. Hachett, L.E. Kirwan, E. O'Keeffe, K.G. Richards, 2008: Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. Journal of Environmental Quality **37**, 138–145, DOI: 10.2134/jeq2006.0547.

Huang, S., S. Gruber, W. Claupein, 2018: Timing and depth of post-harvest soil disturbance can reduce seedbank and volunteers of oilseed rape. Soil and Tillage Research **175**, 187-193, DOI: 10.1016/j.still.2017.09.005.

Hüppi, R., A. Neftel, M.F. Lehmann, M. Krauss, J. Six, J. Leifeld, 2016: N use efficiencies and N_2O emissions in two contrasting, biochar amended soils under winter wheat-cover crop-sorghum rotation. Environmental Research Letters **11**, DOI: 10.1088/1748-9326/11/8/084013.

Jani, A.D., J.M. Grossman, T.J. Smyth, S. Hu, 2015: Influence of soil inorganic nitrogen and root diameter size on legume cover crop root decomposition and nitrogen release. Plant and Soil **393**, 57-68, DOI: 10.1007/s11104-015-2473-x.

Jansons, V., P. Buismanis, I. Dzalbe, D. Kirsteina, 2003: Catchment and drainage field nitrogen balances and nitrogen loss in three agriculturally influenced Latvian watersheds. European Journal of Agronomy **20**, 173–179, DOI: 10.1016/S1161-0301(03)00072-8.

Jenkinson, D.S., 1986: Nitrogen in UK arable agriculture. Journal of the Royal Agricultural Society England **147**, 178-198.

Jenkinson, D.S., S.P. Smith Andrew, J.M. Lynch, M.J. Goss, P.B. Tinker, D.J. Greenwood, P.H. Nye, A. Walker, 1990: The turnover of organic carbon and nitrogen in soil. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences **329**, 361-368, DOI: 10.1098/rstb.1990.0177.

Jenkinson, D.S., N.J. Bradbury, K. Coleman, 1994: How the Rothamsted classical experiments have been used to develop and test models for the turnover of carbon and nitrogen in soil. In: *Long-term experiments in agricultural and ecological sciences*. Eds.: R.A. Leigh, A.E. Johnston, CAB International, 117-138.

Justes, E., B. Mary, B. Nicolardot, 1999: Comparing the effectiveness of radish cover crop, oilseed rape volunteers and oilseed rape residues incorporation for reducing nitrate leaching. Nutrient Cycling in Agroecosystems **55**, 207-220, DOI: 10.1023/A:1009870401779.

Justes, E., B. Mary, B. Nicolardot, 2009: Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: parameterization of the residue decomposition module of STICS model for mature and non mature residues. Plant and Soil **325**, 171-185, DOI: 10.1007/s11104-009-9966-4.

Kaul, H.-P., 2004: Menge und Qualität der Ernterückstände öl- und eiweißreicher Körnerfrüchte. Pflanzenbauwissenschaften **8**, 64-72.

Kendall, S., H.F. Holmes, P.M. Berry, 2017: Updating N fertiliser management guidelines for winter barley. Agriculture and Horticulture Development Board (AHDB), project report no. **571**, 87 pp.

Koch, H.-J., A. Windt, S. Mittler, M. Hauer, 2017: Einfluss der Witterung auf Biomassebildung und N-Aufnahme von Zwischenfrüchten sowie deren Wirkung auf Bodenwasser- und Nmin-Gehalt in Norddeutschland. Journal für Kulturpflanzen **69**, 361-372, DOI: 10.1399/JFK.2017.11.01.

Komainda, M., F. Taube, C. Kluß, A. Herrmann, 2016: Above- and belowground nitrogen uptake of winter catch crops sown after silage maize as affected by sowing date. European Journal of Agronomy **79**, 31-42, DOI: 10.1016/j.eja.2016.05.007.

Kramberger, B., A. Gselman, J. Kristl, M. Lešnik, V. Šuštar, M. Muršec, M. Podvršnik, 2014: Winter cover crop: the effects of grass-clover mixture proportion and biomass management on maize and the apparent residual N in the soil. European Journal of Agronomy **55**, 63-71, DOI: 10.1016/j.eja.2014.01.001.

Kristensen, H.L., K. Thorup-Kristensen, 2004: Root growth and nitrate uptake of three different catch crops in deep soil layers. Soil Science Society of America Journal **68**, 529–537, DOI: 10.2136/sssaj2004.0529.

Lafond, J., D. Pageau, 2008: Economically optimal nitrogen rate and soil nitrate after canola harvest. Canadian Journal of Plant Science **88**, 1035-1042, DOI: 10.4141/CJPS08004.

Lahti, T., P.J. Kuikman, 2003: The effect of delaying autumn incorporation of green manure crop on N mineralization and spring wheat (*Triticum aestivum* L.) performance. Nutrient Cycling in Agroecosystems **65**, 265-280, DOI: 10.1023/A:1022617104296.

Lainé, P., A. Ourry, J. Macduff, J. Boucaud, J. Salette, 1993: Kinetic parameters of nitrate uptake by different catch crop species; effects of low temperatures or previous nitrate starvation. Physiologia Plantarum **88**, 85-92, DOI: 10.1111/j.1399-3054.1993.tb01764.x.

Li, X., P. Sørensen, F. Li, S.O. Petersen, J.E. Olesen, 2015a: Quantifying biological nitrogen fixation of different catch crops, and residual effects of roots and tops on nitrogen uptake in barley using in-situ ^{15}N labelling. Plant and Soil **395**, 273-287, DOI: 10.1007/s11104-015-2548-8.

Li, X., S.O. Petersen, P. Sørensen, J.E. Olesen, 2015b: Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. Agriculture, Ecosystems and Environment **199**, 382-393, DOI: 10.1016/j.agee.2014.10.016.

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

Libutti, A., M. Mucci, M. Francavilla, M. Monteleone, 2016: Effect of biochar amendment on nitrate retention in a silty clay loam soil. Italian Journal of Agronomy **11**, 273-276, DOI: 10.4081/ija.2016.780.

Liu, X., A. Zhang, C. Ji, S. Joseph, R. Bian, L. Li, G. Pan, J. Paz-Ferreiro, 2013: Biochar's effect on crop productivity and the dependence on experimental conditions - a meta-analysis of literature data. Plant and Soil **373**, 583-594, DOI: 10.1007/s11104-013-1806-x.

Liu, J., G. Bergkvist, B. Ulén, 2015: Biomass production and phosphorus retention by catch crops on clayey soils in southern and central Sweden. Field Crops Research **171**, 130-137, DOI: 10.1016/j.fcr.2014.11.013.

Lord, E.I., S.G. Anthony, G. Goodlass, 2002: Agricultural nitrogen balance and water quality in the UK. Soil Use and Management **18**, 363–369, DOI: 10.1111/j.1475-2743.2002.tb00253.x.

Macdonald, A.J., D.S. Powlson, P.R. Poulton, D.S. Jenkinson, 1989: Unused fertiliser nitrogen in arable soils - its contribution to nitrate leaching. Journal of the Science of Food and Agriculture **46**, 407-419, DOI: 10.1002/jsfa.2740460404.

Maidl, F.X., J. Suckert, R. Funk, G. Fischbeck, 1991: Standorterhebungen zur Stickstoffdynamik nach Anbau von Körnerleguminosen. Journal of Agronomy and Crop Science **167**, 259-268, DOI: 10.1111/j.1439-037X.1991.tb00873.x.

Malagoli, P., P. Lainé, L. Rossato, A. Ourry, 2005: Dynamics of nitrogen uptake and mobilization in field-grown winter oilseed rape (*Brassica napus*) from stem extension to harvest I. Global N flows between vegetative and reproductive tissues in relation to leaf fall and their residual N. Annals of Botany **95**, 853-861, DOI: 10.1093/aob/mci091.

Mansoer, Z., D.W. Reeves, C.W. Wood, 1997: Suitability of sunn hemp as an alternative late-summer legume cover-crop. Soil Science Society of America Journal **61**, 246-253, DOI: 10.2136/sssaj1997.03615995006100010034x.

Martre, P., J. He, J. Le Gouis, M.A. Semenov, 2015: In silico system analysis of physiological traits determining grain yield and protein concentration for wheat as influenced by climate and crop management. Journal of Experimental Botany **66**, 3581-3598, DOI: 10.1093/jxb/erv049.

Mary, B., S. Recous, D. Darwis, D. Robin, 1996: Interactions between decomposition of plant residues and nitrogen cycling in soil. Plant and Soil **181**, 71-82, DOI: 10.1007/BF00011294.

Metzger, J.W., 2002: Mikrosensorsysteme zur Bestimmung nitrifikationshemmender Effekte in Abwässern. DBU Abschlussbericht zum Projekt Az 14699.

Mitchell, R., J. Webb, R. Harrison, 2001: Crop residues can affect N leaching over at least two winters. European Journal of Agronomy **15**, 17-29, DOI: 10.1016/S1161-0301(00)00088-5.

Møller Hansen, E., J. Djurhuus, 1997: Nitrate leaching as influenced by soil tillage and catch crop. Soil and Tillage Research **41**, 203-219, DOI: 10.1016/S0167-1987(96)01097-5.

Mueller, T., L.S. Jensen, J. Magid, N.E. Nielsen, 1997: Temporal variation of C and N turnover in soil after oilseed rape straw incorporation in the field: simulations with the soil-plant-atmosphere model DAISY. Ecological Modelling **99**, 247-262, DOI: 10.1016/S0304-3800(97)01959-5.

Munkholm, L.J., E.M. Hansen, 2012: Catch crop biomass production, nitrogen uptake and root development under different tillage systems. Soil Use and Management **28**, 517-529, DOI: 10.1111/sum.12001.

Myrbeck, Å., M. Stenberg, 2014a: Changes in N leaching and crop production as a result of measures to reduce N losses to water in a 6-yr crop rotation. Soil Use and Management **30**, 219-230, DOI: 10.1111/sum.12118.

Myrbeck, Å., M. Stenberg, J. Arvidsson, T. Rydberg, 2012a: Effects of autumn tillage of clay soil on mineral N content, spring cereal yield and soil structure over time. European Journal of Agronomy **37**, 96-104, DOI: 10.1016/j.eja.2011.11.007.

Myrbeck, Å., M. Stenberg, T. Rydberg, 2012b: Establishment of winter wheat - Strategies for reducing the risk of nitrogen leaching in a cool-temperate region. Soil and Tillage Research **120**, 25-31, DOI: 10.1016/j.still.2012.01.007.

Myrbeck, Å., J. Arvidsson, T. Keller, 2014b: Effect of time of autumn primary tillage on soil structure, grain yield and risk of nitrogen leaching in two Swedish clay soils. Acta Agriculturae Scandinavica, Section B – Soil and Plant Science **64**, 33-44, DOI: 10.1080/09064710.2014.882402.

Nardi, S., F. Morari, A. Berti, M. Tosoni, L. Giardini, 2004: Soil organic matter properties after 40 years of different use of orgnic and mineral fertilisers. European Journal of Agronomy **21**, 357-367, DOI: 10.1016/j.eja.2003.10.006.

Nelissen, V., G. Ruysschaert, D. Manka'Abusi, T. D'Hose, K. de Beuf, B. Al-Barri, W. Cornelis, P. Boeckx, 2015: Impact of a woody biochar on properties of a sandy loam soil and spring barley during a two-year field experiment. European Journal of Agronomy **62**, 65-78, DOI: 10.1016/j.eja.2014.09.006.

Öborn, I., A.C. Edwards, E. Witter, O. Oenema, K. Ivarsson, P.J.A. Withers, S.I. Nilsson, A. Richert Stinzing, 2003: Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. European Journal of Agronomy **20**, 211–225, DOI: 10.1016/S1161-0301(03)00080-7.

Øgaard, A.F., 2015: Freezing and thawing effects on phosphorus release from grass and cover crop species. Acta Agriculturae Scandinavica, Section B – Soil and Plant Science **65**, 529-536, DOI: 10.1080/09064710.2015.1030444.

Ogilvy, S.E., B. Bastiman, 1992: The effect of rate and timing of autumn nitrogen on the pre-flowering dry matter production and seed yield of winter oilseed rape. Aspects of Applied Biology **30**, 413-416.

Olesen, J.E., E.M. Hansen, M. Askegaard, I.A. Rasmussen, 2007: The value of catch crops and organic manures for spring barley in organic arable farming. Field Crops Research **100**, 168-178, DOI: 10.1016/j.fcr.2006.07.001.

Olk, D., K.G. Cassman, K. Schmidt-Rohr, M. Anders, J.D. Mao, J. Deenik, 2006: Chemical stabilization of soil organic nitrogen by phenolic lignin residues in anaerobic agroecosystems. Soil Biology and Biochemistry **38**, 3303–3312, DOI: 10.1016/j.soilbio.2006.04.009.

Pandey, A., F. Li, M. Askegaard, I.A. Rasmussen, J.E. Olesen, 2018: Nitrogen balances in organic and conventional arable crop rotations and their relations to nitrogen yield and nitrate leaching losses. Agriculture, Ecosystems and Environment **265**, 350-362, DOI: 10.1016/j.agee.2018.05.032.

Pantoja, J.L., K.P. Woli, J.E. Sawyer, D.W. Barker, 2015: Corn nitrogen fertilization requirement and corn–soybean productivity with a rye cover crop. Soil Science Society of America Journal **79**, 1482–1495, DOI: 10.2136/sssaj2015.02.0084.

Pantoja, J.L., K.P. Woli, J.E. Sawyer, D.W. Barker, 2016: Winter rye cover crop biomass production, degradation, and nitrogen recycling. Agronomy Journal **108**, 841-853, DOI: 10.2134/agronj2015.0336.

Pedersen, A., K. Thorup-Kristensen, L.S. Jensen, 2009: Simulating nitrate retention in soils and the effect of catch crop use and rooting pattern under the climatic conditions of Northern Europe. Soil Use and Management **25**, 243-254, DOI: 10.1111/j.1475-2743.2009.00220.x.

Pekrun, C., P.J.W. Lutman, A. Büchse, A. Albertini, W. Claupein, 2006: Reducing potential gene escape in time by appropriate post-harvest tillage – Evidence from field experiments with oilseed rape at 10 sites in Europe. European Journal of Agronomy **25**, 289-298, DOI: 10.1016/j.eja.2006.06.006.

Peltre, C., M. Nielsen, B.T. Christensen, E.M. Hansen, I.K. Thomsen, S. Bruun, 2016: Straw export in continuous winter wheat and the ability of oil radish catch crops and early sowing of wheat to offset soil C and N losses: A simulation study. Agricultural Systems **143**, 195-202, DOI: 10.1016/j.agsy.2016.01.002.

Peyrard, C., B. Mary, P. Perrin, G. Véricel, E. Gréhan, E. Justes, J. Léonard, 2016: N_2O emissions of low input cropping systems as affected by legume and cover crops use. Agriculture, Ecosystems and Environment **224**, 145-156, DOI: 0.1016/j.agee.2016.03.02.

Pimentel, L.G., D.A. Weiler, G.M. Pedroso, C. Bayer, 2015: Soil N_2O emissions following cover-crop residues application under two soil moisture conditions. Journal of Plant Nutrition and Soil Science **178**, 631–640, DOI: 10.1002/jpln.201400392.

Plaza-Bonilla, D., J.-M. Nolot, S. Passot, D. Raffaillac, E. Justes, 2016: Grain legume-based rotations managed under conventional tillage need cover crops to mitigate soil organic matter losses. Soil and Tillage Research 156, 33-43, DOI: 10.1016/j.still.2015.09.021.

Plaza-Bonilla, D., J.-M. Nolot, D. Raffaillac, E. Justes, 2015: Cover crops mitigate nitrate leaching in cropping systems including grain legumes: Field evidence and model simulations. Agriculture, Ecosystems and Environment **212**, 1–12, DOI: 10.1016/j.agee.2015.06.014.

Premrov, A., C.E. Coxon, R. Hackett, L. Kirwan, K.G. Richards, 2014: Effects of over-winter green cover on soil solution nitrate concentrations beneath tillage land. Science of the Total Environment **470-471**, 967-974, DOI: 10.1016/j.scitotenv.2013.10.057.

Qi, A., T.R. Wheeler, J.D.H. Keating, R.H. Ellis, R.J. Summerfield, P.Q. Craufurd, 1999: Modelling the effects of temperature on the rates of seedling emergence and leaf appearance in legume cover crops. Experimental Agriculture **35**, 327-344.

Ramírez-García, J., J.M. Carrillo, M. Ruiz, M. Alonso-Ayuso, M. Quemada, 2015a: Multicriteria decision analysis applied to cover crop species and cultivars selection. Field Crops Research **175**, 106-115, DOI: 10.1016/j.fcr.2015.02.008.

Ramírez-García, J., J.L. Gabriel, M. Alonso-Ayuso, M. Quemada, 2015b: Quantitative characterization of five cover crop species. Journal of Agricultural Science **153**, 1174-1185, DOI: 10.1017/S0021859614000811.

Ranells, N., M.G. Wagger, 1996: Nitrogen release from grass and legume cover crop monocultures and bicultures. Agronomy Journal **88**, 777-782, DOI: 10.2134/agronj1996.00021962008800050015x.

Ranells, N., M.G. Wagger, 1997: Grass-legume bicultures as winter annual cover crops. Agronomy Journal **89**, 659-565, DOI: 10.2134/agronj1997.00021962008900040019x.

Rasmussen, I.S., D.B. Dresbøll, K. Thorup-Kristensen, 2015: Winter wheat cultivars and nitrogen (N) fertilization - Effects on root growth, N uptake efficiency and N use efficiency. European Journal of Agronomy **68**, 38-49, DOI: 10.1016/j.eja.2015.04.003.

Rasmussen, I.S., K. Thorup-Kristensen, 2016: Does earlier sowing of winter wheat improve root growth and N uptake? Field Crops Research **196**, 10-21, DOI: 10.1016/j.fcr.2016.05.009.

Reau, R., D. Wagner, J.P. Palleau, 1994: End of winter diagnosis: winter rapeseed (*Brassica napus*) and nitrogen fertilization. In: *Proceedings of the Third Congress of the European Society for Agronomy.* Eds.: Borin, M. and M. Sattin, 220-221. Podova: European Society for Agronomy.

Redin, M., S. Recous, C. Sita, G. Dietrich, A.C. Skolaude, W.H. Ludke, R. Schmatz, S.J. Giacomini, 2014: How the chemical composition and heterogeneity of crop residue mixtures decomposing at the soil surface affects C and N mineralization. Soil Biology and Biochemistry 78, 65-75, DOI: 10.1016/j.soilbio.2014.07.014.

Rinnofner, T., J.K. Friedel, R. de Kruijff, G. Pietsch, B. Freyer, 2008: Effect of catch crops on N dynamics and following crops in organic farming. Agronomy for Sustainable Development **28**, 551-558, DOI: 10.1051/agro:2008028.

Rosecrance, R.C., G.W. McCarty, D.R. Shelton, J.R. Teasdale, 2000: Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant and Soil **227**, 283-290, DOI: 10.1023/A:1026582012290.

Rueda-Ayala, V., O. Jaeck, R. Gerhards, 2015: Investigation of biochemical and competitive effects of cover crops on crops and weeds. Crop Protection **71**, 79-87, DOI: 10.1016/j.cropro.2015.01.023.

Ruffo, M.L., G.A. Bollero, 2003: Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal **95**, 900-907, DOI: 10.2134/agronj2003.9000.

Sacco, D., M. Bassanimo, C. Grignani, 2003: Developing a regional agronomic information system for estimating nutrient balances at a larger scale. European Journal of Agronomy **20**, 199-210, DOI: 10.1016/S1161-0301(03)00078-9.

Sainju, U., B.P. Ssingh, 2001: Tillage, cover crop, and kill-planting date effects on corn yield and soil nitrogen. Agronomy Journal **93**, 878-886, DOI: 10.2134/agronj2001.934878x.

Sanz-Cobena, A., S. García-Marco, M. Quemada, J.L. Gabriel, P. Almendros, A. Vallejao, 2014: Do cover crops enhance N_2O, CO_2 or CH_4 emissions from soil in Mediterranean arable systems? Science of the Total Environment **466-467**, 164-174, DOI: 10.1016/j.scitotenv.2013.07.02.

Sapkota, T.B., M. Askegaard, M. Lægdsmand, J.E. Olesen, 2012: Effects of catch crop type and root depth on nitrogen leaching and yield of spring barley. Field Crops Research **125**, 129-138, DOI: 10.1016/j.fcr.2011.09.009.

Schröder, J.J., W. van Dijk, W.J.M. de Groot, 1996: Effects of cover crops on the nitrogen fluxes in a silage maize production system. Netherland Journal of Agricultural Science **44**, 293-315.

Seneviratne, G., 2000: Litter quality and nitrogen release in tropical agriculture: a synthesis. Biology and Fertility of Soils **31**, 60-64, DOI: 10.1007/s003740050624.

Serrago, R.A., D.J. Miralles, 2014: Source limitations due to leaf rust (caused by *Puccinia triticina*) during grain filling in wheat. Crop and Pasture Science **65**, 185-193, DOI: 10.1071/CP13248.

Shepherd, M.A., 1999: The effectiveness of cover crops during eight years of a UK sandland rotation. Soil Use and Management **15**, 41-48, DOI: 10.1111/j.1475-2743.1999.tb00062.x.

Shepherd, M.A., J.P. Newell-Price, 2016: The effects of pig manure type and application timing and frequency on nitrate leaching from a seven-course arable rotation on a retentive alluvial soil. Soil Use and Management **32** (Suppl. 1), 117-126, DOI: 10.1111/sum.12223.

Sieling, K., 2004: Growth stage-specific application of slurry and mineral N to oilseed rape, wheat and barley. Journal of Agricultural Science **142**, 495-502, DOI: 10.1017/S0021859604004757.

Sieling, K., U. Böttcher, H. Kage, 2017a: Sowing date and N application effects on tap root and above-ground dry matter of winter oilseed rape in autumn. European Journal of Agronomy **83**, 40-46, DOI: 10.1016/j.eja.2016.11.006.

Sieling, K., U. Böttcher, H. Kage, 2017b: Effect of sowing method and N application on seed yield and N use efficiency of winter oilseed rape. Agronomy **7**, 21; DOI: 10.3390/agronomy7010021.

Sieling, K., H. Kage, 2006: N balance as an indicator of N leaching in an oilseed rape – winter wheat – winter barley rotation. Agriculture, Ecosystems and Environment **115**, 261-269, DOI: 10.1016/j.agee.2006.01.011.

Sieling, K., H. Kage, 2010: Efficient N management using winter oilseed rape: A review. Agronomy for Sustainable Develpment **30**, 271-279, DOI: 10.1051/agro/2009036.

Sieling, K., U. Böttcher, H. Kage, 2016: Canopy traits in rye, triticale and wheat under varying N supply. Agronomy Research **14**, 1467-1485.

Sieling, K., K. Ni, H. Kage, 2014: Application of pig slurry – first year and residual effects on yield and N balance. European Journal of Agronomy **59**, 13-21, DOI: 10.1016/j.eja.2014.05.003.

Sieling, K., C. Stahl, C. Winkelmann, O. Christen, 2005: Growth and yield of winter wheat in the first three years of a monoculture under varying N fertilization in NW Germany. European Journal of Agronomy **22**, 71-84, DOI: 10.1016/j.eja.2003.12.004.

Sievers, T., R.L. Cook, 2018: Aboveground and root decomposition of cereal rye and hairy vetch cover crops. Soil Science Society of America Journal **82**, 147–155, DOI: 10.2136/sssaj2017.05.0139.

Silgram, M., B.J. Chambers, 2002: Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. Journal of Agricultural Science **139**, 115–137, DOI: 10.1017/S0021859602002435.

Silgram, M., M.A. Shepherd, 1999: The effects of cultivation on soil nitrogen mineralization. Advances in Agronomy **65**, 267-311, DOI: 10.1016/S0065-2113(08)60915-3.

Snapp, S., R. Price, M. Morton, 2008: Seed priming of winter annual cover crops improves germination and emergence. Agronomy Journal **100**, 1506-1510, DOI: 10.2134/agronj2008.0045N.

Soltani, E., S. Gruber, M. Oveisi, N. Salehi, I. Alahdadi, M.G. Javid, 2017: Water stress, temperature regimes and light control induction, and loss of secondary dormancy in *Brassica napus* L. seeds. Seed Science Research **27**, 217-230, DOI: 10.1017/S0960258517000186.

Sørensen, J.N., 1992: Effect of catch crops on the content of soil mineral nitrogen before and after winter leaching. Journal of Plant Nutrition and Soil Science 155, 61-66, DOI: 10.1002/jpln.19921550112.

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

St. Luce, M., C.A. Grant, N. Ziadi, B. Zebarth, J.T. O'Donovan, R.E. Blackshaw, K.N. Harker, E.N. Johnson, Y. Gan, G.P. Laafond, W.E. May, S.S. Malhi, T.K. Turkington, N.Z. Lupwayi, D.L. McLaren, 2016: Preceding crops and nitrogen fertilization influence soil nitrogen cycling in no-till canola and wheat cropping systems. Field Crops Research **191**, 20-32, DOI: 10.1016/j.fcr.2016.02.014.

Stobart, R., N.L. Morris, H. Fielding, A. Leake, J. Egan, R. Burkinshaw, 2015: Developing the use of cover crops on farm through the Kellogg's Origins grower programme. Aspects of Applied Biology **129**, 27-33.

Sylvester-Bradley, R., B.J. Chambers, 1992: The implications of restricting use of fertilizer nitrogen for the productivity of arable crops, their profitability and potential pollution by nitrate. Aspects of Applied Biology **30**, 85-94.

Thöle, H., A. Dietz-Pfeilstetter, 2012: Molecular marker-based identification of oilseed rape volunteers with different secondary dormancy levels in oilseed rape fields. European Journal of Agronomy **43**, 194-200, DOI: 10.1016/j.eja.2012.07.003.

Thönnissen, C., D.J. Midmore, J.K. Ladha, D.C. Olk, U. Schmidhalter, 2000: Legume decomposition and nitrogen release when applied as green manures to tropical vegetable production systems. Agronomy Journal **92**, 253–260, DOI: 10.2134/agronj2000.922253x.

Thomsen, I.K., 2005: Nitrate leaching under spring barley is influenced by the presence of a ryegrass catch crop: Results from a lysimeter experiment. Agriculture, Ecosystems and Environment **111**, 21-29, DOI: 10.1016/j.agee.2005.05.001.

Thomsen, I.K, B.T. Christensen, 1998: Cropping system and residue management effects on nitrate leaching and crop yields. Agriculture, Ecosystems and Environment **68**, 73-84, DOI: 10.1016/S0167-8809(97)00134-5.

Thomsen, I.K., L. Elsgaard, J.E. Olesen, B.T. Christensen, 2016: Nitrogen release from differently aged *Raphanus sativus* L. nitrate catch crops during mineralization at autumn temperatures. Soil Use and Management **32**, 183-191, DOI: 10.1111/sum.12264.

Thorup-Kristensen, K., 1994: The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. Fertilizer Research **37**, 227-234, DOI: 10.1007/BF00748941.

Thorup-Kristensen, K., 2001: Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant and Soil **230**, 185-195, DOI: 10.1023/A:1010306425468.

Thorup-Kristensen, K., M.S. Cortasa, R. Loges, 2009: Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses? Plant and Soil **322**, 101-114, DOI: 10.1007/s11104-009-9898-z.

Thorup-Kristensen, K., D.B. Dresbøll, 2010: Incorporation time of nitrogen catch crops influences the N effect for the succeeding crop. Soil Use and Management **26**, 27-35, DOI: 10.1111/j.1475-2743.2009.00255.x.

Thorup-Kristensen, K., J. Magid, L.S. Jensen, 2003: Catch crops and green manures as biological tools in nitrogen management in temperate zones. Advances in Agronomy **79**, 227-302, DOI: 10.1016/S0065-2113(02)79005-6.

Thorup-Kristensen, K., N.E. Nielsen, 1998: Modelling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops. Plant and Soil **203**, 79-89, DOI: 10.1023/A:1004398131396.

Tonitto, C., M.B. David, L.E. Drinkwater, 2006: Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agriculture, Ecosystems and Environment **112**, 58-72, DOI: 10.1016/j.agee.2005.07.003.

Tosti, G., P. Benincasa, M. Farneselli, R. Pace, F. Tei, M. Guiducci, K. Thorup-Kristensen, 2012: Green manuring effect of pure and mixed barley – hairy vetch winter cover crops on maize and processing tomato N nutrition. European Journal of Agronomy **43**, 136-146, DOI: 10.1016/j.eja.2012.06.004.

Tribouillois, H., J.-P. Cohan, E. Justes, 2016a: Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. Plant and Soil **401**, 347-364, DOI: 10.1007/s11104-015-2734-8.

Tribouillois, H., J. Constantin, E. Justes, 2018: Cover crops mitigate direct greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. Global Change Biology **24**, 2513-2529, DOI: 10.1111/gcb.14091.

Tribouillois, H., C. Dürr, D. Demilly, M.-H. Wagner, E. Justes, 2016b: Determination of germination response to temperature and water potential for a wide range of cover crop species and related functional groups. PLoS ONE **11** (8): e0161185. DOI: 10.1371/journal.pone.0161185.

Trinsoutrot, I., S. Recous, B. Bentz, M. Linères, D. Chèneby, B. Nicolardot, 2000: Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics und nonlimiting nitrogen conditions. Soil Science Society of America Journal **64**, 918-926, DOI: 10.2136/sssaj2000.643918x.

Tuulos, A., M. Yli-Halla, F. Stoddard, P. Mäkelä, 2015: Winter turnip rape as a soil N scavenging catch crop in a cool humid climate. Agronomy of Sustainable Development **35**, 359-366, DOI: 10.1007/s13593-014-0229-2.

Uhlen, G., 1991: Long-term effects of fertilizers, manure, straw and crop rotation on total-N and total-C in soil. Acta Agriculturae Scandinavica **41**, 119-127, DOI: 10.1080/00015129109438593.

Valkama, E., R. Lemola, H. Känkänen, E. Turtola, 2015: Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agriculture, Ecosystems and Environment **203**, 93-101, DOI: 10.1016/j.agee.2015.01.023.

Vaughan, J.D., G.D. Hoyt, A.G. Wollum II, 2000: Cover crop nitrogen availability to conventional and no-till corn: Soil mineral nitrogen, corn nitrogen status, and corn yield. Communications in Soil Science and Plant Analysis **31**, 1017-1041, DOI: 10.1080/00103620009370495.

Vos, J., P.E.L. van der Putten, 1997: Field observations on nitrogen catch crops. I. Potential and actual growth and nitrogen accumulation in relation to sowing date and crop species. Plant and Soil **195**, 299-309, DOI: 10.1023/A:1004281218996.

Vos, J., P.E.L. van der Putten, 2001: Field observations on nitrogen catch crops. III. Transfer of nitrogen to the succeeding main crop. Plant and Soil **236**, 263-273, DOI: 10.1023/A:1012795020139.

Wagger, M.G., 1989: Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. Agronomy Journal **81**, 236-241, DOI: 10.2134/agronj1989.00021962008100020020x.

Wahlström, E.M., E. Møller Hansen, A. Mandel, A. Garbout, H. Lakkenborg Kristensen, L.J. Munkholm, 2015: Root development of fodder radish and winter wheat before winter in relation to uptake of nitrogen. European Journal of Agronomy **71**, 1-9, DOI: 10.1016/j.eja.2015.07.002.

Webb, J., R. Sylvester-Bradley, F.M. Seeney, 1997: Responses of cereals to residual fertiliser nitrogen applied to the preceding potato crop. Journal of the Science of Food and Agriculture **73**, 63-80, DOI: 10.1002/(SICI)1097-0010(199701)73:1<63::AID-JSFA693>3.0.CO;2-8.

Wendling, M., L. Büchi, C. Amossé, S. Sinaj, A. Walter, R. Charles, 2016: Influence of root and leaf traits on the uptake of nutrients in cover crops. Plant and Soil **409**, 419-434, DOI: 10.1007/s11104-016-2974-2.

White, C.A., D.M. Finney, A.R. Kemanian, J.P. Kaye, 2016a: A model-data fusion approach for predicting cover crop nitrogen supply to corn. Agronomy Journal **108**, 2527–2540, DOI: 10.2134/agronj2016.05.0288.

White, C.A., H.F. Holmes, N.L. Morris, R.M. Stobart, 2016b: A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species. Agriculture and Horticulture Development Board (AHDB), Research Review no. **90**.

Wick, K., C. Heumesser, E. Schmid, 2012: Groundwater nitrate contamination: Factors and indicators. Journal of Environmental Management **111**, 178-186, DOI: 10.1016/j.jenvman.2012.06.030.

Yeo, I.-Y., S. Lee, A.M. Sadeghi, P.C. Beeson, W.D. Hively, G.W. McCarty, M.W. Lang, 2014: Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model. Hydrology and Earth System Science **18**, 5239-5253, DOI: 10.5194/hess-18-5239-2014.

Zhou, M., K. Butterbach-Bahl, 2014: Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems. Plant and Soil **374**, 977-991, DOI: 10.1007/s11104-013-1876-9.