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Research article

Effect of catch crops on N dynamics and following crops in organic farming

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Abstract – Green manure catch crops promote the sustainability of agricultural systems by reducing soil erodibility and by nutrient uptake and transfer to the following main crops. This effect efficiently reduces the risk of nitrate leaching. Biological nitrogen fixation by legume catch crops is an additional benefit, mainly in organic farming. Such crops may, however, reduce nitrogen uptake from the soil and increase nitrate leaching. Additionally, under drought conditions, their extra water consumption may outweigh the beneficial effects. To determine the best catch crop management in stockless organic farming under dry, Pannonian site conditions in eastern Austria, four treatments were compared in 2002 and 2004: (1) legumes: field pea, common vetch and chickling vetch, (2) non-legumes: phacelia, oil radish and turnip, (3) a legume and non-legume mixture (all mentioned components), and (4) a bare fallow control. Our results show that catch crop biomass and N yield, biological N fixation, and crop N uptake from the soil were about 4 times higher under moderately dry conditions in 2002 than under drought conditions in summer and autumn 2004. In 2002, the legume/non-legume mixture had the highest biomass and N yield and the highest biological N fixation. Both the legume/non-legume mixture and the non-legumes were more efficient than legumes in N uptake from the soil (+32 kg N ha^{-1}); and in reducing both soil inorganic N contents by –45 kg N ha^{-1} and nitrate concentrations in soil solution by –20 mg N L^{-1}. These findings show that the legume/non-legume mixture combined the positive effects of non-legumes and legumes. In 2004, catch crop effects did not differ except for their above-mentioned effect on inorganic N contents. The only pre-crop effect was that of legumes compared with non-legumes on spring barley grain dry matter of +0.6 Mg DM ha^{-1} and grain N yield of +17 kg N ha^{-1} in 2005. The water consumption of catch crops never adversely affected the following crops.

green manure / biological nitrogen fixation / nitrogen conservation / drought / legume catch crop

1. INTRODUCTION

Catch crops have a wide range of positive effects in cropping systems, in conventional as well as in organic farming (Renius et al., 1992; Kolbe et al., 2004). Using catch crops as fodder is an obvious economic advantage. Green manure catch crops have important ecological functions such as reducing soil erosion by covering the soil, improving soil fertility by an input of organic matter with their roots, and by increasing soil water-holding capacity (Joyce et al., 2002). They can reduce losses of N and other nutrients remaining in the soil after harvest of the main crop and transfer them to the succeeding crops, thus increasing their N supply (Stute and Posner, 1995). In a long-term experiment by Hösch and Dersch (2003) in Eastern Austria, with 900 mm mean annual precipitation, catch crops including legumes and non-legumes reduced the average yearly nitrate leaching compared with the same rotation without catch crops from 48 kg N ha^{-1} to 18 kg N ha^{-1}. Askegaard et al. (2005) determined catch crops as the most efficient means to reduce nitrate leaching in an experiment at three Danish sites with soil texture ranging from sandy loam to coarse sand. If green manure catch crops are incorporated into the soil in late autumn or in spring, nutrients in their biomass become available to the following main crop. In organic farming, especially in stockless farming, where no flexible fertility inputs are available, this may contribute considerably to plant nutrition.

Another benefit of leguminous catch crops is their ability to biologically fix nitrogen. Although legumes exploit available nitrogen (N) in the soil before intensifying biological nitrogen fixation, leguminous catch crops no doubt leave more soil inorganic N (N_{in}) than non-leguminous catch crops (Reents and Möller, 2000; Thorup-Kristensen, 2006a).

In dry regions, like in the Pannonian region of Eastern Austria, the water use by the catch crops may outweigh their beneficial effects because it may limit the yield of the succeeding main crop. This calls for considering the additional water use by catch crops – compared with bare soil.

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No studies are currently available on the effects of differing green manure catch crops on soil N dynamics and succeeding crops in stockless organic farming under dry, Pannonian site conditions. This field trial was therefore designed to optimise green manure catch crop management under these conditions. The objectives were to test, under Pannonian site conditions, if (i) different green manure crop variants – legumes, non-legumes and a mixture of both – produce the same amount of crop biomass and N yield, (ii) a legume + non-legume mixture can incorporate soil N and reduce N_{in} contents in autumn to the same extent as a pure non-legume crop whilst increasing plant-available soil nitrogen by biological nitrogen fixation like a pure legume crop, and (iii) legume and non-legume crops and their mixtures differ in the beneficial effect on yield and N content of the following cash crops.

2. MATERIALS AND METHODS

2.1. Site and experimental set-up

The experiment was conducted on organically managed fields of the University of Natural Resources and Applied Life Sciences, Vienna, Austria. The trial site is located in the Marchfeld area east of Vienna (16°34'E, 48°12'N) at an altitude of 150–160 m above sea level. The soil is a Calcaric Phaeozem (FAO, 1998) from Loess with a high water-holding capacity, a good nutrient availability, a comparably high soil organic matter content (2.2% total organic carbon) and a pH_{CaCl_2} of 7.6 in the Ap horizon. Soil texture varies from sandy loam to silty loam in the topsoil and from loamy sand to sandy silt in the subsoil. The plowing depth was 33 cm on average during conventional farming until 1998 and was then reduced to 25 cm after conversion to organic farming. Horizons with increasing soil depth are: Ap, A, AC and C. In most cases, the transition from the A to C horizon occurred within a soil depth of 50 to 80 cm. The climate is characterised by hot, dry summers with little dew, and cold winters with little snow. The long-term (1971–2000) average annual precipitation is 540 mm, the mean temperature 9.8 °C. No organic manures have been applied since 1978.

Crop rotation during the experimental period was winter wheat (*Triticum aestivum* L.) / green manure crop (2002) – potato (*Solanum tuberosum*) (2003) – winter rye (*Secale cereale*) / green manure crop (2004) – spring barley (*Hordeum vulgare*) (2005). Four treatments, three green manure crop variants differing in their proportion of legumes and a bare fallow variant as a control, were tested in a completely randomised block design on 9 × 6 m plots in four replicates. The legume variant consisted of field pea (*Pisum sativum* L., cv. *speciosum*), common vetch (*Vicia sativa* L.) and chickling vetch (*Lathyrus sativus* L.), the non-legume variant of phacelia (*Phacelia tanacetifolia*), oil radish (*Raphanus sativus* ssp. *oleiformes*) and turnip (*Brassica rapa* var. *rapa* subvar. *esculenta*). The legume + non-legume mixture included all the legumes and non-legumes (Tab. I). In the bare fallow control, the soil was treated once with a moulding cutter.

Table I. Sowing rates of green manure crops (kg ha^{-1}).

Variants	L + NL	L	NL	BF
Field Pea, *Pisum sativum* cv. *speciosum*	40	80	–	–
Common Vetch, *Vicia sativa*	20	40	–	–
Chickling Vetch, *Lathyrus sativus* L.	45	90	–	–
Phacelia, *Phacelia tanacetifolia*	2.5	–	5	–
Oil Radish, *Raphanus sativus*	3	–	6	–
Turnip, *Brassica rapa* var. *rapa*	2	–	4	–

Legend: L: legume mixture; NL: non-legume mixture; L + NL: mixture of legumes and non-legumes; BF: bare fallow.

2.2. Timeline of operations

In 2002, green manure crops were sown after harvesting winter wheat on 30 July and mulched and incorporated into the soil on 5 November. Potatoes were planted in mid-April and harvested in early August 2003. As no catch crops were established in autumn 2003, soil was kept bare for two months until sowing of the following winter rye on 10 October. In 2004, green manure crops were sown on 12 August after harvesting winter rye and incorporated into the soil on 17 November. Treatments were conducted on the same plots as in 2002. The trial ended with the harvest of spring barley in July 2005.

Weather conditions were assessed by a gauging station of the Institute of Agronomy and Plant Breeding adjacent to the experimental field. During the experiment, soil water contents and contents of soil inorganic N (N_{in}) were monitored at a depth of 0–120 cm three times per year: in early spring at the beginning of the growing period, in summer after the harvest of the main crop, and in autumn at the time of incorporation of the green manure crop or at the sowing date of the winter crop, respectively.

2.3. Analytical procedures

Soil water content was measured gravimetrically. Nitrate and ammonium were extracted with 0.0125 M $CaCl_2$ solution at a soil-solution ratio of 1:4. Due to an efficient nitrification under the slightly acidic soil reaction, ammonium contents were negligible. On the soil samples of the Ap horizon (0–30 cm depth), taken at the beginning of the vegetation period, additionally recorded parameters included extractable N (= inorganic + soluble organic N) extracted from the soil with 0.5 M K_2SO_4 solution at a 1:5 ratio, and the N mineralisation potential according to Kandeler (1993).

During the leaching period from autumn to spring, soil solution was collected by suction cups from 140 cm depth and nitrate concentrations were assessed by directly measuring solutions at 210 nm in a photometer according to Navone (1964). Due to drought during the experimental period, soil solution could not be collected on all dates.

Above-ground biomass production of the green manure crops was determined on a harvesting area of 2 m^2 per plot. Below-ground (0–60 cm) crop biomass was derived from four samples per plot taken with a soil corer (10 cm diam.) within the mentioned harvesting area; here, roots were washed out of the soil. Cereal grain yield was assessed by both hand harvesting of 2 m^2 per plot and by a plot combine harvester. Plant N contents were analysed by dry combustion and gas chromatography in a LECO CN-Analyser.

2.4. Calculation of biological N fixation

Biological nitrogen fixation of the legumes was estimated by the extended difference method according to Stülpnagel (1982). Shoot, stubble and root biomass N, and soil N_{in} contents were taken into account. The non-legume catch crop served as a reference crop.

$$BNF = N_{L-shoots} + N_{L-roots} + N_{in\,(L)} - N_{R-shoots} - N_{R-roots} - N_{in\,(R)} \quad (1)$$

BNF	Nitrogen fixed by the legumes from the air ($kg\,N\,ha^{-1}$)
$N_{L-shoots}$	Nitrogen in shoots of legumes ($kg\,N\,ha^{-1}$)
$N_{L-roots}$	Nitrogen in roots of legumes ($kg\,N\,ha^{-1}$)
$N_{in\,(L)}$	Inorganic nitrogen in the soil below legumes ($kg\,N\,ha^{-1}$)
$N_{R-roots}$	Nitrogen in roots of reference crop ($kg\,N\,ha^{-1}$)
$N_{R-shoots}$	Nitrogen in shoots of reference crop ($kg\,N\,ha^{-1}$)
$N_{in\,(R)}$	Inorganic nitrogen in the soil below reference crop ($kg\,N\,ha^{-1}$)

The N uptake from soil of legume and legume + non-legume green manure crops was calculated as the difference between total crop N yield and biological nitrogen fixation.

2.5. Data analysis

Data were analysed statistically by a two-way analysis of variance (ANOVA) with the factors "block" and "treatment". For pairwise comparisons of the means, a Tukey test was used. Additionally, an alternative model, a special form of covariance analysis with the factor "treatment" and the block number as a covariate, was applied. This approach was suggested by Moder (1998) to improve the test efficiency by gaining additional degrees of freedom for estimating the error variance; it improved the test efficiency in most cases. The ANOVA was calculated with SPSS 12.0; for the covariance analysis the SAS program package, release 8.2, was used.

3. RESULTS AND DISCUSSION

3.1. Weather conditions

Weather conditions differed considerably in the three experimental years (Fig. 1). In summer and autumn 2002, precipitation was above the long-term average, which was very beneficial for the growth of the green manure crops. The following

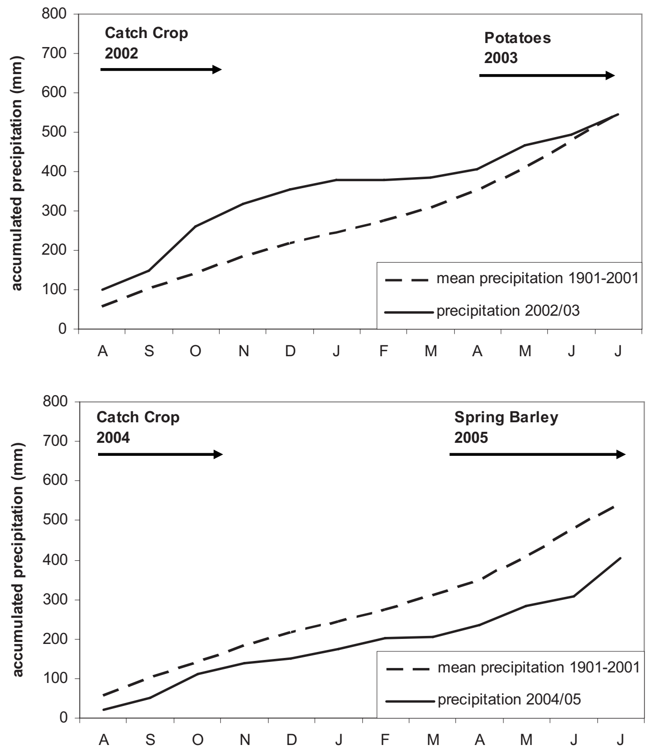


Figure 1. Precipitation during the experimental period. Period of crop growth indicated.

year, 2003, was very dry, with temperatures above the long-term average in summer. The temperature was on average in 2004, and the water supply for winter rye was sufficient. Soil conditions in summer and autumn 2004 were dry and yielded a very small green manure crop biomass production. Growing conditions for spring barley were moderately dry in 2005.

3.2. Biomass and nitrogen yield of green manure crops

In 2002, under moderately dry weather conditions (Fig. 1), the total biomass and total N yield reached up to 6 Mg dry matter (DM) ha^{-1} and 141 $kg\,N\,ha^{-1}$ in the legume + non-legume crop (Tab. II). Biomass and N yield, N content, C-to-N ratio, biological N fixation, and plant uptake of N derived from the soil significantly differed between catch crop variants (Tab. II).

Precipitation was significantly lower in August and October 2004 than in 2002 (Fig. 1). In consequence, total biomass and N yield in 2004 were only around 1 Mg DM ha^{-1} and 20 $kg\,N\,ha^{-1}$, respectively (Tab. II). Biological nitrogen fixation (on average 10 $kg\,N\,ha^{-1}$) and uptake of soil N (15 $kg\,N\,ha^{-1}$) were also low (Tab. II).

The value of green manure catch crops in organic crop rotations is largely due to their potential to reduce N_{in} contents and the risk of nitrate leaching, to fix N from the air, to conserve soil N, and to transfer N to following crops. These traits, in turn, depend on total plant biomass development, total N yield and plant N uptake from the soil. Above-ground

Table II. Biomass yield, nitrogen content, nitrogen yield, biological nitrogen fixation and N uptake from the soil of green manure crops in 2002 and 2004.

Year	Treatment variant	Biomass yield Mg DM ha^{-1}					N content mg N g^{-1} DM	C-to-N ratio	Nitrogen yield kg N ha^{-1}					BNF kg N ha^{-1}	N_{soil} kg N ha^{-1}
		a.g. leg	a.g. n-leg	a.g. total	b.g. total	a.g. + b.g. total	a.g. + b.g. total	a.g. + b.g. total	a.g. leg	a.g. n-leg	a.g. total	b.g. total	a.g. + b.g. total	a.g. + b.g.	a.g. + b.g.
2002	L + NL	1.43a	2.59a	4.02b	1.97b	5.99b	23.6b	16.2b	44a	65a	109c	32b	141b	48b	93b
	L	2.57b	–	2.57a	0.89a	3.46a	27.9c	14.3a	80b	–	80b	16a	96a	34a	62a
	NL	–	2.95a	2.95a	2.60c	5.55b	17.0a	21.9c	–	60a	60a	34b	94a	–	94b
2004	L + NL	0.19a	0.38a	0.57a	0.49a	1.05a	20.5b	17.2a	6a	9a	15a	6a	21a	6a	16a
	L	0.64b	–	0.64a	0.36a	1.00a	24.6c	15.3a	20b	–	20a	4a	24a	13a	11a
	NL	–	0.60a	0.60a	0.46a	1.06a	16.3a	20.7b	–	12a	12a	5a	17a	–	17a

Legend: BNF: biological nitrogen fixation; N_{soil}: nitrogen uptake from soil; DM: dry matter; a.g.: above-ground; b.g.: below-ground; leg: legumes; n-leg: non-legumes; see also Table I. Mean values in one column and year with the same letter do not differ significantly ($P < 0.05$).

biomass (2.57–4.02 Mg DM ha^{-1}), N yield (60–109 kg N ha^{-1}) and total biological nitrogen fixation rates (34–48 kg N ha^{-1}) of green manure crops in 2002, when growing conditions were favourable (Tab. II), were in the range of studies from wetter sites (Reents and Möller, 2000, average annual precipitation: 778–800 mm; Mueller and Thorup-Kristensen, 2001, average annual precipitation: 719 mm; Breland, 1996, average annual precipitation: 770–1550 mm). In 2004, following drought in summer, above-ground biomass (0.57–0.64 Mg DM ha^{-1}), N yield (12–20 kg N ha^{-1}) and total biological nitrogen fixation (6–13 kg N ha^{-1}) were much lower (Tab. II). Hence, the effect of catch crops on the nitrogen cycle and the benefit for following crops by N transfer were much smaller than in 2002 under sufficiently moist conditions.

In 2002, biomass yield was significantly higher in the legume + non-legume mixture than in the legume crop. Compared with the legume crop, mainly the below-ground biomass was increased for non-legume, whereas mainly the above-ground biomass was higher in the legume + non-legume mixture (Tab. II). In this year, more nitrogen was contained in total plant biomass in legume + non-legume (141 kg N ha^{-1}) than in both legume and non-legume treatments (95 kg N ha^{-1} on average). In 2004, in contrast, no differences in total biomass or N yield between the treatments were found (Tab. II). Crop N contents increased in the order non-legume < legume + non-legume mixture < legume in 2002 and in 2004 (Tab. II).

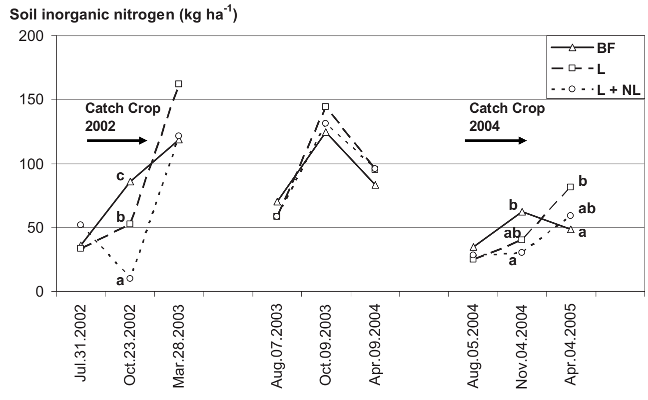
Our result of an increased total plant biomass in non-legume compared with legume, and an equivalent total N yield in both variants in 2002 (Tab. II), contrasts with a higher above-ground biomass of legume versus non-legume green manure crops in organic farming or under unfertilised conditions (Reents and Möller, 2000; Mueller and Thorup-Kristensen, 2001; Breland, 1996). This discrepancy mainly reflects the enhanced below-ground biomass and N yield of our non-legume green manure crop (Tab. II), whereas these parameters were neglected in the cited studies. Crucifers and phacelia, both constituting our non-legume crop, have high root intensities in low soil layers (Thorup-Kristensen, 2001). Askegaard and Eriksen (2007), in contrast, found higher above-ground and root biomass and total N in legume (white clover and kidney vetch) than in non-legume (ryegrass and chicory) catch crops. Those authors explained the low non-legume above-ground and root biomass production (average 0.6 Mg ha^{-1} and 0.96 Mg ha^{-1}, respectively) by the low N status of the sandy soil in that study. To estimate the value of catch crops in organic farming, whole-plant N contents and uptake of soil N are decisive, and below-ground N contents need to be considered. In dry years or when catch crops are sown late in summer, non-legume catch crops may be preferable to legumes due to lower seed costs.

Our legume + non-legume mixture achieved the greatest above-ground and total biomass, and N yield in 2002 (Tab. II). In contrast, Reents and Möller (2000) found the greatest above-ground biomass yield for legumes and a wide range of N yields for different legume + non-legume mixtures. Mixtures with complementary root systems and differing water demand for germination were clearly more advantageous under moderately dry but otherwise fertile conditions at our site in 2002. Under more severe drought, in 2004, green manure crop development was poor irrespective of the crop composition (Tab. II).

In 2002, biological nitrogen fixation was 48 kg N ha^{-1} for legume + non-legume and exceeded that for legume (34 kg N ha^{-1}). In both variants, around 35% of the total N yield was derived from biological nitrogen fixation and 65% from uptake of soil N. The greater total biomass production of the legume + non-legume mixture corresponded to an enhanced N uptake from the soil (93 kg N ha^{-1}) compared with legume (62 kg N ha^{-1}). Biological nitrogen fixation by the legumes in the legume + non-legume did not reduce plant N uptake from the soil compared with the non-legumes but increased N contents (in 2002 and in 2004) and total N yield (in 2002 only) (Tab. II).

3.3. Soil water content and nitrogen dynamics

Gravimetric soil water contents varied between 0.31 g water (g dry soil)$^{-1}$ in winter 2003/04 and 0.11 g water (g dry soil)$^{-1}$ in August 2003 and August 2004 in the Ap horizon of the plots. Water contents in the subsoil (80–140 cm depth) were generally lower (data not shown). Soil moisture in the Ap



Legend: see Table I; Mean values of one date with the same letter do not differ significantly ($P < 0.05$). No letters: no significant differences.

Figure 2. Green manure crop effects on soil inorganic nitrogen contents in 0–120 cm soil depth. Green manure crop growth in 2002 and 2004: early August to early November. Catch crop containing non-legumes reduced inorganic nitrogen contents most efficiently.

horizon did not differ between field plots planted with green manure crops and bare fallow at any sampling date (data not shown). In general, the block effect on soil water contents was more pronounced than the green manure crop effect. This reflects the varying soil texture on the field.

In autumn 2002, green manure crops containing non-legumes (non-legume and legume + non-legume variants) reduced N_{in} contents to values below 10 kg N ha^{-1} in 0–120 cm depth (Fig. 2; non-legume not shown, values largely paralleled those of legume + non-legume). The N_{in} contents, in contrast, increased to 53 and 86 kg N ha^{-1} for legume and bare fallow, respectively. In these variants, nitrate was mostly located between 30 and 90 cm depth in October. No green manure crops were grown in autumn 2003. The N_{in} contents were high (up to 144 kg N ha^{-1}) and did not differ between the treatments, as expected. The small winter rye plants did not take this amount of N_{in} up before winter, and most of it was dislocated below 60 cm in April 2004. Despite a poor catch crop development, N_{in} contents were affected by the catch crop variants in autumn 2004. In the variants with non-legumes (non-legume and legume + non-legume), N_{in} contents were significantly reduced compared with bare fallow, as in autumn 2002 (Fig. 2). This effect did not last until next spring, paralleling the situation two years before.

The reduction of N_{in} contents in 0–120 cm soil depth by the green manure crops in October 2002 and November 2004 (Fig. 2) largely paralleled their N uptake from the soil (Tab. II). Both uptake of soil N and reduction in N_{in} contents were more pronounced for non-legume and legume + non-legume than for legume in 2002.

Elsewhere, all catch crop variants reduced N_{in} contents compared with fallow (Mueller and Thorup-Kristensen, 2001; Thorup-Kristensen, 2006a). Non-legume green manure crops reduced these contents more than legumes (Pagel and Zoschke, 1991; Reents and Möller, 2000; Thorup-Kristensen, 2006a), with legume + non-legume crop mixtures ranging in between (Reents und Möller, 2000). These studies recorded no uptake of N by the catch crops.

Table III. Green manure crop effects on labile, K_2SO_4 extractable nitrogen and nitrogen mineralisation potential in the Ap horizon at the beginning of the vegetation period.

Treatment variant	K_2SO_4 extractable nitrogen (kg N ha^{-1})			Nitrogen mineralisation potential (µg NH_4-N g^{-1} DM 7 d^{-1})		
	2003	2004	2005	2003	2004	2005
L + NL	75c	40b	59ab	35.7a	22.5a	31.3a
L	73bc	34ab	64b	35.0a	24.7a	27.9a
NL	60a	36ab	51a	34.1a	20.5a	33.9a
BF	64ab	31a	50a	31.9a	22.7a	22.4a

Legend: see Table I; mean values in one column with the same letter do not differ significantly ($P < 0.05$).

A general effect on N_{in} contents before winter, increasing in the order non-legumes < legume + non-legume mixtures < legumes, was found in a literature review on catch crops by Miersch and Vetter (2000). This supports above-cited studies and our results (exception: the legume + non-legume mixture was as efficient as the non-legume green manure crop at most sampling dates in our study).

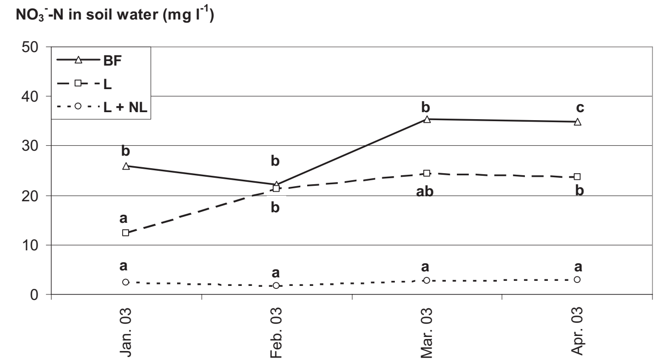
In our study, the reducing effect of green manure crops on N_{in} contents, compared with the bare fallow control, did not last until next spring in 2002/03 and 2004/05 (Fig. 2). In fact, the N_{in} contents, mainly in the upper 60 cm, were increased in legume compared with both bare fallow and non-legume in April 2005 (Fig. 2), indicating an enhanced N mineralisation from the legume residues due to a higher N content and lower C-to-N ratio (Tab. II). This is also indicated by increased contents of soluble N in the Ap horizon in the legume / legume + non-legume treatments in spring 2003, 2004 and 2005, but not by the nitrogen mineralisation potential assessed by anaerobic incubation of samples from the Ap horizon (Tab. III). Accordingly, Thorup-Kristensen (2006a) reported increased N_{in} contents relative to the control in May after incorporation of legume green manure catch crops. The extra amount of N_{in} in the legume variant compared with the bare fallow control in our study in April 2005 (33 kg N ha^{-1}, Fig. 2) even surpassed the total N content of the legume green manure crop (24 kg N ha^{-1}, Tab. II). This cannot be explained by an enhanced N mineralisation from the green manure alone. The extra amount of N_{in} may reflect a limited accuracy of soil inorganic nitrogen measurement. It could also indicate an increased N mineralisation from the soil organic matter due to a positive N priming effect after incorporation of residues with a low C-to-N ratio (Kuzyakov et al., 2000).

The nitrate concentrations in soil solution from 140 cm depth ranged from 2 to 35 mg N L^{-1} from January to April 2003 (Fig. 3; non-legume treatment not shown, values largely paralleled the legume + non-legume treatment). The values were clearly reduced for non-legume and legume + non-legume compared with bare fallow and reflected the N_{in} contents in autumn 2002 (Fig. 2). The legume green manure crop only had a minor reducing effect. In the following year,

Table IV. Green manure crop effects on yield, nitrogen contents and N yield of the main crops.

Treatment	Potato, *Solanum tuberosum* L., 2003			Winter rye, *Secale cereale* L., 2004			Spring barley, *Hordeum vulgare* L., 2005		
variant	tuber yield ($Mg\ DM\ ha^{-1}$)	N content ($mg\ N\ g^{-1}\ DM$)	N yield ($kg\ N\ ha^{-1}$)	grain yield ($Mg\ DM\ ha^{-1}$)	N content ($mg\ N\ g^{-1}\ DM$)	grain N yield ($kg\ N\ ha^{-1}$)	grain yield ($Mg\ DM\ ha^{-1}$)	N content ($mg\ N\ g^{-1}\ DM$)	grain N yield ($kg\ N\ ha^{-1}$)
L + NL	3.4a	14.8a	50a	5.3a	16.4a	86a	3.1ab	14.9a	46ab
L	3.5a	16.2a	57a	5.2a	16.3a	87a	3.3b	17.3a	57b
NL	3.4a	14.9a	51a	5.6a	18.0a	102a	2.7a	14.9a	40a
BF	3.6a	14.2a	51a	4.4a	16.3a	74a	2.7a	16.7a	45ab

Legend: see Table I; DM: dry matter. Mean values in one column with the same letter do not differ significantly ($P < 0.05$).



Legend: see Table I; Mean values of one date with the same letter do not differ significantly ($P < 0.05$).

Figure 3. Effects of a green manure crop in autumn 2002 on nitrate concentration in soil solution from 140 cm depth. Catch crop containing non-legumes reduced nitrate in soil solution most efficiently.

nitrate concentrations in soil solution following the green manure crops containing non-legumes were significantly reduced compared with bare fallow only in March 2004. After the non-legume and legume + non-legume green manure crops in 2004, no significant reduction of the nitrate concentrations in soil solution compared with bare fallow could be determined because of missing values due to drought and a high variability in nitrate concentrations (data not shown).

Despite higher nitrogen mineralisation after incorporation of legume residues, the respective nitrate concentrations in soil solution from the subsoil never increased compared with bare fallow; in fact, they decreased on several dates (Fig. 3). Although N_{in} contents were reduced only transiently, the legume green manure crop clearly reduced nitrate concentrations in soil solution and the related risk of nitrate leaching. Both non-legume and legume + non-legume mixtures, nevertheless, were more efficient in this respect. Dersch and Hösch (2001) likewise found no difference in nitrate concentrations in soil solution and nitrate leaching between non-legume catch crops and legume + non-legume mixtures. In accordance with our results, both legume (clover) and non-legume (ryegrass) catch crops reduced nitrate losses significantly in the study of Askegaard and Eriksen (2008), with ryegrass being more effective than clover. The reduction of nitrate concentrations in the subsoil correlates to the deep root system of both legumes and crucifers (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004) in our catch crop treatments. Thorup-Kristensen (2006b) recommends using deep-rooted crucifer catch crops such as fodder radish and white cabbage to lift the deep N_{in} up to layers where following crops can access it.

3.4. Development, yield, N content and N utilisation of the main crops

Potato development was strongly depressed due to very dry weather conditions and a heavy impact of Colorado Beetle despite repeated application of *Bacillus thuringiensis* during the 2003 vegetation period. This masked any effect of the preceding green manure crops (Tab. IV). The additional amount of N conserved by the green manure crops compared with bare fallow was not used or converted into yield by this first following crop. Also, the second following crop, winter rye, did not clearly benefit, despite somewhat increased yield and N contents in the variants with preceding green manure crops (Tab. IV). The increased grain DM and grain N yield of spring barley following the second legume green manure crop grown in 2004 – compared with bare fallow (+0.6 Mg DM ha^{-1}, +12 kg N ha^{-1}) and with the non-legume green manure crop (+0.6 Mg DM ha^{-1}, +17 kg N ha^{-1}) – are more probably a cumulative effect of the two catch crops grown in 2002 and 2004 than solely of the preceding poorly developed catch crop.

Catch crops may increase the yield and N uptake of following crops, mainly due to N conservation in plant biomass and N transfer in the next spring (Stute and Posner, 1995; Hansen et al., 2000; Helander, 2004). Catch crops, mainly non-legumes, may also have no effect or even depress crop yield and N uptake of a following crop by incorporating large amounts of residues with a low N content (Francis et al., 1998), or because of their water consumption, particularly when water is limited (Ranells and Wagger, 1997). Green manure crops distinctly affected soil nitrogen dynamics in our study, mainly in 2002/03 (Tab. III, Figs. 2, 3), whereas their effects on soil water content and weeds were small and within the natural variability. We therefore assumed positive effects on following crops.

Dachler and Köchl (1994) found less pronounced catch crop effects on a subsequent spring wheat crop for stubble-sown crops than for underseeds. In that study, yield increases generally were more pronounced at a moist (836 mm; 8.5 °C)

Table V. Utilisation by following crops of N fixed by the green manure legumes.

Treatment variant	Potato, 2003		Winter rye, 2004		Spring barley, 2005		Total 2003–2005	
	Increased N uptake (kg N ha^{-1})	% of BNF in 2002	Increased N uptake (kg N ha^{-1})	% of BNF in 2002	Increased N uptake (kg N ha^{-1})	% of BNF in 2004	Increased N uptake (kg N ha^{-1})	% of BNF in 2002 + 2004
L + NL	– 1a	0	12a	25	1a	17	12a	22
L	6a	18	13a	38	12b	92	31a	66
NL	0a	–	28a	-	– 5a	–	23a	–
BF	–	–	–	–	–	–	–	–

Legend: see Table I; BNF: Biological N fixation by the legumes in the green manure crop (see Table II). Mean values in one column with the same letter do not differ significantly ($P < 0.05$).

versus dry site (500 mm; 9.1 °C), resembling the conditions in our experiment. These results generally agree with the minimal effects of stubble-sown catch crops we found under dry site conditions.

Several studies also indicate a decreasing pre-crop effect on the yield of following crops and on cereal protein contents in the order legume > legume + non-legume > non-legume green manure crops (Dachler and Köchl, 1994; Clark et al., 1997a, b; Germeier, 1997; Dersch and Hösch, 2001; Askegaard and Eriksen, 2007).

Thorup-Kristensen (2006a) estimated the pre-crop effect of legume green manures compared with bare fallow by relating the increased N uptake by the subsequent crops to the amount of N fixed by the legumes. The vegetable crops following non-winter hardy legumes increased their N uptake by 9–23 kg N ha^{-1}. This was equivalent to 14–32% of the amount of N fixed by the legumes. Based on this method, a total of 22–66% of the biological nitrogen fixation by the two green manure crops in our study was estimated to be used by the subsequent potato, winter rye and spring barley crops (Tab. V). The total N uptake by the potato, winter rye and spring barley crops was increased by 12 and 31 kg N ha^{-1} in legume + non-legume and legume, respectively (Tab. V). As already noted by Thorup-Kristensen (2006a), however, it is inappropriate to attribute the entire increased N uptake to the N gain by biological nitrogen fixation. Namely, the non-legume crop also increased subsequent N uptake in our study (Tab. V) by reducing N leaching losses. The legume catch crop may also have enhanced the N mineralisation from soil organic matter in April 2005, as mentioned above. Therefore, the increased N uptake by the crops following legume green manures is the combined result of the N gain by biological nitrogen fixation, reduced N leaching losses, and a presumably enhanced N mineralisation from soil organic matter.

The legume + non-legume mixture can be expected to catch up with the legume green manure crop after repeating them several times, because more N is contained in the legume + non-legume crop biomass due to an enhanced biological nitrogen fixation (Tab. II). This N will presumably be mineralised and contribute to N uptake and subsequent long-term yields. The optimal approach to combining the positive effects of N supply and N conservation in the soil may be to grow mixtures of legumes and non-legumes, a strategy also put forward by Wagger et al. (1998).

4. CONCLUSION

Under moderately dry weather conditions, the composition of the green manure catch crop affected biomass and N yield of the following crop, whereas N yield was poor irrespective of crop composition under more severe drought. We found no adverse catch crop effects on following crops due to their water consumption. From an agro-ecological viewpoint, the use of all the tested green manure crops can be recommended in organic farming even under Pannonian site conditions: they cover the soil, reduce nitrate leaching and erosion, and deliver residues that can improve soil biological activity and increase nitrogen availability to following crops. Valuating green manure catch crops in organic farming calls for considering their below-ground N content; for legume crops, the N derived from the air and N uptake from the soil need to be differentiated. The legume green manure crops had the most beneficial effect on following crops. This was apparently due to their higher biomass N content and a lower C-to-N ratio versus green manure crops containing non-legumes. The result was enhanced in situ N mineralisation. The legume + non-legume mixture, in contrast, produced more crop biomass and accumulated more total plant N. It also more efficiently reduced the risk of nitrate leaching by boosting both N uptake from the soil and biological N fixation.

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