Agriculture, Ecosystems and Environment 202 (2015) 31–41

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand

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ARTICLE INFO

Article history:
Received 18 March 2014
Received in revised form 16 December 2014
Accepted 16 December 2014
Available online 9 January 2015

Keywords:
Catch crops
Grazing
Nitrate
Organic agriculture
Reduced tillage

ABSTRACT

Late season catch crops could be an effective tool to conserve highly available N after grazing of green manures. An experiment was established to investigate the productivity and N capturing abilities of barley (*Hordeum vulgare* cv. Cowboy) and oilseed radish (*Raphanus sativus* L.) crops seeded after a grazed green manure. Green manure was a mix of forage pea (*Pisum sativum* cv. 40–10), soybean (*Gylcine max* cv. Prudence) and oat (*Avena sativa* cv. Legget). The experiment was repeated twice in Carman, Manitoba in 2010 and 2011. Catch crops were seeded in late summer either no-till or after soil cultivation of the grazed plots. Wheat (*Triticum aestivum* cv. Waskada) was seeded in the second year as a test crop for both experiments. Catch crop productivity and N uptake was influenced by season (greater in the wetter year) and catch crop type (barley and radish produced 1990 and 1490 kg ha^{-1}, respectively) but not tillage system. The catch crops had their greatest overall effect on soil NO_3-N content in 2010 under conditions of high autumn precipitation when N leaching was more severe. Here, the catch crops significantly reduced NO_3-N at all depths. Under drier conditions in 2011, catch crops only reduced NO_3-N in the top 30 cm. There was average 57 and 12 kg ha^{-1} more soil NO_3-N in plots with no catch crops than plots where catch crops were grown in 2010 and 2011, respectively. Wheat N uptake at maturity was reduced around 25% when grown after catch crops. Similarly, wheat grain yield was 12–31% less after catch crops than no catch crops. This study showed that catch crops can be used to capture excess nutrients after grazing, but N release from the selected catch crops in the following year was not in synchrony with the wheat N demand.

1. Introduction

Excessive nutrient application and losses occur in improperly managed conventional, organic and low-input cropping systems (Stopes et al., 2002). Catch crops are cover crops (i.e., non-commercial) that are grown with the purpose of capturing excess N and preventing leaching losses. Catch crops have been shown to be more effective in capturing excess nutrients than other management techniques such as reduced tillage and reduced N inputs (Thorup-Kristensen et al., 2003; Constantin et al., 2010). Catch crops can be included in the rotation in various ways depending on the cropping system. In conventional systems, catch crops are generally seeded after main crop harvest to capture excess nutrients (Herrera et al., 2010). In organic systems catch crops are generally seeded after animal manure application to capture excess nutrients (Olesen et al., 2000) but rarely seeded after green manures. Because of greater availability of nutrients in grazed green manure systems (Cicek et al., 2014b), an important role of catch crops may be to capture excess nutrients after green manure grazing.

Nitrate (NO_3-N) is of particular importance in catch crop research. As a result of its negative charge, NO_3-N is highly mobile and can leach when N supply exceeds crop requirements. Nitrate leaching in agroecosystems is influenced by soil type, catch crop species, precipitation, temperature, N transformation rates (mineralization, immobilization, dentrification), N input type, drainage and tillage (Campbell et al., 2006; Constantin et al., 2010). Among these factors, catch crop species selection, management and N input type are among the most effective management tools for controlling NO_3-N leaching (Thorup-Kristensen et al., 2003; Constantin et al., 2010). For instance, catch crops were found to decrease N leaching 40–50% in conventional (Aronsson and Torstensson, 1998) and 30–38% in organic systems (Askegaard et al., 2005).

Excess precipitation is one of the main reasons for NO_3-N leaching (Thorup-Kristensen et al., 2003). Therefore, catch crop

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http://dx.doi.org/10.1016/j.agee.2014.12.007
0167-8809/

research has been concentrated in areas where annual precipitation is generally above the crop demand (i.e., north eastern USA, New Zealand and Northern Europe). Under such conditions, catch crops can limit NO_3-N loss by direct uptake of available NO_3-N and/or utilization of excess moisture, hence preventing downward movement of NO_3-N in soil solution (Thorup-Kristensen et al., 2003). Even under the relatively dry conditions in western Canada, Campbell et al. (1994) showed that NO_3-N leaching occurred when precipitation was above the long-term average. Nitrate leaching was more severe in rotations with fallow periods than intensive rotations with crops grown every year.

Grazing of green manures is a recently proposed management technique that has not been investigated in terms of NO_3-N leaching (Thiessen Martens and Entz, 2011). Since risk of NO_3-N leaching is aggravated under grazed systems compared to ungrazed systems (Ryden et al., 1984), there is an urgent need to investigate the risk of NO_3-N leaching in novel crop-livestock integrated systems that include grazed green manures.

Nitrogen loading under cattle (*Bos taurus*) and sheep (*Ovis aries*) urine patches can reach 1000 and 500 kg N ha^{-1} respectively (Haynes and Williams, 1993). Urea in urine patches quickly hydrolyses to NH_4^+, which can be quickly converted to NO_3-N (Di and Cameron, 2002). Unlike slowly mineralizing organic N in green manure residues, inorganic N in urine patches is more susceptible to volatilization, denitrification and leaching (Clough et al., 1998; Whitehead, 2000). Further, in grazed green manure systems grazed plants are often annual species, hence, upon grazing no living plant cover is left behind. Under such circumstances risk of NO_3-N leaching may be greater than under perennial systems, where living plant cover can take up at least some of the water and/or urine N.

Nitrate is considered "lost" only when it leaches beyond the root zone (Thorup-Kristensen et al., 2003). Therefore, the "leaching" of NO_3-N down the soil profile is not equivalent to "leaching loss" of NO_3-N. Nitrate leaching losses under grasslands grazed by sheep with no synthetic N inputs is reported to be 6–7 kg N ha^{-1} y^{-1} in New Zealand (Ruz-Jerez et al., 1995). In the northeastern USA, Stout (2003) applied synthetic urine with N content of 440 to 1340 kg N ha^{-1} in a region where annual precipitation is around 930 mm. It was shown that regardless of the urine volume, approximately 25% of the applied urine was lost through leaching.

The proposed catch crop system represents a new frontier for the optimization of organic cropping systems. This new approach intensifies the green manure phase of organic rotations by adding grazing animals and catch crops. Grazing animals utilize green manures which otherwise is a lost revenue opportunity for the farmer, while catch crops increase biomass production on the same land base within one growing season. Long-term experiments have shown that adding organic matter and fertility through the use of late-season catch crops increases productivity of the agroecosystems (Constantin et al., 2010; Doltra and Olesen, 2013).

Species selection in catch crop studies is an important factor because N uptake capacity of catch crops is determined by speed of establishment, growth rate, rooting depth and cold tolerance (Munkholm and Hansen, 2012). The species selection not only affects N uptake, but also N availability to the subsequent cash crop from decomposing catch crop residue. Therefore, C:N ratio, lignin and N content of the catch crop species are important characteristics to be considered when selecting a catch crop species or mixtures (Thorup-Kristensen et al., 2003). One of the main challenges in legume-based systems is achieving the synchrony of N mineralization from green manures and cash crop demand (Crews and Peoples, 2005; Tonitto et al., 2006). In general N mineralization in crops with low C:N ratio (e.g., some brassicas and legumes) is faster than crops with high C:N ratio (e.g., grasses) (Ranells and Wagger, 1997; Constantin et al., 2011). Accordingly, the ideal catch crop species should readily capture available N after grazing and readily release N to the next crop, resulting in an effective N synchrony. Grasses such as barley (*Hordeum vulgare*) may be effective in capturing N because of its fast growth but release N slower because of its high C:N ratio. Brassicas such as oilseed radish (*Raphanus sativus*) are also known to have rapid N uptake (Thorup-Kristensen et al., 2003), but are thought to release N more quickly as a result of their lower C:N ratio.

Current attempts to reduce tillage in organic agriculture have focused on the green manure phase of the rotation (Peigné et al., 2007; Vaisman et al., 2011) and the system is referred to as organic rotational no-till (Halde et al., 2012). In organic agriculture tillage is applied to control weeds, improve nutrient mineralization and prepare a seedbed. Grazing animals in integrated crop-livestock systems may provide these services by consuming the green manure biomass. For example, after grazing green manures, weeds and biomass left on the soil surface could be minimal (Hatfield et al., 2007). Additionally, nutrients in faeces would reduce the need for tillage to mineralize nutrients. Hence, grazing animals may facilitate no-till seeding of catch crops after grazing of green manures.

An experiment was established to explore the soil NO_3-N uptake and release patterns of catch crops grown after a grazed green manure. The objectives of this study were to investigate: (i) the biomass production and N uptake of two different catch crop species (barley and oilseed radish) seeded after a grazed green manure using no-till and tillage methods, (ii) the effectiveness of catch crops in capturing N released in autumn by the grazed green manure, and, (iii) the N availability to a following wheat crop. As a result of faster N mineralization under tillage (Varco et al., 1993), it was hypothesized that catch crops will produce more biomass and take up more N when grown in tilled plots as opposed to no-till seeded plots. It was also hypothesized that soil NO_3-N content would be lower in catch crop plots than no catch crop plots. Lastly, conservation of N in catch crop plots will increase the wheat productivity compared to no catch crop plots where N is not conserved in catch crop biomass.

2. Materials and methods

2.1. Site description and experimental design

Experiments were conducted at the University of Manitoba Ian N. Morrison Research Farm in Carman, Manitoba (49°29′48″ N, 98°2′ 26″ W, 267 m above sea level). The region is characterized by an extreme continental climate with very cold winters and warm summers. Frost-free period for crop production is 115–125 days, and occurs primarily between May and September (MASC, 2013). Long-term average temperatures, precipitation, as well as 2010–2012 growing season monthly temperatures and precipitation are provided in Table 1. The soil at Carman is an Orthic Black

Table 1
Average monthly growing season air temperatures and precipitation for Carman, Manitoba, Canada from 2010 to 2012.

	Air temperatures (°C)				Precipitation (mm)			
	2010	2011	2012	Average[a]	2010	2011	2012	Average[a]
April	8.7	4.5	6.2	4.2	35	44	19	42
May	11.6	10.4	12.1	12.5	159	72	61	53
June	16.3	16.7	17.7	16.9	63	59	86	73
July	19.6	20.3	21.9	19.4	48	38	28	69
August	18.7	19.3	19.0	18.2	138	12	47	65
September	11.8	14	12.5	12.2	107	65	3	49
October	8.3	8.2	4.2	5.5	57	8	85	34
Total					607	297	328	386

[a] from 1961 to 1990.

Chernozem (Udic Boroll) (Mills and Haluschak, 1993) with a fine sandy loam texture, pH (0–30 cm) of 6.5, and organic matter content (0–30 cm) of 30–35 g kg^{-1}. Soil background nutrient samples were collected at 0–30 cm for the experiments. Soil NO_3-N, P (Olsen) and K levels in the experiment 1 were 21, 24 and 544 kg ha^{-1}, and, in the experiment 2 they were 12, 18 and 712 kg ha^{-1}, respectively. Oat (*Avena sativa* cv. Legget) was the preceding crop for both experiments. Previous investigations of integrated crop-livestock systems have been conducted exclusively under conventional management with fertilizer inputs. The present study was conducted under long-term organic management (since 2004) with no external inputs.

The experimental design was a split-plot design, with four blocks. The whole-plot treatment was seeding management and the sub-plot treatments were catch crops. Two catch crop species and two catch crop seeding management systems were included. Control plots had no catch crops. The catch crop experiment started with an experiment in 2010 (Experiment 1) and was repeated in 2011 (Experiment 2) on a neighbouring site within the experimental station on the same soil type. In the first year of the experiments, green manures were seeded in the spring, and grazed in late summer. Catch crops were seeded as soon as the grazing was complete (Table 2). Spring wheat (*Triticum aestivum* cv. Waskada) was seeded in the second year as a first test crop for both experiments in the following spring (Table 2). Fall rye (*Secale cereale* cv. Hazlet) was seeded after wheat harvest in the autumn as a second test crop for experiment 1 only. Spring wheat and fall rye were seeded using a JT-A10 air drill seeder (R-Tech Industries, Homewood, Manitoba) with a row spacing of 20 cm and a seeding rate of 125 kg ha^{-1} and 110 kg ha^{-1}, respectively.

2.2. Green manure and catch crop species management

The green manure mixture of forage pea (*Pisum sativum* cv. 40–10), soybean (*Glycine max* cv. Prudence) and oat (*Avena sativa* cv. Legget) was seeded in the first week of June with the seeding rates that correspond to 55, 85 and 140 seeds/m^2, respectively. Legumes were inoculated with the appropriate rhizobium species. Cell-Tech liquid inoculator (Novozymes, Franklinton, NC) was used for soybean and NitraStic-C peat based inoculant (Novozymes, Franklinton, NC) was used for pea. Both inoculants were applied at the manufacturer's recommended application rate of 75 mL of inoculant per 27 kg of seed.

Timing for grazing green manures generally coincided with the full bloom stage for legumes and milking stage for oats. Stocking density ranged from 2 to 3 ewes (South African Dorper) and 2 to 5 lambs for 24 h (1111 to 1667 sheep d/ha). Sub-plots were 2 m wide and 9 m long and were surrounded by metal fences for precision and protection. Sheep were put into conditioning plots containing green manure crops for 24 h before they were put into actual experimental plots. Preconditioning meant that sheep started to consume the green manure species being tested a day before they were put into actual plots. Water buckets and shade tents were positioned at opposite ends of the plots to reduce possibility of uneven distribution of feces and urine.

Catch crop species barley (*Hordeum vulgare* cv. Cowboy) and oilseed radish (*Raphanus sativus* L.) were seeded at 350 seeds/m^2 either directly or after rototilling. Catch crops were seeded using a no-till disc drill (Fabro Enterprises Ltd. Swift Current, SK) with a row spacing of 15 cm.

2.3. Plant sampling

Green manure aboveground biomass production in year 1 was determined by clipping 2 randomly chosen areas (0.4 m^2 each) from each replicate both before and within 3 days of grazing. Forage utilization was calculated as the percentage of forage dry matter consumed by sheep by comparing biomass before and after grazing. In order to eliminate soil and faeces adhering to residual biomass, the post-grazing biomass samples were washed before drying for 48 h at 60 °C.

Catch crop biomass was collected from 2 randomly chosen areas (0.4 m^2 each) in each plot, dried for 48 h at 60 °C and weighed for dry matter content. Growth rates of catch crops were calculated by dividing the total dry matter biomass production of a catch crop by the number of days from the seeding to termination of catch crops. Spring wheat and fall rye biomass samples were harvested at the soft dough stage from 2 randomly chosen areas (0.4 m^2 each) in each experimental unit, dried for 48 h at 60 °C and weighed for dry matter content. Spring wheat and fall rye grain for yield estimation was collected from each plot using a Kincaid 8-XP (Kincaid Equipment Manufacturing, Haven, KS) plot harvester. Dry wheat and fall rye biomass samples were ground with a Wiley Mill (No.1 Arthur H. Thomas Co., Philadelphia, PA). Wheat and fall rye grain were ground with a Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO). All ground samples were sub-sampled and analyzed for N concentration by combustion analysis using a LECO FP-528 (LECO, St. Joseph, MI). Wheat and fall rye N uptake at soft dough were calculated as the product of above-ground biomass production (kg ha^{-1}) and its N concentration.

2.4. Soil sampling

Background soil samples were taken immediately before grazing to the depth of 30 cm for both experiments. After seeding of catch crops there were five soil sampling dates for experiment 1, and three for experiment 2. Soil samples in experiment 1 were taken 30 days after seeding of catch crops (September 9, 2010) and on October 20, 2010, when catch crops were terminated. The first soil sampling for experiment 2 was in October 2011, at the time of catch crop termination. Since catch crops were seeded later in experiment 2 than experiment 1, only one soil sample (October 20) was collected. Spring soil samples were taken on May 19, 2011 for experiment 1 and on April 25, 2012 for experiment 2, before wheat establishment. Soil was sampled again in autumn following wheat harvest (September 2011 and 2012). The final soil samples for experiment 1 were collected after fall rye harvest in September 2012. Soil samples were collected using Dutch augers in 2010, and using a hydraulic soil coring rig (The Giddings Machine Co, Windsor, CO, USA) with a 4 cm diameter tip in 2011 and 2012. Soil samples were taken to 120 cm depth, at four depth increments; 0–30, 30–60, 60–90 and 90–120 cm. Soil bulk density value of 1.2 g cm^{-3} was used for all depths when calculating the soil nutrient contents (Mills and Haluschak, 1993). All soil samples

Table 2
Dates of field operations for experiments 1 and 2.

Experiment	Seed green manure	Graze green manures	Seed catch crops	Terminate catch crops	Wheat seeding	Wheat harvest	Fall rye seeding	Fall rye harvest
1	June 4, 2010	August 8, 2010	August 9, 2010	Oct 21, 2010	May 20, 2011	August 25, 2011	Sept 1, 2011	July 31, 2012
2	June 8, 2011	August 20, 2011	August 21, 2011	Oct 11, 2011	April 26, 2012	August 9, 2012	–	–

were sent to Agvise commercial soil analysis laboratory for chemical analysis (AGVISE, Northwood, ND). Soil samples were analyzed for NO_3-N (extracted with KCl solution) at all four depths using the cadmium reduction method, for plant available soil P at 0–30 cm depth using 0.5 M $NaHCO_3$ (P Olsen), and for soil K at 0–30 cm depth using 1 M $NH_4C_2H_3O_2$ extraction. Soil pH was determined with pH electrode in a 1:1 soil:water suspension. Soil organic matter was determined by loss of weight on ignition at 360 °C.

2.5. Statistical analysis

Statistical Analysis System program (SAS Institute, 2001) PROC Mixed procedure was used for data analysis. For the ANOVA, treatment effects were considered as fixed effects and replications as random effects for all measurements. Repeated measures were used to compare the effects of catch crop species and management on soil NO_3-N and wheat productivity over time. As required by analysis of residuals, logarithm transformation was used to achieve normality and homogeneity of variance for soil NO_3-N and wheat productivity data. Prior to analyzing each experiment separately, combined analysis was performed using catch crop species, seeding management and experiment as fixed effects. There were no three-way interactions (i.e., catch crop species x management x experiment). However, there were significant effects of species and experiment on almost all parameters (e.g., catch crop biomass, wheat N uptake), therefore, each experiment was presented separately. Assumptions of ANOVA were tested by using the PROC Univariate procedure. All data were verified for normality of residuals and homogeneity of variance. Differences were considered significant at $p < 0.05$ and means were separated using a Fisher's protected LSD test.

3. Results and discussion

3.1. Environmental and field conditions

Precipitation varied greatly from 2010 to 2012, which affected catch crop and wheat production in both experiments. During the catch crop production phase for experiment 1 (in 2010), precipitation was almost twice the long term average (Table 1). Precipitation received during the catch crop phase of experiment 2 (August–October 2011) was 24% lower than the long-term average (Table 1). As such, while the catch crop phase of experiment 1 was conducted under favorable conditions, deficit moisture conditions prevailed for experiment 2. Excess precipitation in autumn 2010 meant that the wheat production phase of experiment 1 and the green manure production phase of experiment 2 started with waterlogged soils.

Green manure dry matter biomass production was 5620 and 2780 kg ha^{-1} for experiment 1 and 2, respectively. Lower green manure biomass production in experiment 2 was attributed to excessively wet soils. Utilization of green manure by sheep was 66% and 44% for experiment 1 and 2, respectively. Lower utilization of green manures in experiment 2 may be the result of trampling or flattening of already low amount of dry matter by sheep.

3.2. Catch crop productivity and N uptake

Barley and oilseed radish productivity in experiment 1 was 3440 and 2620 kg ha^{-1}, respectively compared to 550 and 360 kg ha^{-1}, respectively in experiment 2 (Table 3). Higher catch crop biomass production in experiment 1 than experiment 2 was attributed to the following. Catch crops were seeded earlier in experiment 1 than in experiment 2 (August 9, 2010 vs. August 21, 2011; Table 2) and terminated later (October 21, 2010 vs. October 11, 2011; Table 2). Second, more moisture was available to catch crops in experiment 1 than experiment 2 (Table 1). Therefore it could be argued that catch crop production in experiment 1 was under ideal environmental conditions, while in experiment 2 the conditions were not favorable for late season plant growth. Results in the present study mirror those from other temperate environment catch crop studies. For example, in Denmark, a series of catch crop experiments over 12 years tested various double-cropped or relay-cropped catch crop species and mixtures (Munkholm and Hansen, 2012). Relay-cropped perennial ryegrass (*Lolium perenne* L.) produced 1500 kg ha^{-1} of dry matter biomass, while fodder radish (*Raphanus sativus* L.) in the same study produced up to 1800 kg ha^{-1} of biomass when undersown to barley 2–3 weeks before barley harvest in early August. Fodder radish and oilseed radish are among the alternative common names for *Raphanus sativus*. In a long term study (17 years) in northern France, radish and Italian ryegrass catch crops produced 1470 and 2320 kg ha^{-1} of dry matter biomass, respectively (Constantin et al., 2010).

There is a limited amount of information on late season cover crops or catch crops in organic systems, particularly in the northern Great Plains of North America. Of the limited information available, most is on relay-cropping (i.e., underseeding a cover crop into cash crop; Liebman et al., 2012; Blackshaw et al., 2010), whereas in the present study, catch crops were double-cropped. Thiessen Martens et al. (2001) reported 750 and 630 kg ha^{-1} of biomass production for chickling vetch (*Lathyrus sativus* L.) and lentil (*Lens culinarus* L.), respectively, when double cropped after fall rye. Cicek et al. (2014a) reported that among the eight late season cover crops tested, only relay cropped red clover (*Trifolium pretense)* and double cropped forage pea produced acceptable amount of biomass from mid August to early October. Double cropped oilseed radish in their study produced up to 350 kg ha^{-1}

Table 3
Effect of catch crop species (barley and oilseed radish) and seeding management (direct seeding and conventional seeding) on catch crop dry matter biomass production, daily growth rate, N uptake and N concentration for experiments (Exp) 1 and 2.

	Growth rates		Biomass		N uptake		N concentration	
Treatments	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2
Species	kg ha^{-1} d^{-1}		kg ha^{-1}				%	
Oilseed radish	36b	7	2620b	360	58	15	2.4a	4.2a
Barley	47a	10	3440a	550	55	19	1.6b	3.5b
Management								
Direct seeding	38	7	2790	360	56	13	2.1	3.8
Conventional seeding	45	10	3270	550	57	20	1.9	3.9
Analysis of Variance	P values							
Species (S)	0.019	0.081	0.015	0.094	0.531	0.165	0.001	0.049
Management (M)	0.403	0.148	0.393	0.128	0.906	0.137	0.183	0.542
S x M	0.183	0.295	0.168	0.343	0.187	0.714	0.412	0.126

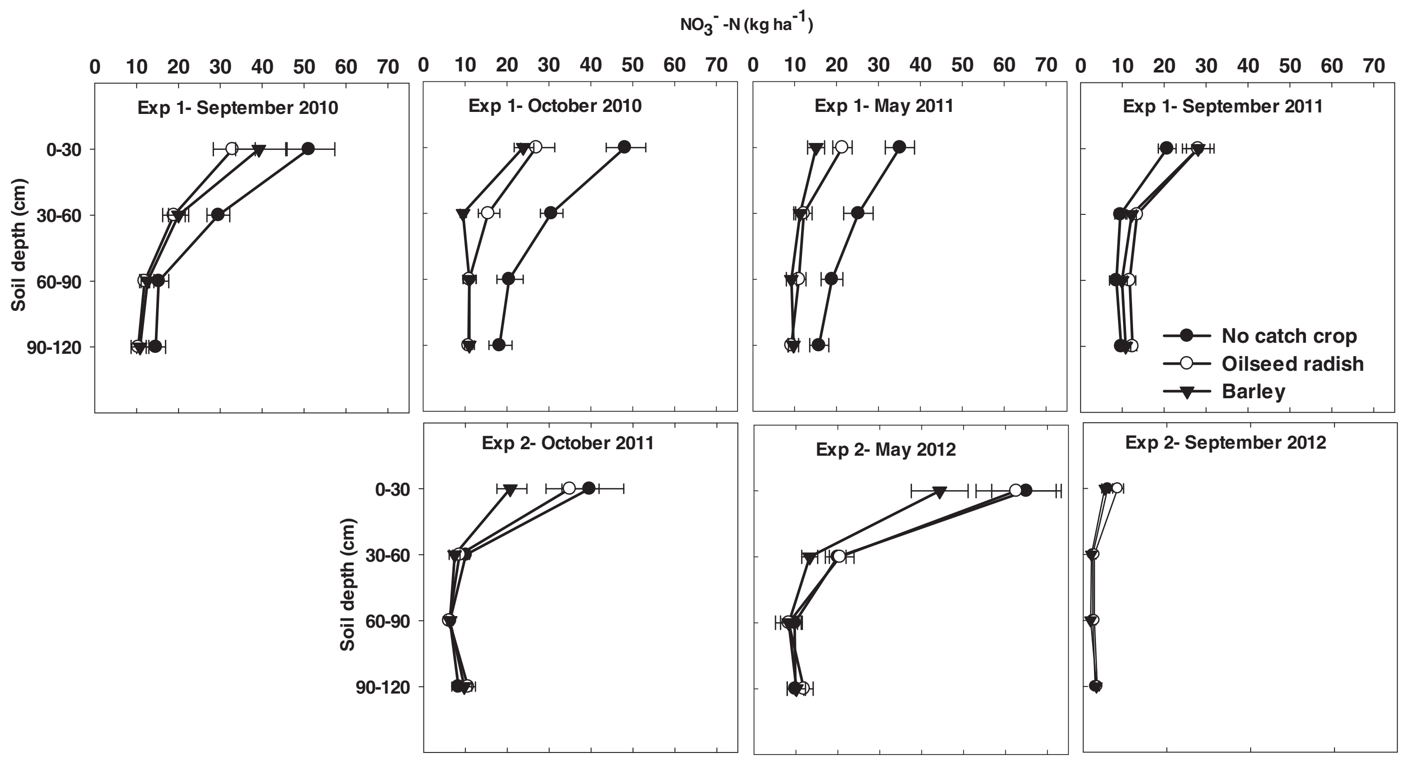

Fig. 1. Soil nitrate as affected by catch crop species (no catch crop, barley and oilseed radish) at depths of 0–30, 30–60, 60–90 and 90–120 cm over two years for the experiments 1 and 2. Please refer to Table 4 for analysis of variance of soil nitrate as affected by species, management and time. Horizontal bars are standard errors.

when seeded after tillage, but produced only 70 kg ha^{-1} when no-till seeded.

Daily growth rates were significantly different between catch crop species in experiment 1 but not in experiment 2 (Table 3). In experiment 1, while barley grew at 47 kg ha^{-1} d^{-1}, oilseed radish grew at a rate of 36 kg ha^{-1} d^{-1}. In experiment 2 growth rates were much lower for barley (11 kg ha^{-1} d^{-1}) and oilseed radish (7 kg ha^{-1} d^{-1}). Two other studies also investigated growth rates of late season crops in Manitoba. In the first study, growth rates of four late season legumes ranged from 2 to 18 kg ha^{-1} d^{-1} (Thiessen Martens et al., 2001). In the second study, growth rates of legumes under organic management ranged from 3 to 32 kg ha^{-1} d^{-1} (Cicek et al., 2014a). While growth rates of late season crops in the experiment 1 were much higher than two Manitoba studies, the rates were similar in experiment 2. Catch crops grew faster in experiment 1 than experiment 2 because of better growing conditions (i.e., early seeding, moisture and heat) in experiment 1. Hence, the growth rate differences between experiment 1 and two other Manitoba studies may be related to greater amount of rainfall received during the experiment 1.

Additionally, there are two major differences between the present experiment and the two previous Manitoba studies (Thiessen Martens et al., 2001; Cicek et al., 2014a). One difference is the crop type: non-legumes in the present study versus legumes in the previous Manitoba studies. The second difference regards soil nutrient status. In the present study catch crops were established after grazed legumes, where soil nutrient availability would be expected to be high, while legumes in the two previous Manitoba studies were established after fall rye harvest where soil nutrient availability is expected to be low. Hence, faster growth rates of non-legumes in the present study may be explained by (i) low post emergence growth rates of legume establishment compared to other crops (Liebman and Dyck, 1993; Biederbeck et al., 1993), or (ii) higher N availability after grazing increasing the growth rates of catch crops (Berger et al., 2007). There was no seeding management effect on growth rates for both experiments, indicating that tillage did not affect plant growth differently between two plant species in this study.

It is also important to recognize that root biomass of catch crops was not investigated in the present study. In northern France, root biomass represented 15% of the total biomass of a forage radish catch crop (Constantin et al., 2010). The root:shoot ratio of annual cereals usually decrease toward maturity (Hoad et al., 2001). Since, in experiment 1, barley reached only booting stage (i.e., Zadoks 45–49), root biomass may have represented more than 50% of the total biomass (Hoad et al., 2001).

No differences in N uptake were observed between barley and oilseed radish. Barley and oilseed radish took up 55 and 58 kg N ha^{-1}, respectively in experiment 1, and 19 and 15 kg N ha^{-1}, respectively in experiment 2 (Table 3). Averaged over two years, Munkholm and Hansen (2012) also reported similar N uptake values for perennial ryegrass and fodder radish; 37 and 55 kg ha^{-1}, respectively. Averaged over 17 years, radish and Italian ryegrass catch crops took up 34 and 35 kg N ha^{-1} in northern France (Constantin et al., 2010).

Nitrogen concentration of oilseed radish (2.3–4.2%) was significantly higher than barley (1.6–3.5%) in both experiments. A similar observation was made in Denmark where oilseed radish (fodder radish) N concentration was highest among the three catch crops tested and N concentration ranged from 2.7 to 3.8% (Munkholm and Hansen, 2012). Similar to results with total biomass production, differences in N uptake and N concentration in the present study appeared to be related to differences in sowing date and weather conditions between experiments. Catch crop N uptake could be reduced 1–2 kg N ha^{-1} per day when seeded late (Vos and Van der Putten, 1997). In the present study, average N uptake was 0.8 kg ha^{-1} d^{-1} under the favourable growing conditions in experiment 1 compared with 0.3 kg ha^{-1} d^{-1} under dry conditions in experiment 2 (data not shown).

Averaged over two years barley produced more biomass than oilseed radish, 1994 vs. 1492 kg ha^{-1}. Despite the lower biomass amounts as compared to barley, oilseed radish took up similar amounts of N in the present study. Greater N uptake by oilseed radish may be attributed to its deeper root system (Thorup-Kristensen, 2001), faster nitrate uptake rates (Laine et al., 1993) and cold tolerance (Laine et al., 1994) in comparison to monocots (e.g., rye or Italian ryegrass).

There were no significant seeding management effects for catch crop biomass production, N uptake and N concentration in the present study (Table 3). Both crops performed similarly under both no-till and conventional seeding. These results are supported by studies from southern Brazil and Georgia USA where no-till seeded crops performed similarly to conventional tilled ones when grazing was the preceding management (Franzluebbers and Stuedemann, 2007; Carvalho de Faccio et al., 2010). The authors concluded that rumen processing of the green manures improved N availability to no-tilled crops. A similar conclusion can be made for the present study. Excellent growth of catch crops in the no-till system can be explained by the improved N availability after

Table 4
Analysis of variance for the effect of catch crop species (no catch crop, barley and oilseed radish), seeding management (direct seeding and conventional seeding) and time (September 2010, October 2010, May 2011 and September 2011 for experiment 1, and October 2011, May 2012 and September 2012 for experiment 2) on soil NO_3^-–N content at depths of 0–30, 30–60, 60–90 and 90–120 cm for experiments 1 and 2.

	Soil NO_3^- -N content				
Source of variation	0–30 cm	30–60	60–90 cm	90–120 cm	Total (0–120 cm)
Experiment 1	-----------------------	-----------------------	*P* values	-----------------------	-----------------------
Species (S)	<.0001	<.0001	0.015	0.001	<.0001
Management (M)	0.362	0.981	0.419	0.976	0.915
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001
S x M	0.904	0.550	0.358	0.300	0.901
S x T	<.0001	<.0001	0.0005	0.012	<.0001
M x T	0.873	0.406	0.368	0.443	0.605
S x M x T	0.089	0.437	0.145	0.661	0.129
Experiment 2					
Species (S)	0.0003	0.009	0.645	0.262	0.003
Management (M)	0.693	0.694	0.590	0.397	0.864
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001
S x M	0.101	0.741	0.920	0.837	0.365
S x T	0.363	0.582	0.911	0.990	0.547
M x T	0.055	0.540	0.674	0.787	0.353
S x M x T	0.840	0.989	0.994	0.884	0.923

grazing. Slow N mineralization from green manures is one of the greatest challenges that organic no-till systems face (Vaisman et al., 2011). Grazing of green manures improves the N availability and may make organic no-till achievable. More research is needed to investigate strategic grazing of green manures to reduce tillage in organic systems.

3.3. Soil nitrate and N leaching potential

Soil NO_3-N content to 30 cm immediately before grazing averaged 21 and 12 kg ha^{-1} for experiment 1 and 2, respectively. Sixty days after grazing, soil NO_3-N in the no catch crop plots were 49 and 40 kg ha^{-1} for experiment 1 and 2, respectively (0–30 cm) (Fig. 1), indicating large increases in available soil NO_3-N in the absence of catch crops.

The ability of catch crops to reduce nitrate leaching potential was determined by measuring the difference between the soil NO_3-N content to 120 cm between catch crop and no catch crop plots. Catch crops in experiment 1 reduced the soil NO_3-N content at all depths compared with the no catch crop control treatment (Table 4 and Fig. 1). For example, there was significantly less soil NO_3-N in catch crops plots than no catch crop plots at 0–30 and 30–60 cm after 30 days, and at all depths 60 days after the seeding of catch crops. Further, barley and oilseed radish were equally effective at reducing soil NO_3-N content compared to no catch crop plots in experiment 1. The ability of catch crops to reduce NO_3-N leaching has been shown previously by a number of studies (Hansen and Djurhuus, 1997; Thorup-Kristensen et al., 2003; Berntsen et al., 2006).

A significant species x time interaction in experiment 1 showed that extraction of soil NO_3-N by barley and oilseed radish was progressively stronger as time passed. One month after the catch crop seeding in experiment 1, oilseed radish and barley plots contained 36 and 28 kg ha^{-1} less NO_3-N than the no catch crop plots at 0–120 cm, respectively (Table 4 and Fig. 2). This difference increased to 53 and 62 kg ha^{-1} 60 days after seeding catch crop. The change in soil NO_3-N is similar to N uptake by the catch crops. For instance, in experiment 1 oilseed radish and barley aboveground biomass samples taken 60 days after seeding contained 58 and 55 kg ha^{-1} of N respectively (Table 3). A long-term organic catch crop study in Denmark reported lower soil N values than the present study (Sapkota et al., 2012). Fodder radish and ryegrass reduced soil N ($NO_3 + NH_4$) by 20 and 15 kg ha^{-1}, respectively. Similar to the present study, soil N differences in the Danish study were explained by catch crop N uptake differences. For example, fodder radish and ryegrass biomass N uptake were 45 and 22 kg N ha^{-1}, respectively.

Lower NO_3-N capture by catch crops in experiment 2 was attributed to lower biomass productivity than in experiment 1 (Table 3 and Fig. 1). In experiment 2, at 50 days after catch crop seeding, oilseed radish and barley plots contained 5 and 19 kg ha^{-1} less NO_3-N, respectively, in the 0–30 cm soil depth than the no catch crop plots (Table 4 and Fig. 1). Aboveground N uptake by barley biomass (19 kg ha^{-1}) was equivalent to the difference in soil NO_3-N content between the control (40 kg ha^{-1}) and barley (21 kg ha^{-1}) plots (0–30 cm). However, soil NO_3-N content was similar for control and oilseed radish plots at all sampled depths and did not reflect oilseed radish biomass N uptake (15 kg ha^{-1}). Vyn et al. (1999) also found no difference in soil NO_3-N after an oilseed radish cover crop and no cover crop.

When selecting a catch crop, N uptake ability of the catch crop may be considered to be more important than biomass producing ability. Vos and Van der Putten (1997) showed that N concentration of catch crops did not explain the catch crop biomass production especially when biomass was less than 1000 kg ha^{-1}. Generally, as the amount of biomass increased, N concentration decreased. Results of the experiment 1 are in agreement with their observations. Although oilseed radish produced less biomass than barley, oilseed radish accumulated the same amount of N as barley in both experiments.

The present study is unique because catch crops were established after the N build-up phase (i.e., green manure), rather than after cash crop production, as commonly practiced. Catch crops seeded after grazing green manures (high NO_3-N availability) may behave differently than catch crops that are seeded under low N situations. For instance, catch crops seeded under high N fertility situations may produce greater biomass than when seeded in low fertility situations (Vos and Van der Putten, 1997). Under low N fertility, catch crops can also immobilize soil N and negatively affect cash crop production in the following year (Schroder et al., 1997).

There were no significant differences in soil NO_3-N between no-till and conventionally seeded crops in either experiment. The absence of significant catch crop species by seeding management interactions indicated that both catch crops responded similarly to tillage in terms of NO_3-N uptake. Once again, grazing of green manures appeared to be an effective strategy to improve N availability in reduced till organic systems.

3.4. Wheat and fall rye N uptake and productivity

Wheat productivity was negatively affected by the presence of catch crops in both experiments. In experiment 1, biomass production at stem elongation, anthesis and maturity and wheat

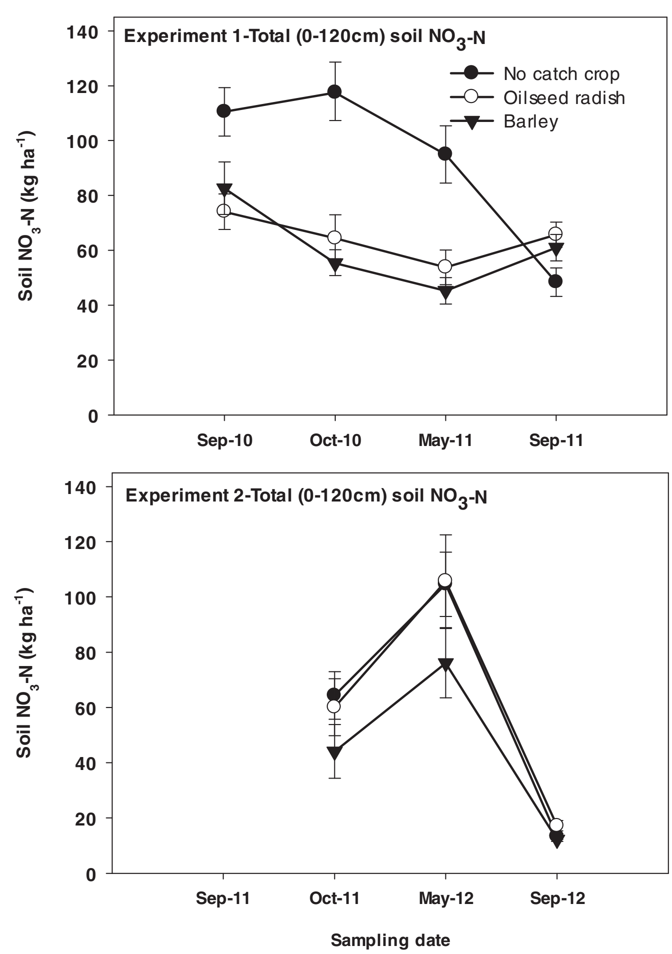

Fig. 2. Total (0–120 cm) soil nitrate as affected by of catch crop species (no catch crop, barley and oilseed radish) over two years for the experiments 1 and 2. Please refer to Table 4 for analysis of variance of soil nitrate as affected by species, management and time. Vertical bars are standard errors.

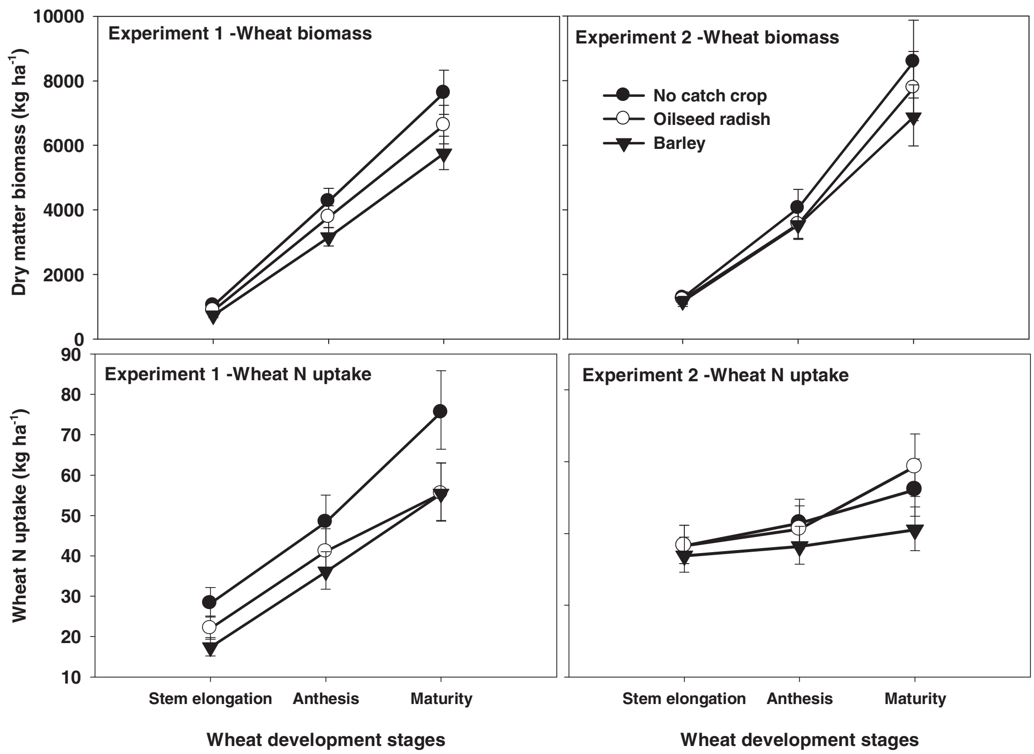

Fig. 3. Effect of catch crop species (no catch crop, barley and oilseed radish) on wheat dry matter biomass and N uptake at stem elongation, anthesis and maturity development stages for experiments 1 and 2. Please refer to Table 5 for analysis of variance of soil nitrate as affected by species, management and time. Vertical bars are standard errors.

grain yield were significantly reduced by catch crops (Figs 3 and 4). In experiment 2, biomass production at maturity and wheat grain yield were significantly reduced by catch crops. Therefore, the hypothesis that productivity of wheat would be greater when grown after catch crop plots was rejected. Between the two catch crops tested, wheat grown in barley plots was most negatively affected, producing significantly less biomass than wheat grown in oilseed radish and no catch crop plots in experiment 1 (at stem elongation and anthesis) and in experiment 2 (at maturity). Wheat yields were similar in barley and oilseed radish plots in both experiments (Fig. 4). Lower wheat biomass in barley plots suggests that N release from barley biomass was slower than radish and did not meet wheat N demand.

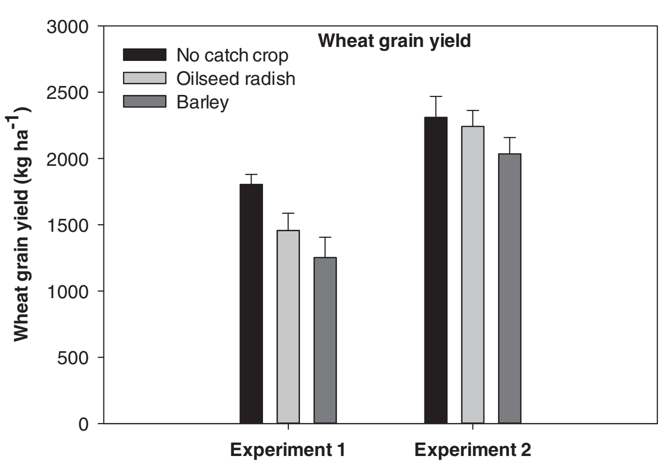

Fig. 4. Effect of catch crop species (no catch crop, barley and oilseed radish) on wheat grain yield for experiments 1 and 2. Vertical bars are standard errors.

A series of long-term experiments conducted at three locations with varying soil, weather and fertility conditions across Denmark showed that the response of spring cereals to catch crops are species (catch crop and cash crop), management (manure, rotation), and soil type (sandy loam, coarse sand) dependent (Olesen et al., 2007, 2009; Doltra and Olesen, 2013). While oat yields and grain N were increased by inclusion of catch crops, barley yields were not affected. The authors concluded that slower early vegetative development of oat compared to barley, made it possible for the oat crop to better synchronize the N uptake with the N release from the catch crops. It appears that selection of catch crops with fast N release properties may improve cash crop productivity.

In one run of the present experiment oilseed radish released N faster than barley catch crop and wheat N uptake at stem elongation was significantly higher in oilseed radish plots than barley plots in experiment 1 (Fig. 3). Similarly, in experiment 2, wheat N uptake at maturity was higher in oilseed radish plots than barley. Although oilseed radish appeared to be more promising catch crop than barley in terms of providing timely N release to cash crops, wheat took up more N and produced more biomass after no catch crop than after oilseed radish.

Treatment effects on soil NO_3-N (0–120 cm) were tested on different dates over the study period providing the opportunity to better understand how stable treatment effects were over time. Results showed significantly more NO_3-N in the no catch crop compared to catch crop treatments in the catch crop year (Table 4, Fig. 2). At time of wheat seeding, the following year, treatment differences still remained. Therefore, lower N by catch crops was maintained through the winter and early spring. After wheat harvest, on the other hand, soil NO_3-N levels were higher in the catch crop treatments compared with the control treatment (Table 4, Fig. 2). These observations also provide evidence that N mineralization from catch crop biomass was slow and may not have been in synchrony with wheat N requirements, and this may explain greater availability of N after wheat harvest in the catch crops compared with the control treatment. One possible explanation is that wheat may have taken up more N in the no catch crop system than the catch crop system, leaving more N in the soil in the catch crop system. For example, in experiment 1, soil NO_3-N (0–120 cm) in the no catch crop treatment after wheat harvest was 17 and 13 kg ha^{-1} less than oilseed radish and barley plots, respectively (Fig. 2). This may be attributed to slow mineralization of organic N in catch crop biomass not being taken up by wheat crop in synchrony (Ladd et al., 1983; Mohr et al., 1998), as well as, faster depletion of readily available soil NO_3-N from urine in no catch crop plots by the wheat crop (Cicek et al., 2014b). In experiment 2, there were no significant differences between treatments, where both crops acted similarly.

Although both catch crops performed well in terms of biomass production and N uptake, the N release from the catch crop biomass was not in synchrony with the wheat N uptake for optimum productivity. Both in experiment 1 and 2, the wheat biomass difference between the treatments (i.e., catch crops vs. no catch crops) progressively increased from stem elongation to maturity. By maturity, wheat grown in the no catch crop treatment had more biomass than wheat grown in either catch crop treatments (Table 5, Fig. 3). Similarly, N uptake of wheat at maturity was significantly greater without a catch crop in experiment 1 as result of greater soil NO_3-N availability and the disadvantage was found again for the barley catch crop in experiment 2. Future investigations should examine faster decomposing catch crops than barley and oilseed radish. For instance, in Ontario, Vyn et al. (2000) found that compared to legume red clover, which increased corn productivity, radish, fall rye or oat catch crops had negative or no effect on corn productivity.

Tillage management of catch crops did not affect wheat productivity (Table 5). All catch crop plots were tilled prior to wheat establishment, hence, wheat was sown into tilled plots. Nevertheless, the present study illustrated that reducing tillage during catch crop production had no negative effect on wheat productivity. Absence of tillage x catch crop species interaction on wheat productivity also confirmed that for each of the two catch crop species used here, reducing tillage had no effect on wheat productivity.

There was also no effect of tillage management or catch crops on fall rye productivity (data not shown). Fall rye biomass production ranged from 6290 to 7670 kg ha^{-1} and grain yield ranged from 3160 to 3640 kg ha^{-1}. Bullied et al. (2002) also reported no effect from a low N single year green manure to the second grain crop. Similar to what was observed in the wheat year, N “stored” in catch crop biomass did not benefit fall rye productivity. Soil NO_3-N after fall rye harvest was not affected by any of the treatments (data not shown). Total soil NO_3-N (0–120 cm) was very low and around 15 kg ha^{-1} for all treatments. This observation showed that soil N was equally depleted in all treatments. Therefore the hypothesis that catch crop biomass stored N would be released during the fall rye year and increase fall rye productivity compared to no catch crop treatment (Hoyt, 1990), was rejected. Perhaps some of the N in the biomass transformed into more stable organic N fractions and became less available.

3.5. Strategies to improve N benefit from catch crops

In their meta-analysis Tonitto et al. (2006) found that, in general, legume based systems need to provide around 110 kg ha^{-1} of N (in legume biomass) for following crop yields to be similar to the conventional fertilized systems. Tonitto et al. (2006) considered N in legume biomass as equivalent to the synthetic fertilizer N (i.e., 110 kg ha^{-1} of N in legume biomass = 110 kg ha^{-1} of N in synthetic fertilizer). If we use the soil mineral N (i.e., NO_3-N) content as an indication of level of N availability to plants, the following reasoning can be made for the present study. Total soil NO_3-N content in the spring before the wheat production was well below 110 kg ha^{-1} in plots where catch crops were grown (Fig. 2). Soil NO_3-N content in no catch crop plots, on the other hand, were 95 and 105 kg ha^{-1}, respectively, for experiments 1 and 2. Therefore, although successful in capturing soil NO_3-N, catch crops in this study reduced available N at seeding time below the threshold for optimum wheat production.

The present study illustrated that extra N made available by grazing of green manures can be captured by catch crops but N release from catch crops was not in synchrony with the demands of a following wheat crop. Even though oilseed radish released slightly more N than barley, it appeared that the slow mineralization of catch crop biomass was the reason. Including low C:N ratio catch crops or legume/grass mixtures and manure addition during the catch crop phase have been suggested as ways to increase the speed of mineralization from catch crop residues. For instance, in France, N mineralization from a low C:N (12.8) mustard catch crop was faster than radish and ryegrass catch crops with higher C:N ratios; 17 and 28.3 respectively (Constantin et al., 2011). In Denmark, increased ryegrass proportion in legume/grass catch crop mixtures, decreased the N release rate (Doltra and Olesen, 2013). Another strategy to increase N availability from catch crops is grazing the catch crops in late autumn after they have “secured” the N in their biomass, which has not been investigated by earlier studies. Grazing would be expected to release biomass bound N faster than soil decomposition of catch crop biomass during the

Table 5
Analysis of variance for the effect of catch crop species (no catch crop, barley and oilseed radish), catch crop seeding management (direct seeding and conventional seeding) and time (stem elongation, anthesis and maturity stages) on wheat dry matter biomass, biomass N concentration, biomass N uptake for experiments (Exp) 1 and 2.

	Dry matter		N concentration		N uptake	
Source of variation	Exp1	Exp 2	Exp1	Exp 2	Exp1	Exp 2
Wheat biomass	———— *P* value ————					
Species (S)	<.0001	0.082	0.025	0.05	0.0004	0.096
Management (M)	0.319	0.394	0.597	0.673	0.518	0.162
Time (T)	<.0001	<.0001	<.0001	<.0001	<.0001	0.002
S x M	0.632	0.818	0.286	0.313	0.415	0.457
S x T	0.982	0.906	0.378	0.57	0.537	0.758
M x T	0.472	0.628	0.831	0.249	0.632	0.959
S x M x T	0.384	0.808	0.43	0.819	0.525	0.992
Wheat grain						
S	0.002	0.043	0.141	0.195	–	–
M	0.408	0.172	0.873	0.879	–	–
S x M	0.839	0.988	0.121	0.013	–	–

cold winter months. Grazing of catch crops, on the other hand, may not be an effective strategy in wetter environments where leaching and runoff of N is likely.

4. Conclusions

This study was conducted under contrasting growing seasons. When precipitation was high, catch crops produced high amounts of biomass and reduced soil NO_3-N loading. When precipitation was low, catch crops produced little biomass and had limited effect on soil nitrate. Although catch crops were successful at capturing soil NO_3-N, productivity of wheat grown after catch crops was much lower than wheat grown in the no catch crop treatment. Nitrogen captured in catch crop biomass was not released in synchrony (i.e., slower) with the wheat demand. Between the catch crops, oilseed radish released N faster than barley.

Catch crops were able to reduce soil NO_3-N loading up to 120 cm depth when conditions were favorable (above-average precipitation) for catch crop biomass production. Hence, catch crops reduced the risk of leaching when precipitation was above average. As a result of lower biomass productivity in a dry year, catch crops did not reduce soil NO_3-N content as a result of lower biomass productivity. Under such dry conditions, catch crops may be considered as organic matter building, cover or forage crops with less utility in, and perhaps less need for, N capture.

Cultivating soil before catch crop seeding did not offer any N uptake or biomass accumulation advantages over no-till seeding into grazed green manure residue. The present study, therefore, provided a strong evidence for possibility of reducing tillage in organic crop-livestock integrated systems because of greater N availability after grazing.

Mineralization of N from catch crop biomass appeared to be very slow. Future studies should consider leguminous species with higher mineralization rates than oilseed radish or barley. Legumes also add more N to soil, thereby improving the potential N benefit to the following crops. On the other hand, mixtures of legumes and non-legumes may be needed to capture soil N effectively and release it in a timely manner. Grazing of catch crops should also be considered for timely and improved N release from catch crops. It may be possible to avoid autumn and spring tillage to mineralize N for wheat if catch crops are grazed in late autumn.

Acknowledgements

We sincerely thank the anonymous reviewer who has significantly contributed to this paper. Funding for the experiment was provided by Agriculture and Agri-Food Canada and Canadian Wheat Board. Additional funding to senior author was provided by National Science and Engineering Research Council, University of Manitoba Graduate Fellowship and Manitoba Graduate Scholarship from Manitoba Government.

References

Askegaard, M., Olesen, J., Kristensen, K., 2005. Nitrate leaching from organic arable crop rotations: effects of location manure and catch crop. Soil Use Manage. 21, 181–188.
Aronsson, H., Torstensson, G., 1998. Measured and simulated availability and leaching of nitrogen associated with frequent use of catch crops. Soil Use Manage. 14, 6–13.
Berger, A., Mcdonald, A.J., Riha, S.J., 2007. Does soil nitrogen affect early competitive traits of annual weeds in comparison with maize? Weed Res. 47, 509–516.
Berntsen, J., Olesen, J.E., Petersen, B.M., Hansen, E.M., 2006. Long-term fate of nitrogen uptake in catch crops. Eur. J. Agron. 25, 383–390.
Biederbeck, V.O., Bouman, O.T., Looman, J., Slinkard, A.E., Bailey, L.D., Rice, W.A., Janzen, H.H., 1993. Productivity of four annual legumes as green manure in dryland cropping systems. Agron. J. 85, 1035–1043.
Blackshaw, R.E., Molnar, L.J., Moyer, J.R., 2010. Suitability of legume cover crop-winter wheat intercrops on the semi-arid Canadian prairies. Can. J. Plant Sci. 90, 479–488.
Bullied, W., Entz, M., Smith, S., Bamford, K., 2002. Grain yield and N benefits to sequential wheat and barley crops from single-year alfalfa berseem and red clover, chickling vetch and lentil. Can. J. Plant Sci. 82, 53–65.
Campbell, C.A., Selles, F., Zentner, R.P., De Jong, R., Lemke, R., Hamel, C., 2006. Nitrate leaching in the semiarid prairie: effect of cropping frequency crop type, and fertilizer after 37 years. Can. J. Soil Sci. 86, 701–710.
Campbell, C., Lafond, G., Zentner, R., Jame, Y., 1994. Nitrate leaching in a udic haploboroll as influenced by fertilization and legumes. J. Environ. Qual. 23, 195–201.
Carvalho de Faccio, P.C., Anghinoni, I., de Moraes, A., de Souza, E.D., Sulc, R.M., Lang, C.R., Cassol Flores, J.P., Terra Lopes, M.L., Silva da Silva, J.L., Conte, O., Wesp d, C.L., Levien, R., Fontaneli, R.S., Bayer, C., 2010. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. Nutr. Cycl. Agroecosyst. 88, 259–273.
Cicek, H., Thiessen-Martens, J.R., Bullock, P., Entz, M.H., 2014a. Productivity and nitrogen benefits of late season legume cover crops in organic wheat production. Can. J. Plant Sci. 94, 771–783.
Cicek, H., Thiessen-Martens, J.R., Bamford, K., Entz, M.H., 2014b. Effects of grazing two green manure crop types in organic farming systems: N supply and productivity of following grain crops. Agric. Ecosyst. Environ. 190, 27–36.
Clough, T.J., Ledgard, S.F., Sprosen, M.S., Kear, M.J., 1998. Fate of N-15 labelled urine on four soil types. Plant Soil 199, 195–203.
Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., Beaudoin, N., 2010. Effects of catch crops: no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agric. Ecosyst. Environ. 135, 268–278.
Constantin, J., Beaudoin, N., Laurent, F., Cohan, J., Duyme, F., Mary, B., 2011. Cumulative effects of catch crops on nitrogen uptake, leaching and net mineralization. Plant Soil 341, 137–154.
Crews, T., Peoples, M., 2005. Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review. Nutr. Cycl. Agroecosyst. 72, 101–120.
Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources: factors and mitigating strategies. Nutr. Cycl. Agroecosyst. 64, 237–256.
Doltra, J., Olesen, J.E., 2013. The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. Eur. J. Agron. 44, 98–108.
Franzluebbers, A.J., Stuedemann, J.A., 2007. Crop and cattle responses to tillage systems for integrated crop-livestock production in the Southern Piedmont, USA. Renew. Agric. Food Syst. 22, 168–180.
Halde, C., Gulden, R., Hammermeister, H., Ominski, A.M., Tenuta, K.H., M, Entz, M.H., 2012. Using mulches to reduce tillage in organic grain production in Western Canada. Proceedings of the Canadian Organic Science conference, University of Manitoba, Winnipeg, MB, Canada, 21-23 Feb.
Hansen, E., Djurhuus, J., 1997. Nitrate leaching as influenced by soil tillage and catch crop. Soil Tillage Res. 41, 203–219.
Hatfield, P.G., Lenssen, A.W., Spezzano, T.M., Blodgett, S.L., Goosey, H.B., Kott, R.W., Marlow, C.B., 2007. Incorporating sheep into dryland grain production systems II: Impact on changes in biomass and weed density. Small Ruminant Res. 67, 216–221.
Haynes, R.J., Williams, P.H., 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49, 119–199.
Herrera, J.M., Feil, B., Stamp, P., Liedgens, M., 2010. Root growth and nitrate-nitrogen leaching of catch crops following spring wheat. J. Environ. Qual. 39, 845–854.
Hoad, S., Russell, G., Lucas, M., Bingham, I., 2001. The management of wheat, barley, and oat root systems. Adv. Agron. 74, 193–246.
Hoyt, P.B., 1990. Residual effects of alfalfa and bromegrass cropping on yields of wheat grown for 15 subsequent years. Can. J. Soil Sci. 70, 109–113.
Ladd, J., Amato, M., Jackson, R., Butler, J., 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 15, 231–238.
Laine, P., Ourry, A., Macduff, J., Boucaud, J., Salette, J., 1993. Kinetic-parameters of Nitrate uptake by different catch crop species – effects of low-temperatures or previous nitrate starvation. Physiol. Plantarum. 88, 85–92.
Laine, P., Bigot, J., Ourry, A., Boucaud, J., 1994. Effects of low-temperature on nitrate uptake, and xylem and phloem flows of nitrogen: in *Secale-Cereale* L. and *Brassica-Napus* L. New Phytol. 127, 675–683.
Liebman, M., Dyck, E., 1993. Crop-rotation and intercropping strategies for weed management. Ecol. Appl. 3, 92–122.
Liebman, M., Graef, R.L., Nettleton, D., Cambardella, C.A., 2012. Use of legume green manures as nitrogen sources for corn production. Renew. Agr. Food Syst. 27, 180–191.
MASC, Manitoba Agricultural Services Corporation. URL: http://www.masc.mb.ca/masc.nsf/index.html?OpenPage (accessed 10.02.13).
Mills, G.F., Haluschak, P., 1993. Soils of the Carman Research Station. Special Report Series No. 93-1 Manitoba Soil Survey Unit and Manitoba Land Resource Unit. Agriculture Canada, Manitoba Department of Agriculture, and Department of Soil Science of the University of Manitoba, Winnipeg, MB, Canada.
Mohr, R.M., Janzen, H.H., Bremer, E., Entz, M.H., 1998. Fate of symbiotically-fixed N-15 as influenced by method of alfalfa termination. Soil Biol. Biochem. 30, 1359–1367.

Munkholm, L.J., Hansen, E.M., 2012. Catch crop biomass production: nitrogen uptake and root development under different tillage systems. Soil Use Manage. 28, 517–529.
Olesen, J., Askegaard, M., Rasmussen, I., 2000. Design of an organic farming crop-rotation experiment. Acta Agric. Scand. Sect. B-Soil Plant Sci. 50, 13–21.
Olesen, J.E., Hansen, E.M., Askegaard, M., Rasmussen, I.A., 2007. The value of catch crops and organic manures for spring barley in organic arable farming. Field Crops Res. 100, 168–178.
Olesen, J.E., Askegaard, M., Rasmussen, I.A., 2009. Winter cereal yields as affected by animal manure and green manure in organic arable farming. Eur. J. Agron. 30, 119–128.
Peigné, J., Ball, B.C., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. 23, 129–144.
Ranells, N., Wagger, M., 1997. Grass-legume bicultures as winter annual cover crops. Agron. J. 89, 659–665.
Ruz-Jerez, B.E., White, R.E., Ball, P.R., 1995. A comparison of nitrate leaching under clover-based pastures and nitrogen-fertilized grass grazed by sheep. J. Agric. Sci. 125, 361–369.
Ryden, J., Ball, P., Garwood, E., 1984. Nitrate leaching from grassland. Nature 311, 50–53.
Sapkota, T.B., Askegaard, M., Laegdsmand, M., Olesen, J.E., 2012. Effects of catch crop type and root depth on nitrogen leaching and yield of spring barley. Field Crops Res. 125, 129–138.
Schroder, J., TenHolte, L., Janssen, B., 1997. Non-overwintering cover crops: a significant source of N. Neth. J. Agric. Sci. 45, 231–248.
Stopes, C., Lord, E.I., Philipps, L., Woodward, L., 2002. Nitrate leaching from organic farms and conventional farms following best practice. Soil Use Manage. 18, 256–263.
Stout, W.L., 2003. Effect of urine volume on nitrate leaching in the northeast USA. Nutr. Cycl. Agroecosyst. 67, 197–203.
Thiessen Martens, J.R., Hoeppner, J.W., Entz, M.H., 2001. Legume cover crops with winter cereals in southern Manitoba Establishment, productivity, and microclimate effects. Agron. J. 93, 1086–1096.
Thiessen Martens, J.R., Entz, M.H., 2011. Integrating green manure and grazing systems: a review. Canad. J. Plant Sci. 91, 811–824.
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 Soil 230, 185–195.
Thorup-Kristensen, K., Magid, J., Jensen, L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302.
Tonitto, C., David, M.B., Drinkwater, L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112, 58–72.
Vaisman, I., Entz, M.H., Flaten, D.N., Gulden, R.H., 2011. Blade roller-green manure interactions on nitrogen dynamics weeds, and organic wheat. Agron. J. 103, 879–889.
Varco, J., Frye, W., Smith, M., Mackown, C., 1993. Tillage effects on legume decomposition and transformation of legume and fertilizer N-15. Soil Sci. Soc. Am. J. 57, 750–756.
Vos, J., Van der Putten, P., 1997. Field observations on nitrogen catch crops 1: potential and actual growth and nitrogen accumulation in relation to sewing date and crop species. Plant Soil 195, 299–309.
Vyn, T.J., Janovicek, K.J., Miller, M.H., Beauchamp, E.G., 1999. Spring soil nitrate accumulation and corn yield response to preceding small grain N fertilization and cover crops. Agron. J. 91, 17–24.
Vyn, T.J., Faber, J., Janovicek, K.J., Beauchamp, E.G., 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. 92, 915–924.
Whitehead, D.C., 2000. Nutrient Elements in Grassland: Soil-plant-animal Relationships. CABI Publishing, New York, NY.