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Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops

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ABSTRACT

Components of the field nitrogen (N) balance (input and surplus) are often used to predict nitrate leaching from agricultural lands. However, management factors, such as use of catch crops, greatly affect the actual loss and are a key to reduce N leaching. The present study is based on the 4th cycle of a long-term crop rotation experiment in Denmark, and it aims to quantify, from a crop rotation perspective, the influence on N leaching from N input and surplus or management factors. The experiment included three cropping systems (two organic and one conventional) with or without use of animal manure and catch crops. N leaching was calculated from measurements of nitrate in soil water sampled with ceramic suction cups installed at 1 m depth in all plots. At the rotation level, over a four years period, N leaching was positively related to N input and surplus. However, the overall effect of N input and surplus on N leaching was lower than the effect of use of catch crops. The response rates of N leaching to increasing N inputs and N surplus were about 0.08 and 0.19–0.25, respectively. Catch crops reduced N leaching by 23 kg N ha^{-1}, irrespective of conventional and organic management system, with legume-based catch crops being as effective as non-legumes. Animal manure increased N leaching in one of the organic systems. The organic system with two years of green manure per rotation cycle was the one at highest risk of N leaching, especially from crops following green manure incorporation. Spring wheat and potatoes were the two crops with highest N leaching, and a stable low level of N leaching was only achieved above a crop-specific threshold in catch crop biomass.

1. Introduction

Nitrogen (N) is one of the most essential elements for plants growth, and agricultural production benefitted substantially from the increase in N input brought by the Haber-Bosch process (Erisman et al., 2011). N fertilizers are responsible for feeding approximately 48% of the global population, but a large portion of the N applied to the agricultural land is lost to the environment (Erisman et al., 2008). In this way, agriculture contributes significantly to global N pollution, which occurs through gaseous losses (e.g. N_2O, NH_3) and leaching (e.g. NO_3^-, dissolved organic N). N leaching contributes to groundwater pollution and to eutrophication of aquatic ecosystems, which represent a threat to water quality and biodiversity (Haygarth and Jarvis, 2002; Chislock et al., 2013). For this reason, in the last decades N pollution has been under the attention of European institutions, and several directives and action plans have been implemented in order to reduce it. As agriculture is one of the main sources of N to the environment, measures to reduce N losses from agricultural fields have been a priority. At the European level, though, around 40% of surface waters are still affected by diffuse pollution from agriculture (European Environment Agency, 2015).

In Denmark, norms for the utilization of organic and mineral fertilizers aimed at improving N use efficiency (NUE) and reducing N surplus have been proven successful in reducing N losses to the environment (Kronvang et al., 2008; Dalgaard et al., 2014). As a national average, during the past 30 years N leaching from the root zone has been almost halved, but the goal is to decrease it further in most coastal catchments to comply with the EU Water Framework Directive. As N application to crops in Denmark is already below the economic optimum and NUE has significantly increased in recent decades, other focused strategies are required to further reduce N leaching (Dalgaard et al., 2014).

N surplus is the difference between field N input and output. N surplus has been suggested as indicator of the potential loss of N to the environment (OECD, 2001), and this has also been applied in Denmark. Blicher-Mathiesen et al. (2014) reported that N leaching correlates positively with N surplus. In their study, N surplus was able to explain up to 60% of the variation in average N leaching over a 20-year period,

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with response coefficients of 0.21 and 0.66 for loamy and sandy soils, respectively. However, much of this response was related to variation in precipitation and associated leaching of nitrate between sites. To address the effect of N surplus as a measure of N leaching potential on a given site, measurements of N leaching should be made within long-term experiments varying in N surplus.

Besides N surplus, crop and soil management strategies, such as tillage, rotations and use of catch crops, can influence the actual N losses (Hansen et al., 2015). Several studies have been conducted about the role of catch crops in N leaching reduction (e.g. Thorup-Kristensen et al., 2003; Olesen et al., 2007; Constantin et al., 2010; Tosti et al., 2014), showing their potential as a mitigation tool. In line with this, use of catch crops was one of the measures emphasized in the Danish Nitrate Action Programme 2008–2015, where catch crops are defined as "specific high N assimilating crops". Non-leguminous species (e.g. ryegrass, winter rye, fodder radish) are well recognized as being effective in recovering soil mineral N, but pre-emptive competition with the following crop can occur, which reduces the benefits of catch crops for N supply to the following crop (Thorup-Kristensen and Dresboll, 2010). The use of legumes as catch crops is debated, as their ability to reduce N leaching is not as clear (Valkama et al., 2015). Nonetheless, especially in organic arable systems, the green manuring effect of legume-based catch crops is valuable (Valkama et al., 2015), and mixtures of legumes and non-legumes can combine N retention and green manure functions (Tribouillois et al., 2016). If the potential benefits of using a mixture of legumes and non-legumes have been shown (e.g. Tosti et al., 2014; Tribouillois et al., 2016), a broad, system perspective is still needed. In general, the ability of catch crops to take up soil mineral N, and thus reduce N leaching, can be limited by their growing conditions, such as temperature and, if undersown, competition with the main crop (Doltra and Olesen, 2013; Burger et al., 2017). Therefore, when investigating the role of catch crops in the reduction of N leaching, variations in growth of the catch crops have to be considered.

The main objectives of this study are i) to quantify how N leaching is related to N surplus and N input, ii) to compare different cropping systems and management strategies in terms of N leaching, iii) to assess the effect of legume and non-legume based catch crops on N leaching, and iv) to investigate the inter-annual variation in the effect of catch crops on N leaching and how this depends on catch crop biomass. We hypothesized that i) N leaching is positively correlated to N surplus, ii) legume-based catch crops can reduce N leaching just as well as non-legume based catch crops, and iii) catch crops growth depends on growing degree days (GDD) and biomass of the main crop.

2. Materials and methods

A crop rotation experiment was started in 1997 at Foulum (56° 30′ N, 9° 34′ E), Denmark, in order to study the productivity and environmental impacts of different rotation types and management strategies over a long period of time (Olesen et al., 2000). In particular, two organic and one conventional crop rotations are tested, with and without use of animal manure, green manure and catch crops. N leaching has been one of the focus points from the beginning, and previous studies have investigated how different management factors affect it (Askegaard et al., 2005; Askegaard et al., 2011; Jabloun et al., 2015). The installation of ceramic suction cups in all plots in 2011 combined with a long-term management history (the organic systems ran for 17 years) provides a unique source of information.

2.1. Field site

The present study is based on the 4th cycle of the crop rotation experiment, from 2010 to 2014. The soil is defined as a sandy loam, with 78% sand, 13% silt and 9% clay and a Soil Organic Carbon (SOC) content of around 23 g kg^{-1} (Djurhuus and Olesen, 2000). In 2012 the average soil pH was 5.9.

2.2. Cropping systems and management

The experiment comprised three cropping systems: organic with green manure (OGM – named O2 in previous publications), organic with grain legume (OGL – named O4 in previous publications) and conventional with grain legume (CGL – named C4 in previous publications). The organic systems included plots differing in the use of animal manure (+/−M) and legume based catch crops (+/− CC), for a total of three treatments: +M/−CC, +M/+CC, −M/+CC. The combination −M/-CC was excluded from the experiment since 2005, 8 years after the beginning of the experiment, because this treatment developed a too low fertility level over time that did not allow realistic agronomic management (Askegaard et al., 2011). The conventional system was characterized by the use of mineral fertilizers (F), with and without non-legume catch crops: +F/+CC, +F/−CC. The organic systems with manure (+M) received anaerobically digested animal manure, while the organic systems without manure (−M) received Patentkali®, a potash fertilizer suitable for organic farming containing 30% K_2O, 10% MgO and 42.5% SO_3 in water-soluble forms. The conventional systems were amended with mineral nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) fertilizers. The N application rates were based on Danish national standards (Plantedirektoratet, 2009).

Initially, the experimental field was designed for 4 years crop rotations. It was divided into two completely randomized blocks, each consisting of 32 plots (8 treatments × 4 crops). In this way all the crops in the different systems and treatments could be represented every year, in two real replicates (Olesen et al., 2000). To obtain better control of perennial weeds (*Cirsium arvense* L. and *Elytrigia repens* L.) the crop rotations were converted in 2010 from 4 to 5 years. In particular, an additional year of green manure was added in OGM, while hemp was introduced in OGL and CGL. Green manures suitable for mowing have been identified as a strategic option for managing perennial weeds (Melander et al., 2016), while hemp is known to be highly competitive against many weed species (Van Der Werf, 1994).

OGL and CGL had the same crop sequence: spring barley (*Hordeum vulgare* L.), hemp (*Cannabis sativa* L.), an intercrop of pea (*Pisum sativum* L.) and barley, spring wheat (*Triticum aestivum* L.) and potatoes (*Solanum tuberosum* L.). In OGM, instead of hemp and pea-barley, a green manure crop was undersown in spring barley and kept on the field for the following two years. The green manure was either alfalfa (*Medicago sativa* L.) or a mixture of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.). Due to the original experimental design, four crops were represented each year in two replicates, with all the plots receiving the full crop sequence during the 5 years from 2010 to 2014 (Table 1).

Catch crops were either undersown in May or, if stubble cultivation for weed control was needed and always for potatoes, sown after harvest of the main crop. Catch crop biomass was always incorporated by ploughing in the following spring, before sowing of the main crop. In OGM and OGL, catch crops included both legumes and non-legumes with the undersown catch crop consisting of a mixture of perennial ryegrass, chicory (*Chicorium intybus* L.), white clover and red clover, and the catch crop sown after harvest consisting of a mixture of winter rye (*Secale cereale* L.), winter vetch (*Vicia villosa* Roth) and winter rape (*Brassica napus* L.). In CGL no legumes were included in the catch crops mixture: fodder radish (*Raphanus sativus* L.) was undersown in cereals shortly before harvest, while a mixture of winter rye and winter rape was used when the catch crop was sown after harvest (e.g. after potatoes).

In OGM, the green manure cuttings (3 in a year) were left on the field (mulched) in the −M treatments, while they were removed in +M, as explained in detail by Brozyna et al. (2013). Briefly, in −M treatments the green manure cuts were left on the field in order to provide N to the following crops, as no additional fertilization was provided. In +M treatments, instead, the green manure cuts were

Table 1
Crop sequence during the fourth cycle of the experiment (2010–2014). Four crops were represented every year (crops shown in brackets were not grown that particular year). OGL and CGL were identical rotations under organic and conventional management, respectively.

Cropping system	Field	2010	2011	2012	2013	2014
OGM (Organic with GM)	1	S. barley:GM	GM 1st year	GM 2nd year	S. wheat[cca]	Potato[ccb]
	–	(GM 1st year)	(GM 2nd year)	(S. wheat[cca])	(Potato[ccb])	(S. barley:GM)
	2	GM 2nd year	S. wheat[cca]	Potato[ccb]	S. barley:GM	GM 1st year
	3	S. wheat[cca]	Potato[ccb]	S. barley:GM	GM 1st year	GM 2nd year
	4	Potato[ccb]	S. barley:GM	GM 1st year	GM 2nd year	S. wheat[cca]
OGL/CGL (Organic/conventional with grain legume)	1	S. barley[cca]	Hemp	Pea/barley[cca]	S. wheat[cca]	Potato[ccb]
	–	(Hemp)	(Pea/barley[cca])	(S. wheat[cca])	(Potato[ccb])	(S. barley[cca])
	2	Pea/barley[cca]	S. wheat[cca]	Potato[ccb]	S. barley[cca]	Hemp
	3	S. wheat[cca]	Potato[ccb]	S. barley[cca]	Hemp	Pea/barley[cca]
	4	Potato[ccb]	S. barley[cca]	Hemp	Pea/barley[cca]	S. wheat[cca]

OGM = organic with green manure; OGL = organic with grain legume; CGL = conventional with grain legume; S. = spring; GM = green manure; cc = catch crop (indicates where cc were established in +CC treatments).
[a] Undersown.
[b] Sown after harvest of the main crop.

removed and digested manure was returned to the field. This was done to simulate anaerobic digestion of the harvested plant material as a source of fertilizer. However, no attempt was done in this experiment to match the amount of N applied in manure with the N in harvested material.

Weeds were controlled mechanically in OGM and OGL, while pesticides were used in CGL to control weeds, pests and diseases.

2.3. Plant sampling and analysis

Every year during the experimental period (2010–2014), total above-ground biomass samples were taken from two 0.5 m^2 subplots in each plot two weeks before harvest in annual crops, except for potatoes where ten plants (2.25 m^2, approximately) were sampled. In the green manure crop samples of above-ground biomass were similarly taken shortly before each cut. Above-ground biomass of catch crops and weeds was assessed by sampling from an area of two 0.5 m^2 subplots in each plot in early November. Both green manure and catch crop samples were sorted into legumes and non-legumes, except for 2010 and 2012 when catch crop samples were not divided. Crop yields were assessed by harvesting 24 m^2 net plot areas with a Haldrup harvester.

Plant samples were oven-dried (60 °C for 48 h) to determine dry matter content, then finely milled for total N determination using the Dumas method (Hansen, 1989). For cereal grain, total N and dry matter were assessed by near-infrared spectroscopy (Buchmann et al., 2001) with an Infratec™ 1241 Grain Analyser (Foss A/S, Hillerød, Denmark).

As the relation between the proportion of N from clover and N in the total catch crop sample was consistent (R^2 = 0.7, data not shown), it was used to calculate N from the clover component in the catch crop in 2010 and 2012.

2.4. Nitrate leaching

Until 2011, one crop plot for each treatment was equipped with ceramic suction cups at 1 m depth. From 2011 on, suction cups were installed in all the plots, giving a better representation of the inter-annual variation in leaching related to crops. Water samples were collected every one to four weeks by applying a suction of approximately 80 kPa three days prior to sampling, and were then analyzed for nitrate content. The EVACROP model (Olesen and Heidmann, 1990) was used to calculate drainage, based on daily precipitation, temperature and evapotranspiration as measured at a meteorological station located within 1 km from the field site. The calculation of N leaching was then based on the simulated daily drainage by interpolating nitrate concentration between sampling dates according to cumulated drainage flow. In 2011, 2012, 2013 and 2014 the cumulative yearly N leaching was calculated for the period from 1 April to 31 March. In this way, the growing season and the period after harvest of the crop were included, since the main leaching occurs during autumn and winter.

2.5. N balance

The N balance was calculated at the treatment level for each cropping system, as a mean of all respective plots over the period from 2011 to 2014, in order to be comparable with the N leaching from all the plots (from 2011). In compliance with the OECD (2001) model, the surface balance was calculated as the difference between N input and output. Input included N in manure or mineral fertilizer, atmospheric N deposition, biological N_2 fixation by legumes and N in seeds. Output consisted of N removed from the field, including green manure cuts in OGM/+M. Atmospheric N deposition was set to 12 kg N ha^{-1}, which was the average deposition in Danish agricultural lands in 2013 (Ellermann et al., 2015). An empirical model (Høgh-Jensen et al., 1998; Høgh-Jensen et al., 2004) was used to quantify N_2 fixation (N_{fix}) by green manure, pea and catch crops:

$$N_{fix} = N_{shoot} * P_{fix} * (1 + P_{root} + P_{transoil} + P_{immobile})$$

Where N_{shoot} is the amount of N in the shoot and P_{fix} is the fixed N as a proportion of total shoot N. N fixed in the shoot is then corrected with root (P_{root}), soil transfer ($P_{transoil}$) and immobilization ($P_{immobile}$) parameters. N_{shoot} for pea was calculated based on the plant sample dry matter (total pea above-ground biomass) and a N content of 3.7%; P_{fix} was set to 0.82 and P_{root} to 0.12 (Høgh-Jensen et al., 1998). For both the green manure and the catch crops, N_{shoot} was derived from plant samples (legumes fraction) analysis, while P_{fix} was set to 0.9, P_{root} to 0.25, $P_{transoil}$ to 0.05 and $P_{immobile}$ to 0.25 (Høgh-Jensen et al., 1998).

2.6. Growing Degree Days calculation

Cumulative Growing Degree Days (GDD, °Cd) during the catch crops growing period were calculated as:

$$GDD = \Sigma (T_m - T_b)_+$$

where T_m is the average daily temperature and T_b (4 °C) is the base temperature (Mcmaster and Wilhelm, 1997; Moot et al., 2000; Brennan and Boyd, 2012). The subscript + denotes that the contribution was set to 0 when $T_m < T_b$. The catch crop growing period was considered as the period from harvest of the main crop until sampling of above-ground biomass of the catch crop.

2.7. Statistical analysis and data exploration

Statistical analysis and data exploration were conducted using R (R Core Team, 2016), according to the protocol described by Zuur et al.

(2010). After visual investigation, analysis of variance (ANOVA) tests were performed to assess the effect of treatment and crop on N input, output, surplus and leaching, with each cropping system being analyzed separately. In the OGM system the −M treatment was excluded from the analysis because of the management of green manure cuts (mulching), which made it incomparable with +M treatments (cuts removed) in terms of N balance.

Potatoes and spring wheat were found to be the major contributors to N leaching, although being associated with a high variability. Based on this, further exploration focused on these two crops. ANOVA tests were performed to examine the effect of rotation, fertilization, catch crops and year on N leaching, with possible interactions among the factors. The assumptions of normality and homoscedasticity were checked with the Shapiro-Wilk test and visual examination of the residuals against fitted values. When the assumptions were not met, the dependent variable data were log transformed. Post-hoc comparisons were conducted using the HSD.test of the agricolae package (DE Mendiburu, 2016).

The relation between N leaching and catch crop above-ground dry matter in potatoes and wheat was assessed by visual investigation and the lm function of the R Stats package. The relations between catch crops above-ground dry matter and growing degree days (GDD) or yield of the main crop were assessed with Pearson correlation coefficients, using the cor.test function of the R Stats package. For all statistical tests $\alpha = 0.05$.

3. Results

3.1. Climate

The average annual temperature during the period 2010–2014 was 7.9 °C, varying from 6.2 °C in 2010 to 9.6 °C in 2014. The annual precipitation varied from 519 mm in 2010 to 776 mm in 2014 with an average over the five years of 665 mm. Fig. 1 shows the monthly average temperature and cumulative precipitation during the whole period.

3.2. N input, output and balance

At the crop rotation level, N budgets were calculated as yearly averages for each treatment and cropping system on a four years basis

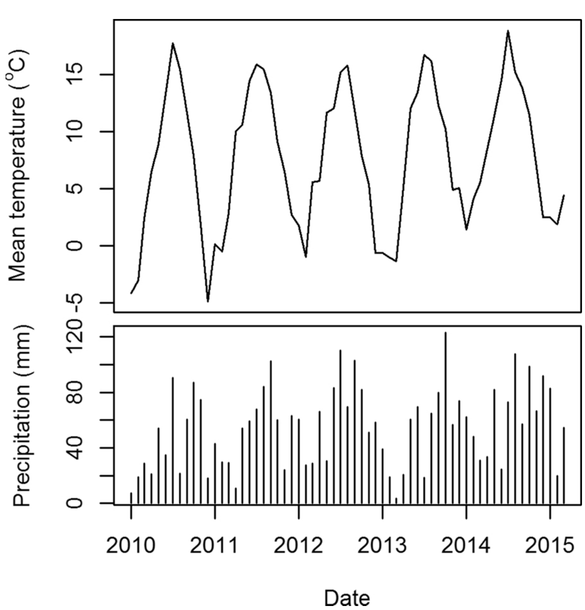

Fig. 1. Mean monthly temperature and cumulative precipitation from January 2010 to March 2015 at the experimental site.

(2011–2014), including four crops every year in two replicates (Table 2). The conventional system (CGL) received 101 kg N ha^{-1} y^{-1}, distributed to the different crops according to Danish norms (Plantedirektoratet, 2009). For the organic systems, 49 and 71 kg N ha^{-1} y^{-1} were applied in manured treatments (+M) in OGM and OGL, respectively. N input from N_2-fixation was greatest in OGM due to the large contribution by the green manure (169–194 kg N ha^{-1} y^{-1}), while the mean N_2 fixation from pea in OGL and CGL ranged from 29 to 37 kg N ha^{-1} y^{-1}. Legume-based catch crops fixed an average of 10–23 kg N ha^{-1} y^{-1} in OGL, and 2 kg N ha^{-1} y^{-1} in OGM. The amount of biologically fixed N_2 in main crops and catch crops varied across years (Supplementary material, Tables S1 and S2). In total, OGM was the system with the highest N input, while OGL had the lowest N input.

The average N output ranged from 33 kg N ha^{-1} y^{-1} in OGM/-M, where the green manure cuts were left in the field, to 152–162 kg N ha^{-1} y^{-1} in OGM/+M, where the cuts were removed (Table 2). N output in OGL varied between 64 and 84 kg N ha^{-1} y^{-1}, with no significant differences in mean N outputs between OGL/+CC/−M and OGL/−CC/+M treatments and a 20 kg N ha^{-1} y^{-1} significantly higher output in OGL/+CC/+M. In CGL mean N outputs amounted to 120 and 121 kg N ha^{-1} y^{-1} in CGL/+CC and CGL/−CC, respectively.

The mean N surplus varied according to the different inputs and outputs (Table 2), ranging from 178 kg N ha^{-1} y^{-1} in OGM/+CC/−M, where the green manure was left in the field, to 6 kg N ha^{-1} y^{-1} in OGL/+CC/−M, which had the lowest N input. In general, OGM was the system with the highest N surplus, mainly due to N_2 fixation by the green manure, with 1st and 2nd year alfalfa and the grass-clover having average surpluses of 230, 282 and 213 kg N ha^{-1} y^{-1}, respectively (Fig. 2).

3.3. N leaching

At the crop rotation level, nitrate leaching (called N leaching in the following) was calculated as yearly averages for each treatment and cropping system, based on the period from 2011 to 2014 (Table 2). The effect of treatment on N leaching was tested individually for each cropping system. The OGM/+CC/−M treatment was excluded from the analysis due to the different management of green manure cuts. In the −M treatment the cuts were left on the field and resulted in an exceptionally high N surplus if compared to +M treatments, where the cuts were removed. A significant effect of treatment ($P < .001$) was found in CGL and OGL, but not in OGM, where a tendency ($P = .14$) was nonetheless clear. In general, treatments without catch crops resulted in higher N leaching, with approximately a 60% increase if compared to the treatments with catch crops, corresponding to an average of 23 kg N ha^{-1} y^{-1}. In OGL, a significant difference in N leaching was also found between +CC/+M and +CC/−M treatments, with an average of 9 kg N ha^{-1} y^{-1} lower leaching in +CC/−M (Table 2).

To offer a comprehensive perspective on the relation between N leaching and N balance elements, the focus was set first on the plot level and then broadened to the crop rotation level.

At the plot level, N leaching appeared to be influenced by the main crop type, especially in treatments −CC, with no general correlation with N surplus (Fig. 3). Among the other crops, hemp had a relatively low and stable N leaching (26 kg N ha^{-1} y^{-1}, sd = 9) even if it was never followed by CC. In general, the variation in N leaching within the same crop and treatment was mainly related to year, except for green manure in OGM/+CC, where the relation between N surplus and leaching was significant ($P < .01$).

At the crop rotation level, there was a clear distinction in N leaching between +CC and −CC, irrespective of catch crop type (with or without legumes) (Fig. 4). Within the range of the studied cropping systems, changes in N input influenced N leaching to a lower degree

Table 2
Nitrogen inputs, outputs and surplus during the period 2011–2014. Data are annual means ($kg\,N\,ha^{-1}\,yr^{-1}$) for the three cropping systems and the relative treatments, based on four crops each year and two replicates for each crop (n = 32). Numbers in brackets are standard errors.

	CGL		OGM			OGL		
	+CC/+F	−CC/+F	+CC/+M	+CC/−M	−CC/+M	+CC/+M	+CC/−M	−CC/+M
N inputs:								
Fertilizer	101	101	0	0	0	0	0	0
Manure	0	0	49	0	49	71	0	71
Seeds	5	4	4	4	4	5	5	4
Deposition	12	12	12	12	12	12	12	12
Fix. main	37	36	169	194	181	29	31	29
Fix. CC	0	0	2	2	0	10	23	0
Total N input	155 (7) a	153 (6) a	235 (33) a	211 (44)	245 (35) a	127 (8) a	71 (13) b	117 (7) a
N output	120 (7) a	121 (6) a	152 (21) a	33 (6)	161 (22) a	84 (6) a	65 (6) b	64 (5) b
N surplus	35 (8) a	32 (8) a	84 (18) a	178 (49)	84 (17) a	44 (8) a	6 (11) b	52 (5) a
N leaching	31 (5) a	51 (7) b	39 (8) a	36 (5)	63 (11) a	33 (4) a	24 (4) b	54 (5) c

CGL = conventional with grain legume; OGM = organic with green manure; OGL = organic with grain legume; CC = catch crop; F = mineral fertilizer; M = manure. Within each cropping system and dependent variable, values followed by different letters are significantly different. OGM/+CC/−M was excluded from the statistical analysis due to the different management of the green manure cuts in this treatment that greatly affects N surplus.

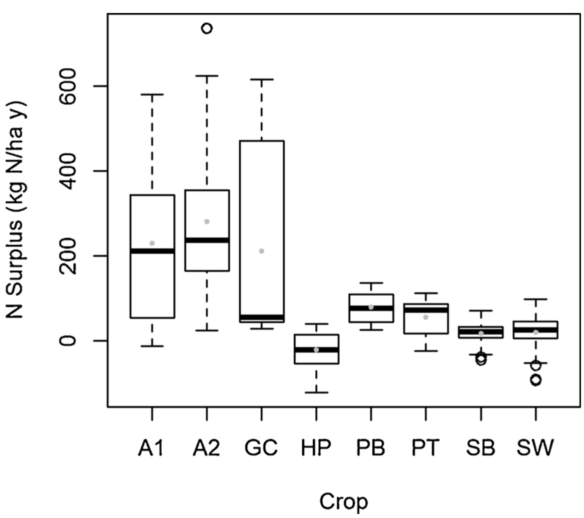

Fig. 2. N surplus ($kg\,N\,ha^{-1}\,y^{-1}$) in relation to the different crops. Dots indicate mean values, the line within the box the median, box boundaries include the 25th and 75th percentiles, the dotted lines above and below the box the 10th and 90th percentiles and empty circles represent the observations that fall outside this range. A1 = alfalfa 1st year, A2 = alfalfa 2nd year, GC = grass-clover, HP = hemp, PB = pea-barley, PT = potato, SB = spring barley, SW = spring wheat.

than N surplus. The response coefficients of N leaching to N input and N surplus were 0.08 and 0.19–0.25, respectively. In any case, N input and surplus were shown to affect N leaching to a lower degree than the effect related to catch crops.

3.4. N leaching from spring wheat and potatoes and the effect of catch crops

The arable crops associated to the highest average N leaching were potatoes with 52 and 123 $kg\,N\,ha^{-1}\,y^{-1}$ and spring wheat with 33 and 67 $kg\,N\,ha^{-1}\,y^{-1}$ with and without catch crops, respectively (Fig. 5). N leaching in these two crops was significantly affected by year ($P < .05$), catch crop ($P < .001$) and rotation ($P < .001$), with interaction between catch crop and year ($P < .01$) (Table 3). In most years catch crops decreased N leaching, except for potatoes in 2012. In this case, a higher leaching was observed in the systems with catch crops (Table 3) due to poor growth of catch crops.

In general, OGM had significantly higher N leaching than the other two systems, from both spring wheat and potatoes. The difference between OGL and CGL was only significant in spring wheat, between CGL/+CC/+F and OGL/+CC/+M, with the organic system having on average 13 $kg\,N\,ha^{-1}\,y^{-1}$ higher leaching than the conventional system. OGL/+CC/+M had a significantly higher leaching also when compared to OGL/+CC/−M ($P < .05$), in agreement with the overall trend of higher N leaching in organic systems with manure application.

The effect of catch crops on N leaching from spring wheat and potatoes varied considerably between years, suggesting that catch crops growth influenced their ability to reduce N leaching. In both spring wheat and potatoes a threshold in catch crop above-ground biomass was identified, above which N leaching was reduced to a low stable level (Fig. 6). In particular, N leaching from spring wheat averaged 15 (sd = 8) $kg\,N\,ha^{-1}\,y^{-1}$ with catch crop biomass above 0.9 $Mg\,ha^{-1}$, and 41 (sd = 29) $kg\,N\,ha^{-1}\,y^{-1}$ with catch crop biomass below 0.9 $Mg\,ha^{-1}$. The OGM system contributed the most to the high N leaching with a low catch crop biomass. In potatoes, the average N leaching was 11 (sd = 6) $kg\,N\,ha^{-1}\,y^{-1}$ with catch crop biomass above 1.5 $Mg\,ha^{-1}$. When lower, the average N leaching was 80 (sd = 36) $kg\,N\,ha^{-1}\,y^{-1}$, with all systems showing similar patterns.

3.5. Inter-annual variation in growth of catch crops

Catch crop above-ground biomass was significantly correlated ($P < .001$) to the cumulated GDD after harvest of the main crop (Fig. 7). The above-ground dry matter ranged from 1.0 to 2.7 $Mg\,ha^{-1}$ with 857 GDD (2014), while it ranged from 0 to 1.2 $Mg\,ha^{-1}$ with 525 GDD (2012). Catch crops growing after potatoes accumulated the largest GDD, due to the early harvest of potatoes (e.g. 1381 °Cd in 2014). In addition to the climate factor, also biomass of the main crop had a significant effect on catch crop growth (Fig. 8). The negative correlation between catch crops above-ground dry matter and main crop yield was significant for spring wheat ($P < .001$), spring barley ($P < .01$), and pea-barley ($P < .01$), but with different coefficients for different years. For potatoes no general correlation was found between crop yield and catch crop biomass.

4. Discussion

The productivity of the conventional systems analyzed in this study was in the range of average Danish production. For example, the average Danish yield for spring wheat is 4.7 $Mg\,ha^{-1}$ (EUROSTAT, 2016), which reflects yields from both conventional and organic systems. Across the whole studied period, the conventional system (CGL) had an average wheat production of 4.7 $Mg\,ha^{-1}$, the organic system with green manure (OGM) had an average yield of 4.5 $Mg\,ha^{-1}$ while

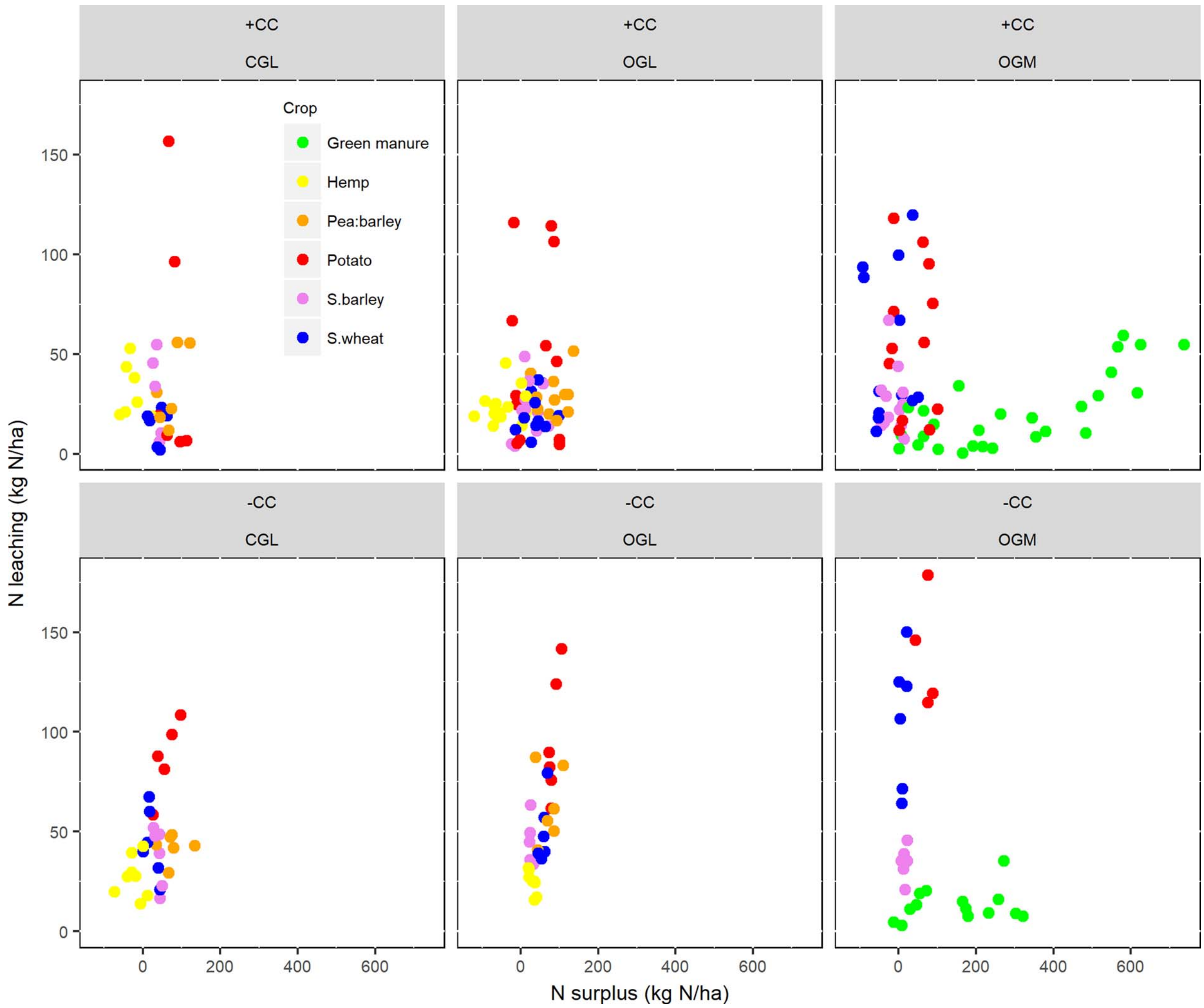

Fig. 3. N leaching as related to N surplus at the plot level (kg N ha^{-1}) in the different systems, with catch crops (+CC) and without catch crops (−CC). Every data point represents a single observation and indicates the relation between N leaching and N surplus for each crop, in each plot, in a single year. Different main crops are indicated by different colors. CGL = conventional with grain legume; OGM = organic with green manure; OGL = organic with grain legume. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

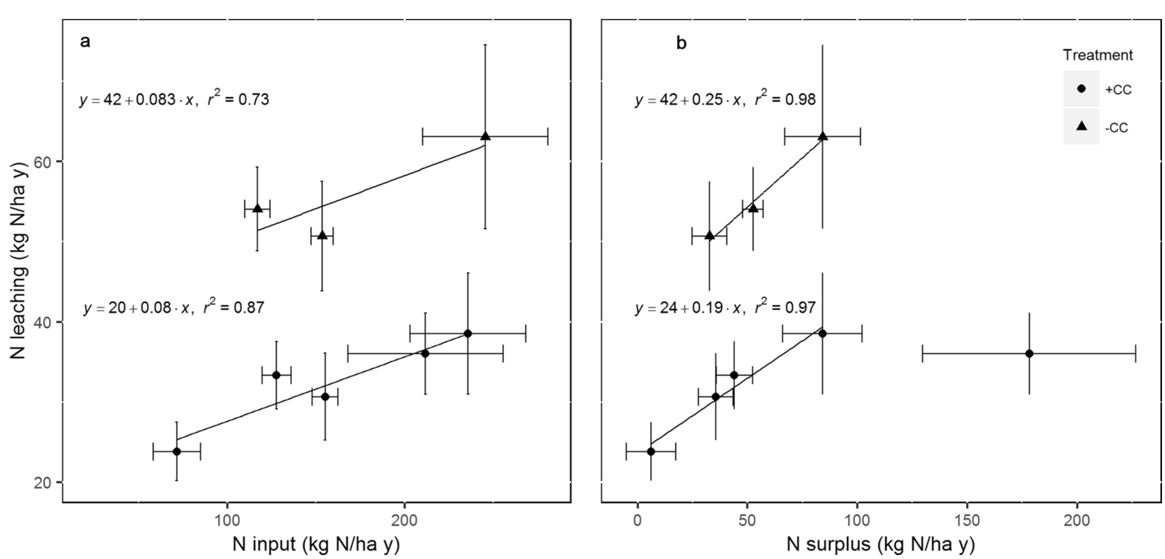

Fig. 4. Mean N leaching in relation to a) mean N input and b) surplus (kg N ha^{-1} y^{-1}). All combinations of cropping systems and treatments are included and represented by a data point, with error bars indicating standard error (n = 32). Regression lines are shown separately for treatments with catch crops (+CC, dots) and without catch crops (−CC, triangles). OGM/+CC/−M is excluded from the regression lines in b because of the different management of green manure cuts (mulched).

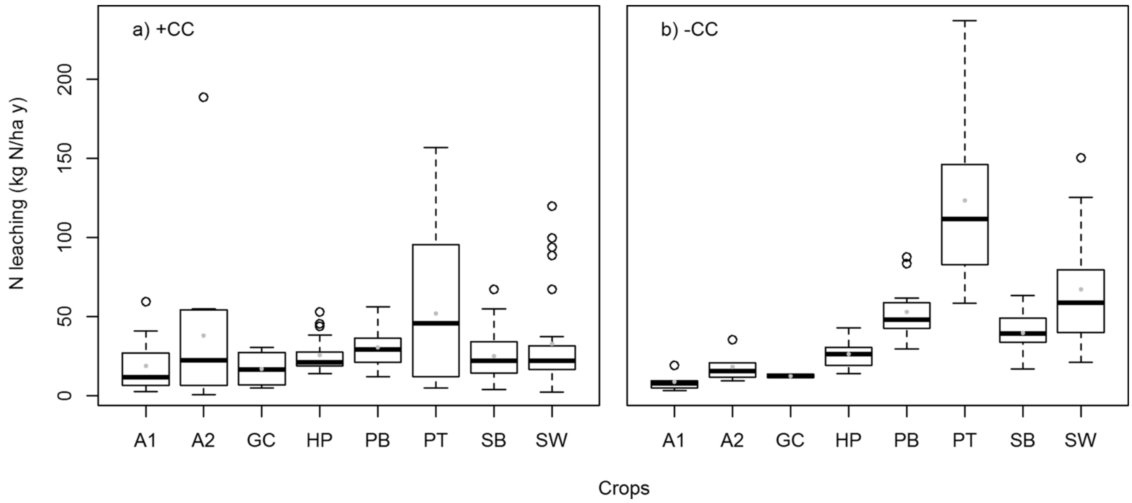

Fig. 5. N leaching (kg N ha^{-1} y^{-1}) in relation to the different crops a) with catch crops (+CC), b) without catch crops (−CC). Dots indicate mean values, the line within the box the median, box boundaries include the 25th and 75th percentiles, the dotted lines above and below the box the 10th and 90th percentiles and empty circles represent the observations that fall outside this range. A1 = alfalfa 1st year, A2 = alfalfa 2nd year, GC = grass-clover, HP = hemp, PB = pea-barley, PT = potato, SB = spring barley, SW = spring wheat.

the average yield in OGL ranged from 2.6 Mg ha^{-1} in OGL/+CC/−M to 4.0 Mg ha^{-1} in OGL/+CC/+M. In general organic farmers apply manure to their crops, therefore +M treatments reflect the common practice. When comparing organic systems to the conventional, the yield gap varies according to the rotation type and the management strategy, with an average yield reduction that falls in the 19–25% range reported by recent meta-analyses (Seufert et al., 2012; Ponisio et al., 2015).

4.1. N balance and N leaching

Surface N balances were calculated as annual means over a four years period, including all crops in the rotation. This allowed a system perspective on the N balance, overcoming the variation related to conditions in individual years and different crops (Parris, 1998). N output, expressed as N yield in crops and N in green manure cuts, did not always reflect the changes in N input. Looking at the organic system OGL in particular, N output in OGL/+CC/−M was not significantly different from OGL/−CC/+M, even though the latter had a higher N input due to manure fertilization. The highest N output in the OGL system was obtained when manure and catch crops were combined, with OGL/+CC/+M yielding 20 kg N ha^{-1} y^{-1} more than OGL/−CC/+M. The same trend was shown for the previous cycles of the experiment (Doltra and Olesen, 2013; Shah et al., 2017), where there was a positive effect of catch crops on spring cereal yields in the OGL system.

The relation between N leaching and N input or N surplus was consistent at the crop rotation level, with a pronounced difference between treatments with and without catch crops. This suggests that, more than the N balance elements themselves, strategies to retain N in the system (e.g. by using catch crops) are of crucial importance for reducing N leaching. Our findings agree with the concept that N balances can provide a proxy of the potential N loss, but that management strategies are more important in determining the actual loss (Öborn et al., 2003; Hansen et al., 2015). Nonetheless, it is worth noting that, within the same catch crop treatment, N leaching increased with increasing N surplus at a rate of 19 and 25% with and without catch crop, respectively. The coefficients found in this study are in agreement with the results of Blicher-Mathiesen et al. (2014), who reported a 0.21 coefficient in loamy soils. The higher N surplus than N leaching is in accordance to the expectations since, besides N leaching, N surplus includes also gaseous losses due to denitrification, ammonia volatilization and changes in the soil N pool (OECD, 2001). Use of catch crops was shown to increase soil N stocks (Constantin et al., 2010; Berntsen et al., 2006), which can explain why the relation between N surplus and N leaching in +CC treatments had a slightly lower response coefficient than −CC. The exception to the general trend was OGM/+CC/−M, where green manure cuts were left on the field, leading to a high surplus without higher leaching. A number of reasons could explain the results from OGM/+CC/−M. Firstly, it is possible that N surplus in OGM/+CC/−M was overestimated in relation to N_2 fixation from the green manure, which might have been reduced by mulching (Hatch et al., 2007). Another possible explanation to the discrepancy of OGM/+CC/−M from the general trend are increased gaseous losses in relation to mulching (Moeller, 2009). In a study on the 3rd cycle of the same crop rotation experiment, Pugesgaard et al. (2017) found a significant relation between N_2O emissions and crop residues, in agreement with Brozyna et al. (2013). However, when comparing OGM/+CC/−M with OGM/+CC/+M, no significant difference in N_2O emissions could be found in relation to management of green manure cuts (Brozyna et al., 2013). Similarly, Nadeem et al. (2012) reported a

Table 3
N leaching (kg N ha^{-1}) in spring wheat and potato as affected by year, cropping system, catch crop and manure (n = 2). Numbers in brackets are standard errors.

Crop	Year	CGL		OGM			OGL		
		+CC/+F	−CC/+F	+CC/+M	+CC/−M	−CC/+M	+CC/+M	+CC/−M	−CC/+M
S. wheat	2011	21 (2)	26 (5)	29 (1)	26 (5)	68 (4)	33 (2)	15 (1)	49 (8)
	2013	18 (1)	42 (2)	83 (16)	91 (3)	116 (9)	33 (4)	15 (3)	38 (1)
	2014	3 (1)	64 (4)	73 (46)	15 (3)	137 (14)	16 (3)	16 (10)	64 (16)
Potato	2011	14 (5)	70 (11)	66 (10)	58 (13)	162 (16)	50 (4)	27 (2)	83 (7)
	2012	127 (30)	93 (6)	101 (5)	85 (33)	117 (2)	110 (4)	91 (25)	72 (10)
	2014	6 (0)	165 (56)	17 (5)	14 (2)	213 (24)	6 (1)	6 (1)	133 (9)

CGL = conventional with grain legume; OGM = organic with green manure; OGL = organic with grain legume; CC = catch crop; F = mineral fertilizer; M = manure.

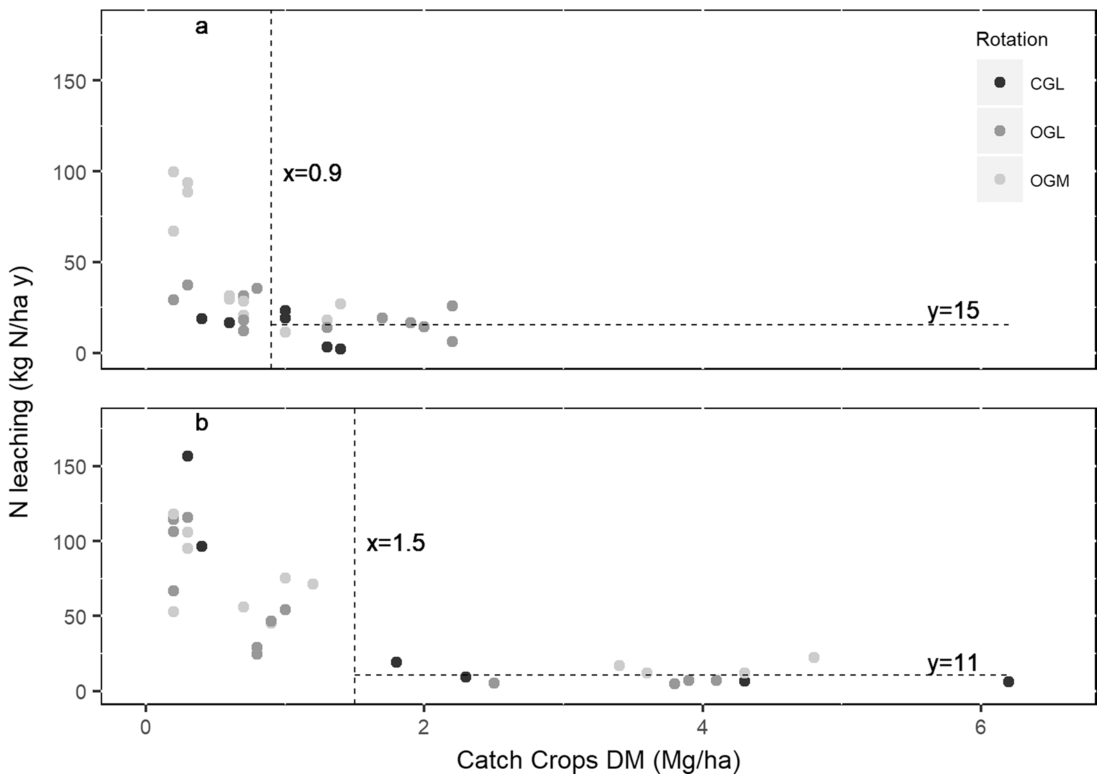

Fig. 6. N leaching (kg N ha^{-1} y^{-1}) in relation to catch crops above-ground dry matter (Mg ha^{-1}) in a) spring wheat and b) potato. Only plots with catch crops were included. CGL = conventional with grain legume; OGM = organic with green manure; OGL = organic with grain legume.

small increase in N_2O emissions when green manure cuts were left on the field, and that mulching was not a major contributor to gaseous losses. Ammonia losses up to 10% of the N input have been observed after green manure cutting (Whitehead and Lockyer, 1989; Båth et al., 2006). Finally, Pugesgaard et al. (2017) estimated changes in soil N stocks and suggested that N surplus in OGM was not lost, but stored in the soil as organic matter.

Leaching in spring wheat and potatoes was generally higher in OGM than in the other two systems, in particular in treatments without catch crops. A higher risk of N leaching in these two crops can be associated to their position in the rotation, as they follow the buildup of N in green manure. N derived from the green manure is mostly in organic form and its mineralization can occur over a long period of time (Peoples et al., 2004).

The difference between the plot and crop rotation perspectives is evident when considering the OGM system. N leaching at the plot scale was mainly determined by the effects of catch crop, main crop and year, as also discussed by Jabloun et al. (2015). A significant relation between N surplus and leaching was nonetheless found for green manure in OGM/+CC (Fig. 3), indicating that the higher N surplus associated with the −M treatment led to an increased N leaching in the short term. However, this effect evened out at the crop rotation scale. Overall, we found that a crop rotation perspective provides a good indication of the main factors affecting N leaching. Catch crop was the factor with the highest impact on leaching, while N input and surplus had a weaker influence. These effects are less evident or even absent when

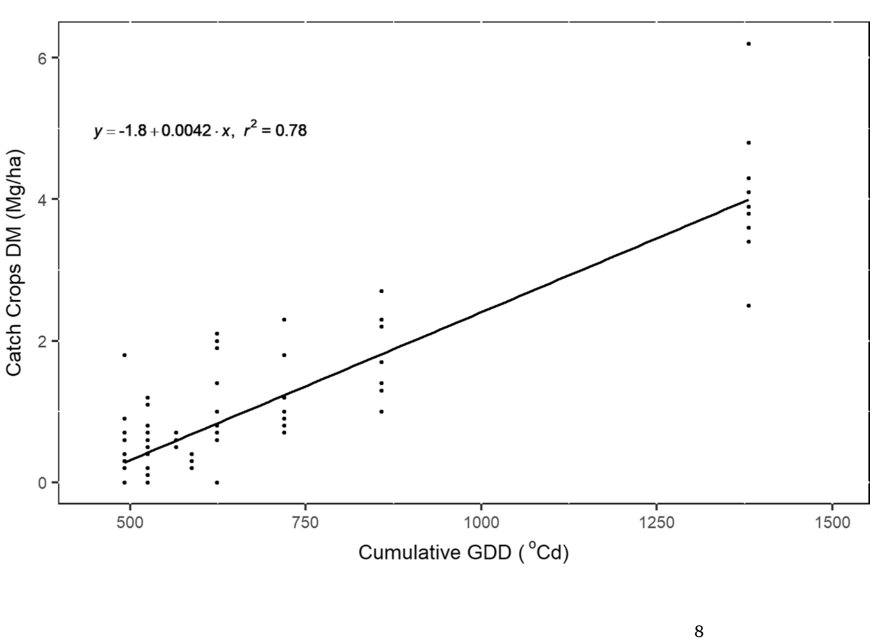

Fig. 7. Catch crop above-ground dry matter (Mg ha^{-1}) in relation to cumulative growing degree days (GDD) after harvest of the main crop. Only plots with catch crops were included.

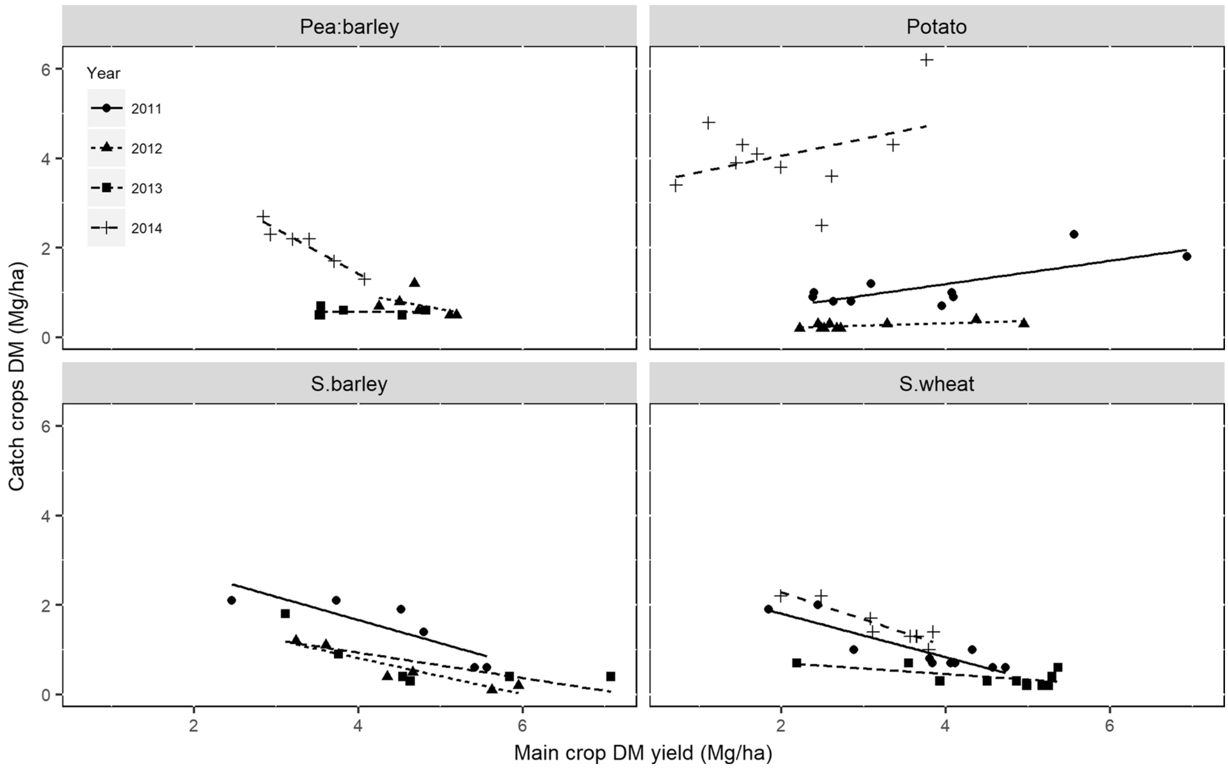

Fig. 8. Catch crop above-ground dry matter (Mg ha^{-1}) in relation to yield of main crops (Mg ha^{-1}). Different shapes and line types indicate different years. Only plots with catch crops were included.

considering N leaching from individual crops and years.

4.2. Effects of catch crops and manure on N leaching

The effect of manure and catch crop treatments on N leaching was statistically significant in CGL and OGL (Table 2), and it was consistent also in the OGM system, although the degree of variation was higher due to the green manure. Both non-leguminous catch crops (CGL) and mixtures with legumes (OGL) reduced N leaching by an average of 23 kg N ha^{-1} y^{-1} (60%). This agrees with the meta-analysis by Tonitto et al. (2006), who reported a 40–70% reduction in N leaching by both leguminous and non-leguminous cover crops. Askegaard et al. (2005) and Askegaard et al. (2011) reported a smaller and more variable effect of catch crops in the first 3 cycles of the experiment, providing several reasons behind their result. One of the contributing reasons was the fact that winter cereals were included in the first years of the experiment, which reduced the frequency of catch crops in the rotation.

In the present study, catch crops were included in 4/5 of the crops in OGL and CGL, and 2/5 in OGM (due to the green manure). The plots with catch crops had been under the same treatment for 17 years, except for CGL, which was introduced in 2005 (Chirinda et al., 2010). Other studies have reported how a high catch crop frequency was necessary to obtain a significant reduction of N leaching (Constantin et al., 2010), and it is reasonable to argue that the high frequency of catch crops in the present study was the key to a closer N cycle in the system. A continuous use of catch crops provides a positive effect in the long term, whereas the termination of catch crop use would cause a partial loss of the accumulated N (Hansen et al., 2000; Berntsen et al., 2006), as also indicated from N leaching measured in 2012, when catch crop growth was poor.

In the OGL system, manure had a significant effect on N leaching, in addition to catch crop. In particular, OGL/+CC/+M had an average of 9 kg N ha^{-1} y^{-1} higher leaching than OGL/+CC/−M, equal to 13% of the average yearly manure N input. This effect was not reported for the previous cycles of the experiment (Askegaard et al., 2005; Askegaard et al., 2011; Jabloun et al., 2015). A less accurate methodology for N leaching measurement could be the reason behind this difference, as suction cups were previously installed just in selected plots. Nonetheless the possibility of a long-term effect of manure application should be considered (Edmeades, 2003; Webb et al., 2013). In general, at the system level there was no difference between N leaching in the conventional (CGL) and the organic (OGL) rotations, although N output was lower in the organic rotation.

4.3. Variation in catch crop effect

Spring wheat and potatoes were identified as the two crops with the highest N leaching. This was related to their position in the crop rotation after legume crops (Jabloun et al., 2015) and the early harvest of potatoes (Neumann et al., 2012). The general effect of rotation underlines how the rotation with green manure (OGM) is the system with a higher risk of N leaching, especially from spring wheat, which follows green manure. Incorporation of green manure residues prior to sowing of the spring cereal was the cause identified by Jabloun et al. (2015), in agreement with other studies (Eriksen et al., 2004; Askegaard et al., 2011).

Sowing of a catch crop significantly reduced N leaching from both spring wheat and potatoes, in all the cropping systems. Nonetheless, the effect of catch crop varied across years. This effect related to catch crop growth, and thresholds in catch crop above-ground biomass were identified, indicating that catch crops need a minimum biomass to effectively reduce N leaching. In general, if N availability is not a limiting factor, insufficient catch crop growth can limit N uptake (Thorup-Kristensen et al., 2003). A short growing season is one of the main reasons for a reduced N uptake, leading to a lower effect on N leaching (Thorup-Kristensen et al., 2003). An example of the crucial importance of well-developed catch crops is potatoes in 2014. Due to early leaf senescence from potato late blight, growth of potatoes in OGL was compromised and, as a consequence, N leaching in treatments without catch crop was considerably higher than in previous years. In treatments with catch crop, instead, a warm season and an early establishment allowed a high catch crop biomass production, reducing N leaching substantially. In the case of spring wheat, catch crop growth was particularly important in OGM, where the N leaching risk was higher than in OGL. With a low biomass (as in 2013) N leaching was as high as 91 kg N ha^{-1} y^{-1}, in contrast to the average 15 kg N ha^{-1} y^{-1} obtained with 0.9 Mg ha^{-1} or more of catch crop biomass.

The variation in catch crops biomass, and consequently their ability to retain soil N, can be determined by more than one factor (Thorup-Kristensen et al., 2003). Previous studies have investigated the relation between non-leguminous catch crop biomass accumulation and N uptake with GDD and found it to be significant (Schroder et al., 1996; Komainda et al., 2016). In this study, a linear relation between catch crop above-ground biomass and cumulative GDD was found, with GDD being able to explain almost 80% of the variation. Similar results were reported by Brennan and Boyd (2012), who investigated the variation in catch crop biomass in a 8-years study on fields with organic vegetables, and Burger et al. (2017), who studied canopy and root system development of cover crops with contrasting root systems.

Early sowing is a valuable strategy to enhance growth of catch crops (Thorup-Kristensen et al., 2003). For undersown catch crops, the growth period starts from the time of harvesting of the main crop. Catch crops were undersown in cereals and legumes in the present study, and here competition between main crop and catch crops can occur (Doltra and Olesen, 2013). A competitive main crop with high yields will reduce the growth of the catch crop as shown by the negative correlation between catch crop above-ground biomass and main crop yield. This calls for finding new solutions to manage competition as one of the means to reduce N leaching. Catch crops are a valuable tool to reduce N leaching, but to realize their potential they need to accumulate a certain biomass (identifiable as a threshold). As it is not possible to manipulate climatic factors, further research should focus on how to stabilize catch crop biomass production by prolonging its growing period and reducing the competition with the main crop.

5. Conclusions

In the 4th cycle of the studied crop rotation experiment, during the period from 2011 to 2014, N leaching was positively correlated to N surplus at the rotation scale, with coefficients of 0.25 and 0.19 without and with catch crops, respectively. Use of catch crops was the main factor affecting N leaching. Both in the conventional (CGL) and in the organic systems (OGM and OGL), catch crops were able to reduce N leaching by an average of 23 kg N ha^{-1} y^{-1} (60%) across the four years. This effect was obtained both with non-legumes (CGL) and with mixtures including legumes (OGM and OGL). In the OGL system, use of catch crops also increased N output by an average of 20 kg N ha^{-1} y^{-1}. N leaching risk was higher in OGM than in the other systems, especially from crops following the green manure. Variations in the effect of catch crops on N leaching were associated to their growth, which was correlated to GDD and biomass of the main cereal crop. Threshold levels of catch crop biomass, above which N leaching was low and stable, were identified for spring wheat and potatoes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.12.009.

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