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Evaluation of grain legume cropping systems for animal fodder potential and impacts on subsequent wheat yield under less favourable soil conditions in organic agriculture in Luxembourg

Untersuchungen von Körnerleguminosen-Anbausystemen als proteinreiches Futtermittel und deren Einfluss auf den nachfolgenden Weizenertrag unter ungünstigen Bodenbedingungen im ökologischen Landbau in Luxemburg

Abstract

Grain legumes are important crops required for protein-rich animal fodder. The aim of this study was to (i) examine the suitability of grain legume cropping systems for cultivation as protein-rich fodder, (ii) compare the performance of winter and spring types of faba beans and peas, as well as to compare the performance of peas sown in pure stand and in mixture with cereals, and (iii) determine the impact of previous legume crop on succeeding wheat under less favorable soil conditions in organic agriculture. In a field trial on a commercial farm in Luxembourg, eight grain legume cropping systems (as given under ii plus soybean and blue lupin) and a non-nitrogen fixing control crop (triticale) were cultivated followed by wheat in two consecutive seasons, employing a randomized complete block design with four replicates. All cropping systems except for winter pea in pure stand, were suitable for cultivation as protein-rich fodder even under less favourable soil conditions. Given sufficient soil moisture, faba beans constituted the best choice (protein yield: 961–1193 kg ha^{-1}). Semi-leafless peas reached a significantly better yield when sown in pure stand ($p \leq 0.05$; 3539–4154 kg ha^{-1}) compared with the mixture (2920–3852 kg ha^{-1}), whereas full-leaf types should be cultivated with a cereal partner. Winter vs. spring faba beans did not perform significantly different while for peas, the spring form performed best, likely again depending on leaf type rather than sowing time. The lower previous crop value of mono-cropped cereals (yield first experimental sequence: 2056 kg ha^{-1}) compared with cereals in mixture with grain legumes was confirmed, with best performance of wheat succeeding spring pea in pure stand (first experimental sequence, yield: 3661 kg ha^{-1}). Grain legumes in pure stand exhibited a higher previous crop value than winter triticale or grain legumes grown in mixture. In conclusion, grain legumes were promising candidates for generating protein-rich feedingstuffs, even under less favorable soil conditions in organic agriculture in Luxembourg.

Key words: Grain legume, previous crop, unfavorable soil conditions, organic agriculture, LegoLux, Cobra

Zusammenfassung

Körnerleguminosen sind wichtige Kulturen für die Bereitstellung von Protein in der Tierernährung. Ziel dieser Studie war es: (i) die Eignung verschiedener Körnerlegu-

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minosen-Anbausysteme für den Anbau als proteinreiches Futtermittel zu prüfen, (ii) der Vergleich von Sommer- und Winterform von Ackerbohnen und Erbsen, sowie der Erbse in Reinsaat und im Gemenge mit Getreide, und (iii) der Vergleich des Einflusses der Leguminosen als Vorfrüchte auf den nachfolgenden Weizen unter ungünstigen Bodenbedingungen im ökologischen Landbau. In einem Feldversuch auf einem kommerziellen landwirtschaftlichen Betrieb in Luxemburg, wurden acht Körnerleguminosen-Anbausysteme (wie in ii beschrieben plus Sojabohne und Blaue Lupine) und eine nicht Stickstoff fixierende Kontroll-Kultur (Triticale) in zwei aufeinanderfolgenden Jahren, in einem vollständig randomisierten Blockdesign mit vier Wiederholungen, angebaut. Als Folgekultur wurde Weizen angebaut. Alle Anbausysteme, mit Ausnahme der Winter-Erbse in Reinsaat, waren für den Anbau als proteinreiches Futtermittel geeignet. Bei ausreichender Bodenfeuchte stellte die Ackerbohne die beste Wahl dar (Proteinertrag: 961–1193 kg ha^{-1}). Halbblattlose Erbsen erzielten einen signifikant höheren Ertrag in Reinsaat ($p \leq 0.05$; 3539–4154 kg ha^{-1}) als im Gemenge mit Getreide (2920–3852 kg ha^{-1}), wobei Vollblatt-Typen im Gemenge mit Getreide angebaut werden sollten. Es wurden keine signifikante Unterschiede festgestellt zwischen Winter- und Sommer-Ackerbohnen, dagegen schnitt die Sommerung bei den Erbsen besser ab, dies war wahrscheinlich eher abhängig vom Blatt-Typ als vom Saatzeitpunkt. Der niedrigere Vorfruchtwert von Getreide-Monokultur (Ertrag Jahr 1: 2056 kg ha^{-1}) im Vergleich zu Getreide mit Körnerleguminosen in der Fruchtfolge wurde bestätigt, wobei der Weizen am besten nach Sommer-Erbse in Reinsaat abschnitt (Ertrag Jahr 1: 3661 kg ha^{-1}). Körnerleguminosen-Reinsaaten erzielten einen höheren Vorfruchtwert, als Winter-Triticale oder Körnerleguminosen im Gemenge mit Getreide. Körnerleguminosen sind demnach vielversprechende Kulturen für die Bereitstellung proteinreicher Futtermittel auch unter ungünstigen Bodenbedingungen im ökologischen Landbau in Luxemburg.

Stichwörter: Körnerleguminose, Vorfrucht, ungünstige Bodenbedingungen, ökologische Landwirtschaft, Legolux, Cobra

1 Introduction

Grain legumes are important crop plants needed in animal husbandry to cover dietary protein requirements. In the European Union (EU), the cultivation of protein crop plants has strongly decreased over the last ten years, leading to a substantial protein deficiency today, resulting in reliance on imports (Beste and Boeddinghaus, 2011). However, at present, through the greening instrument of the Common Agriculture Policy (CAP) from 2015, many European countries are again promoting the cultivation of legumes (European Commission, 2015).

Farmers in Central Europe, especially in such countries as Luxembourg, with soils that are classed as Less Favoured Areas (LFA) by the European Commission, do not always have the possibility to cultivate their grain legumes on the best site with the optimum soil conditions for their specific species. The farmers will nevertheless cultivate grain legumes, even on less favorable soils, to produce protein feed on their own farm and to benefit from the high previous crop value of these crops and/or to fulfil the requirements of the greening program. In most studies, the performance of grain legumes has been analyzed on research farms under good soil conditions for the specific grain legume species and on separate sites for different species (Jensen et al., 2010; Köpke and Nemecek, 2010; Urbatzka et al., 2011). Few studies have compared different grain legume cultivation systems in a single location, on a commercial farm under less favourable soil conditions, to show the cultivation limits of these crops. Furthermore, to the best of the authors' knowledge there exist no studies comparing the impact of previous crop common grain legume cropping systems on succeeding wheat on the same site with less favourable soils in organic agriculture.

Therefore, the aim of this study was to (i) test the suitability of frequently used grain legumes in different cropping systems for cultivation as protein-rich animal fodder, (ii) compare the performance of winter and spring forms of faba beans and peas, as well as to compare the performance of peas sown in pure stand and in mixture with cereals, and (iii) determine the impact of previous crop legume crop on succeeding wheat when growing under less favourable soil conditions in organic agriculture in Central Europe.

2 Materials and Methods

2.1 Site description

The experiment was conducted at the "Karelshaff" in Colmar-Berg Luxembourg (49°49'44,7" N, 6°03'42,4" E). The farm was converted to organic farming between 2000 and 2002 and is a certified member of the organic farming association "Bio-Lëtzebuerg – Vereenegung fir Bio-Landwirtschaft Lëtzebuerg a.s.b.l." The site is located at 353 m above sea level. Mean annual precipitation was 770 mm and mean annual temperature 10°C (30-years mean). Soil type was a loam according to the World Reference Base (WRB) classification system. Soils had a high stone fraction and consequently, a low water holding capacity, so they warmed up quickly.

2.2 Trial description

The field trial was comprised of two steps and was established in two consecutive seasons, starting in October 2011 at the field "Schäfferei 1", and October 2012 at the field "Schäfferei 2", respectively. The two fields were located next to each other. The experiment was integrated into the usual rotation system of the farm. Previous crops were the same in both experimental years: grass-clover mixture – grass-clover mixture– winter wheat – winter triticale – oat – spelt – winter wheat.

In a first step, eight different grain legume cropping systems and a non-nitrogen fixing control crop were cultivated as previous crops (PC) (Table 1): winter and spring peas in pure stand and in mixture with cereals, winter and spring faba beans, soybean, blue lupin and triticale (control) were tested in a randomized complete block design with four replicates and a plot size of 15 m^2 (1.5 × 10 m). Borders of 15 m^2 were established on either side of each trial plot to avoid border effects. In the borders the same crop was sown than in the main plot and management was also the same than in the main plot. For each grain legume cropping system, sowing density was chosen according to official recommendations (Table 1). Distance between rows was 25 cm for crops in pure stand and 13.8 cm for crops in mixture and for triticale. Soybean and blue lupin were inoculated with their specific *Bradyrhizobia*. Weed control was performed by hand-weeding and with a mechanical hoe (only in plots sown with 25 cm distance between rows).

After harvesting the previous crops, plots were marked and later plowed. Afterwards, winter wheat (variety: Achat, sowing density: 350 germinable kernels m^{-2}, distance between rows: 13.8 cm) was sown in the plots of the different grain legume cropping systems, to test the impact of the previous crop (seasons in 2012/13 and 2013/14, respectively).

Hence, an experimental sequence consisted of a grain legume cropping system (previous crop) and a winter wheat crop, which were sown in two consecutive seasons (2011/12 – 2012/13 and 2012/13 – 2013/14). In Table 2, the management of the field trial and the nutrient soil status are summarized.

2.3 Measurements of previous crops

Survival rate of winter types (Urbatzka et al., 2011), diseases and pests and lodging at harvest were assessed according to the guidelines of the Federal Plant Variety Office (Bundessortenamt, 2000). At physiological maturity, plants were harvested by a plot combine. Yield (kg ha^{-1} at 100% dry matter (DM)) was determined at final harvest. Protein content of grains (g kg^{-1}) was measured according to Kjeldahl at the Laboratory of the "Administration des Service Techniques de l'Agriculture (ASTA) Luxembourg", and carbon – nitrogen ratio of straw (C:N straw) was determined according to Dumas. Protein yield (kg ha^{-1}) was calculated. Soil mineral nitrogen content (kg nitrate-N ha^{-1}) at 0 to 30 cm soil depth was measured by the ASTA Laboratory shortly after harvest of the grain legumes (Nmin1), according to Schalvo (Kuzyakov et al., 1997).

2.4 Measurements of winter wheat

Tillers m^{-2}, plant density (ears m^{-2}), plant length at harvest (cm) and lodging at harvest were assessed according to the guidelines of the Federal Plant Variety Office (Bundessortenamt, 2000). At flowering, content of nitrogen in leaves of winter wheat was measured by a Yara-N tester (YARA GmbH & Co. KG, Germany). At physiological maturity, winter wheat was harvested with a plot combine. Yield (kg ha^{-1} at 100% DM) and thousand kernel weight (TKW) (g) were determined at final harvest. Protein content (g kg^{-1}) of grains was determined according to Kjehldahl at ASTA Laboratory, and protein yield (kg ha^{-1}) was calculated. Soil mineral nitrogen content (kg nitrate-N ha^{-1}) at 0–30 cm soil depth was measured, according to Schalvo (Kuzyakov et al., 1997), by the ASTA Laboratory in spring at the start of the vegetation period (April 2013 and May 2014, respectively) (Nmin2) and shortly after harvest (Nmin3).

2.5 Statistical analysis

Analysis of variance, standard errors and estimation of least square means were performed using the MIXED procedure of the software package SAS 9.2 (SAS Institute 2002–2008). Pairwise comparisons were performed using the Tukey-test ($p \leq 0.05$). Normal distribution and homogeneity of variance were checked by diagnostic plots based on studentized residuals in SAS. The different response variables (Y) were analyzed according to the model Y = REP + PC, where REP stands for complete replicate and PC for previous crop. A p-value below 0.05 was considered statistically significant.

Table 1. Previous crops tested in the field trial in Colmar-Berg (Luxembourg)

Number	Culture	Variety	Phenology	Sowing density (kernels m^{-2})
1	Winter pea	E.F.B. 33	tall growing, colored flower	80
2	Winter pea in mixture with triticale	E.F.B. 33/Benetto	tall growing, colored flower	40/150
3	Winter faba bean	Husky	colored flower	35
4	Winter triticale	Benetto		350
5	Spring pea	Alvesta	short growing, white flower	80
6	Spring pea in mixture with barley	Alvesta/Eunova	short growing, white flower	80/100
7	Spring faba bean	Fuego	colored flower	35
8	Blue lupin	Boregine	branched genotype	100
9	Soybean	Merlin	maturity group 000	65

Table 2. Management of the field trial and soil nutrient status in Colmar-Berg (Luxembourg) and dates of respective treatments

	First experimental sequence		Second experimental sequence	
	2011/12 Previous crops	2012/13 Winter wheat	2012/13 Previous crops	2013/14 Winter wheat
Fertilizer				
Dolomac (1500 kg ha^{-1})	01.09.11	–	–	–
Tillage (plow)	05.09.11	15.10.12	22.10.13	30.10.13
Sowing date				
winter pea, winter pea in mixture, winter faba bean, triticale	03.10.11	–	24.10.12	–
spring pea, spring pea in mixture, spring faba bean, blue lupine	22.03.12	–	08.04.13	–
Soybean	14.05.12	–	27.05.13	–
Winter wheat	–	24.10.12	–	31.10.13
Plant protection				
Hand-weeding	27.03.12	–	28.06.13	–
Hand-weeding	16.04.12	–	–	–
Hand-weeding	03.05.12	–	–	–
Hand-weeding	23.05.12	–	–	–
Hand-weeding	08.06.12	–	–	–
Hand-weeding	04.07.12	–	–	–
Mechanical hoe	–	–	19.04.13	–
Mechanical hoe	–	–	03.05.13	–
Mechanical hoe	–	–	27.05.13	–
Mechanical hoe	–	–	01.07.13	–
Harvest				
Spring pea, spring pea in mixture	26.07.12	–	05.08.13	–
Winter pea, winter pea in mixture, triticale	13.08.12	–	05.08.13	–
Winter faba bean	13.08.12		10.08.13	–
Spring faba bean	23.08.12	–	21.08.13	–
Blue lupine	17.09.12	–	27.09.13	–
Soybean	11.10.12	–	09.10.13	–
Winter wheat	–	10.08.13	–	05.08.14
Soil nutrient status before sowing				
pH	5.4	–	5.8	–
K_2O (mg per 100 g soil)	16	–	13	–
P_2O (mg per 100 g soil)	13	–	12	–
Mg (mg per 100 g soil)	7	–	7	–
Na (mg per 100 g soil)	1	–	1	–
C_{org} (%)	1.1	–	1.3	–

In the tables, means significantly differing from each other are followed by different letter(s) at the 5% level of probability using the Tukey-test. For description of stochastic variability, the average of the standard error of differences between two means (*mean SED*) are shown.

For the data on protein yield and C:N ratio of straw on previous crops in both experimental sequences and for weeds at harvest of winter wheat in the second experimental sequence, a logarithmic transformation was used to conform to the ANOVA model's assumption of a normal distribution. Adjusted treatment means were transformed back for presentation of the data, representing median estimates on the original scale (Piepho, 2009).

Due to technical problems and predation damage in certain cropping systems in both experimental sequences, the authors decided not to analyze data over the two experimental sequences but to analyze each sequence separately.

3 Results

3.1 Previous crops

Grain yield, protein content, protein yield and C:N ratio of straw of the previous crop showed significant differences in both experimental sequences and Nmin1 in the second experimental sequence (Table 3).

In the first experimental sequence, grain yield was highest for spring faba bean and winter faba bean (Table 4). Grain yield was lowest for winter peas in pure stand and in mixture and for soybean, which can be explained by technical problems that occurred at harvest of winter peas, due to severe lodging of these crops. Consequently, many grains fell out and could not be harvested with the plot harvester, but remained on the field. For soybean, predation damage by hares was observed in the first leaf stage. In the second experimental sequence, the highest grain yield was reached by winter faba bean, spring pea in pure stand and spring pea in mixture. Grain yield was lowest for blue lupin. At flowering, severe predation

Table 3. P-values for F-tests of sources of variation (ANOVA) of the treatments effects for grain yield, protein content, protein yield, C:N ratio of straw and Nmin after harvest of previous crops in autumn (Nmin1), for the nine previous crops and two experimental sequences (2011/12 and 2012/13)

	2011/12	2012/13
Grain yield (kg ha^{-1} at 100% DM)	**< 0.0001**	**< 0.0001**
Protein content (g kg^{-1})	**< 0.0001**	**< 0.0001**
Protein yield (kg ha^{-1})	**< 0.0001**	**< 0.0001**
C:N ratio of straw	**< 0.0001**	**0.0003**
Nmin1 (after harvest) (kg nitrate-N ha^{-1})	0.3473	**0.0002**

P-values in bold represent significant effects at the 5% level.

Table 4. Means of grain yield, protein content, protein yield, C:N ratio in straw and Nmin after harvest of previous crops in autumn (Nmin1) in the first (2011/12) and second experimental sequence (2012/13), and average of the standard error of differences between two means (mean SED)

Crop	Grain yield (kg ha^{-1} at 100% DM)		Protein content (g kg^{-1})		Protein yield**** (kg ha^{-1})		C:N ratio straw****		Nmin1 (kg nitrate-N ha^{-1})	
	2011/12	2012/13	2011/12	2012/13	2011/12	2012/13	2011/12	2012/13	2011/12	2012/13
Winter pea*	289 d	2351 bc	274 c	254 d	95 d	584 b	/*****	/	12	38 a
Winter pea in mixture*	1106 dc	3220 ab	266 c	255 d	290 c	780 ab	/	/	11	30 bc
Winter faba bean	3675 a	4251 a	269 c	284 c	976 ab	1193 a	44.7 bc	58.1 b	10	30 bc
Winter triticale	1459 cd	1174 cd	93 e	96 f	134 c	111 d	100.9 a	145.1 a	7	30 bc
Spring pea	3539 ab	4154 a	231 d	224 e	802 ab	931 ab	25.0 e	58.8 b	10	30 bc
Spring pea in mixture	2920 ab	3852 a	223 d	225 e	650 ab	866 ab	30.7 de	62.3 b	13	28 bc
Spring faba bean	3877 a	3549 ab	278 c	272 c	1047 a	961 a	37.2 cd	61.4 b	11	34 ab
Blue lupin**	2089 bc	870 d	299 b	333 b	598 ab	285 c	56.8 b	39.7 b	12	29 bc
Soybean***	1450 cd	2319 bc	420 a	414 a	576 b	958 a	45.3 bc	78.7 ab	9	25 c
Mean SED******	*436.8*	*372.6*	*5.1*	*4.3*	–	–	–	–	–	*2.2*

Means followed by a common letter, within each column, are not significantly different at p ≤ 0.05 according to Tukey's test
* technical problems at harvest in 2011/12, ** predation damage in 2012/13, *** predation damage in 2011/12
**** log transformed data of protein yield and C:N ratio straw with SED are shown in Table 8.
***** representative samples could not be taken because of lodging of winter pea
****** For back-transformed means, there is no common SED

damage by hares was observed on blue lupins. As a consequence, most lupin plants developed only a single pod.

Protein content was significantly highest for soybean (420 and 414 g kg^{-1}) followed by blue lupin (299 and 333 g kg^{-1}), spring faba bean (278 and 272 g kg^{-1}) and winter faba bean (269 and 284 g kg^{-1}) in the two experimental sequences. Lowest protein content was measured for spring peas in pure stand and in mixture.

In the first experimental sequence, protein yield was significantly highest for spring faba bean and lowest for soybean and winter triticale. In the second experimental year, the highest protein yield was observed for winter and spring faba beans as well as soybean, which did not differ significantly from spring peas in pure stand and in mixture or winter pea in mixture. Winter triticale and blue lupin had the lowest protein yield. Overall, the differences between previous crops were less pronounced for their protein yield when compared with their protein content.

In the first experimental sequence, the highest C:N ratio in straw was determined for winter triticale, followed by blue lupin, soybean and winter faba bean. The lowest C:N ratios were found for spring peas in mixture and in pure stand. C:N ratio was significantly highest for winter triticale and soybean in the second experimental sequence.

Nmin1 did not show significant difference in the first experimental sequence but did so in the second experimental sequence (Table 3). The highest Nmin1 was measured for winter pea.

3.2 Winter wheat

In both experimental sequences, winter wheat showed significant effects of previous crops for thousand kernel weight, grain yield and protein yield (Table 5). In the second experimental sequence, tillers m^{-2}, plant density, kernels per ear, Yara N, plant length at harvest, weed biomass at harvest and protein content differed significantly. As these parameters did not show significant effects in the first experimental sequence, only means of the second experimental sequence are shown (Table 6).

In the first experimental sequence, the highest winter wheat grain yield was measured after spring pea, followed by winter wheat after blue lupin and after spring faba bean, which did not differ significantly from each other (Table 6). There was no significant difference between the grain yields of winter wheat after the remaining previous crops. The lowest yield was measured after winter triticale. In the second experimental sequence, grain yield of winter wheat after winter pea in mixture, spring pea in mixture and winter triticale were significantly lower than after the other previous crops.

Protein content of winter wheat did not differ significantly among treatments in the first experimental sequence. In the second experimental sequence, a significant difference in protein content of winter wheat was observed between winter wheat grown after winter pea in mixture (highest protein content) and winter wheat grown after soybean (lowest protein content).

In the first experimental sequence, protein yield of winter wheat was highest after spring pea, followed by blue lupin and spring faba bean. The other previous crops did not show a significant difference in protein yield of winter wheat. In the second experimental sequence, protein yield of winter wheat was lowest after winter triticale and both spring and winter pea in mixture.

According to the F-test (Table 5), thousand kernel weight (TKW) of winter wheat was significantly influenced by the previous crop in the first experimental

Table 5. P-values for F-tests of sources of variation (ANOVA) of the treatment effects for Nmin in spring (Nmin2), Nmin after harvest of winter wheat (Nmin3), tillers m^{-2}, Yara N, plant length at harvest, weed biomass at harvest, plant density, kernels per ear, thousand kernel weight (TKW), grain yield, protein content and protein yield for winter wheat, after nine different previous crops and two experimental sequences (2012/13 and 2013/14)

Variable	2012/13	2013/14
Nmin2 (spring) (kg nitrate-N ha^{-1})	0.0885	0.8166
Nmin3 (after harvest) (kg nitrate-N ha^{-1})	0.8471	0.3861
Tillers m^{-2}	0.1091	**0.0073**
Yara N	0.0574	**< 0.0001**
Plant length at harvest (cm)	0.0761	**< 0.0001**
Weed biomass at harvest (g m^{-2})	/*	**< 0.0001**
Plant density (ears m^{-2})	0.8133	**0.0003**
Kernels per ear	0.3344	**0.0377**
TKW (g)	**0.0385**	**< 0.0001**
Grain yield (kg ha^{-1} at 100% DM)	**0.0001**	**< 0.0001**
Protein content (g kg^{-1})	0.0578	**0.0157**
Protein yield (kg ha^{-1})	**< 0.0001**	**< 0.0001**

P-values in bold represent significant effects at the 5% level.
* Data not available

Table 6. Means of winter wheat grain yield, protein content, protein yield and thousand kernel weight (TKW) after different previous crops in first (2012/13) and second experimental sequence (2013/14), and average of the standard error of differences between two means (mean SED)

Previous crops	Grain yield (kg ha^{-1} at 100% DM)		Protein content (g kg^{-1})		Protein yield (kg ha^{-1})		TKW (g)	
	2012/13	2013/14	2012/13	2013/14	2012/13	2013/14	2012/13	2013/14
Winter pea	2629 bc	1857 a	110	104 ab	288 bc	192 a	47.0 a	46.1 a
Winter pea in mixture	2063 c	988 b	108	107 a	223 c	105 c	43.8 a	37.0 b
Winter faba bean	2700 bc	1768 a	111	100 ab	299 bc	176 ab	46.8 a	47.4 a
Winter triticale	2056 c	749 b	108	104 ab	221 c	76 d	45.1 a	36.2 b
Spring pea	3661 a	1782 a	110	102 ab	400 a	182 ab	46.9 a	46.8 a
Spring pea in mixture	2581 bc	894 b	109	103 ab	282 bc	92 cd	44.7 a	38.5 b
Spring faba bean	2763 abc	1855 a	113	102 ab	311 abc	189 ab	46.5 a	47.8 a
Blue lupin	3133 ab	1708 a	111	102 ab	347 ab	174 ab	46.6 a	46.5 a
Soybean	2292 bc	1692 a	111	98 b	254 bc	164 b	46.1 a	46.0 a
Mean SED	*276.1*	*74.7*	–	*2.1*	*29.4*	*8.0*	*1.0*	*1.5*

Means followed by a common letter within each column are not significantly different at $p \leq 0.05$ by Tukey's test.

sequence ($p = 0.0385$), but pairwise comparisons by the Tukey-test were not significant (Table 6). In the second experimental sequence TKW was significantly lower after winter pea in mixture, spring pea in mixture and winter triticale.

In the second experimental sequence, a significant difference in tillers m^{-2} of winter wheat was observed between winter wheat following winter pea or spring faba bean (highest number of tillers m^{-2}) and winter wheat following winter pea in mixture (lowest number of tillers m^{-2}; Table 7). Yara N of winter wheat was significantly lowest for winter triticale, winter pea in mixture and spring pea in mixture. In this second experimental year, wheat was affected by *Puccinia striiformis* and black head molds.

Table 7. Means of winter wheat tillers m^{-2}, plant density, kernels per ear, Yara N, plant length at harvest and weed biomass at harvest after different previous crops in the second experimental sequence (2013/14), and average of the standard error of differences between two means (mean SED)

Previous crop	Tillers m^{-2}	Yara N	Plant density (ears m^{-2})	Kernels per ear	Plant length at harvest (cm)	Weed biomass at harvest* (g m^{-2})
Winter pea	358.1 a	525 a	209.6 ab	22.5 a	72 a	42.3 bc
Winter pea in mixture	279.0 b	436 bc	156.0 abc	18.5 ab	57 bcd	65.3 ab
Winter faba bean	351.5 ab	482 ab	207.2 ab	18.1 ab	62 abc	32.4 c
Winter triticale	295.9 ab	388 c	132.7 bc	14.0 b	53 cd	95.2 a
Spring pea	344.8 ab	484 ab	216.7 ab	17.8 ab	64 abc	26.9 c
Spring pea in mixture	329.1 ab	447 bc	100.6 c	15.2 b	47 d	78.4 ab
Spring faba bean	370.2 a	487 ab	225.0 a	18.6 ab	65 abc	40.6 bc
Blue lupin	327.3 ab	482 ab	198.2 ab	19.1 ab	68 ab	39.7 bc
Soybean	354.5 ab	461 b	223.8 a	18.2 ab	65 abc	26.2 c
Mean SED	*22.6*	*20.3*	*26.2*	*2.1*	*4.0*	–

Means followed by a common letter within each column are not significantly different at $p \leq 0.05$ by Tukey's test.
* log transformed data of weed at harvest with SED are shown in Table 9.

These diseases were much more pronounced when the previous crops were peas grown in mixture with cereals or winter triticale. Furthermore, plant length and density of wheat at harvest were significantly lower for the same previous crops (Table 7). Additionally, weed biomass at harvest was highest for these three previous crops. The number of kernels per ear was lowest for winter triticale and spring pea in mixture.

4 Discussion

4.1 Suitability of previous crops as protein-rich animal fodder

In order to determine the suitability of common grain legume cropping systems as protein-rich animal fodder under less favourable soil conditions in Central Europe, protein yield is an important parameter. On average, not considering the cropping systems where problems at harvest or predation damage occurred, grain legume cropping systems exhibited an average protein yield of 84% (first experimental sequence) and 88% (second experimental sequence), respectively, higher than the protein yield of the control crop winter triticale. For the production of protein-rich fodder on farm, the best grain legume cropping systems were winter and spring faba beans for both experimental sequences because of their high protein content. However, it is important to note that in both experimental sequences, weather conditions were very favourable for faba beans (Fig. 1 and Fig. 2*)* because soil moisture and water supply were always sufficient for this water-demanding crop growing on the low water holding capacity soils of the experimental site. In the second experimental sequence, soybean proved also to be suitable for cultivation as protein-rich fodder. Protein content of soybean (414 g kg^{-1}) was above the average reported in that season in comparable climate regions in Germany, but yield (2319 kg ha^{-1}) was below the average (Wilbois et al., 2014). For the production of grains for sale, yield is the decisive parameter. For this purpose, not only were winter and spring faba beans suitable in both experimental years, but so were spring peas in pure stand and in mixture.

4.2 Comparison of winter and spring faba beans and peas, and of peas sown in pure stand and in mixture

In this study, protein yield of winter peas in mixture tended to be higher than in pure stand. As their protein content was at the same level, the difference can be explained by a difference in grain yield. Sowing density of winter peas in mixture was half of that in pure stand, but yield was lower in pure stand. This difference in grain yield can be explained by the severe lodging in the winter pea in pure stand, due to the pea type (full leaf type) and the lack of a supporting crop (Urbatzka et al., 2011). For spring peas, it was the pure stand that had higher yield and comparable protein contents than the mixture. Spring peas in pure stand and in mixture were sown at the same sowing density. Here, the difference in yield can be attributed to the domination of the cereal partner in the mixture (Urbatzka et al., 2011). As the spring pea was a semi-leafless type, no supporting crop was needed to prevent lodging, and the cereal partner was only competing for nutrients, light and water. These data indicate that the leaf type of the pea is the most important factor when deciding whether to grow peas in mixture or in pure stand. Shorter, semi-leafless types do not benefit from a cereal partner and are best grown in pure stand for protein-rich animal fodder.

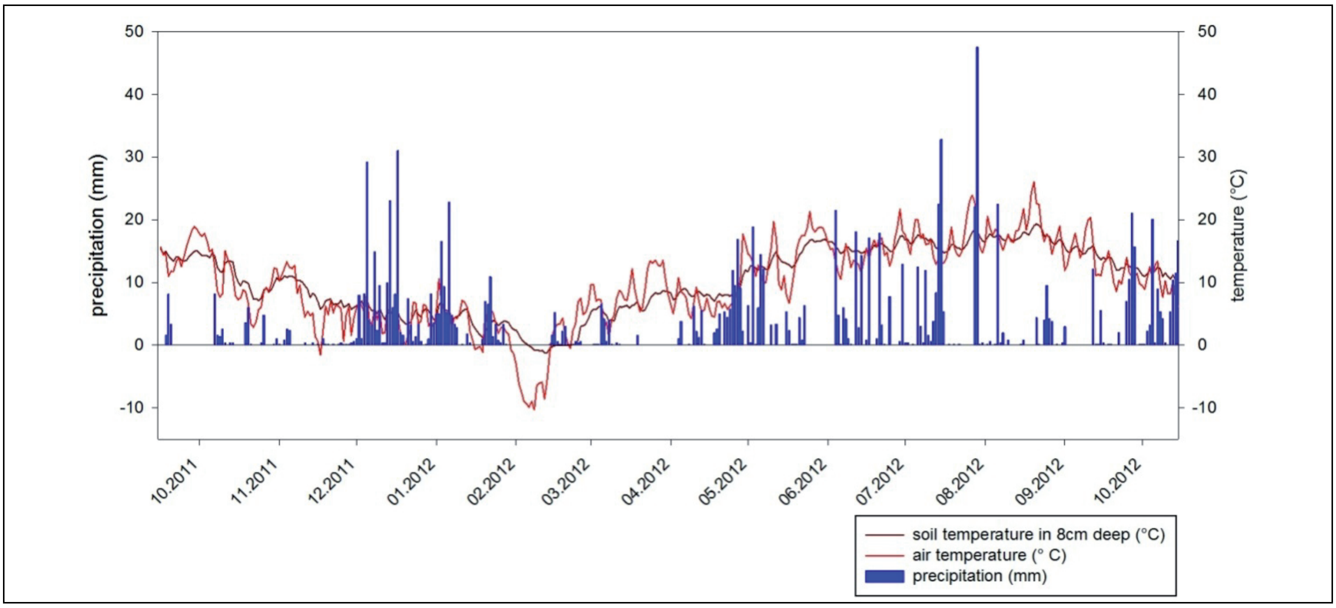

Fig. 1. Precipitation, air temperature and soil temperature at 8 cm depth in the vegetation period 2011/12 at the experimental site Karelshaff, Luxemburg (coordinates: 49°49'44,7" N, 6°03'42,4" E).

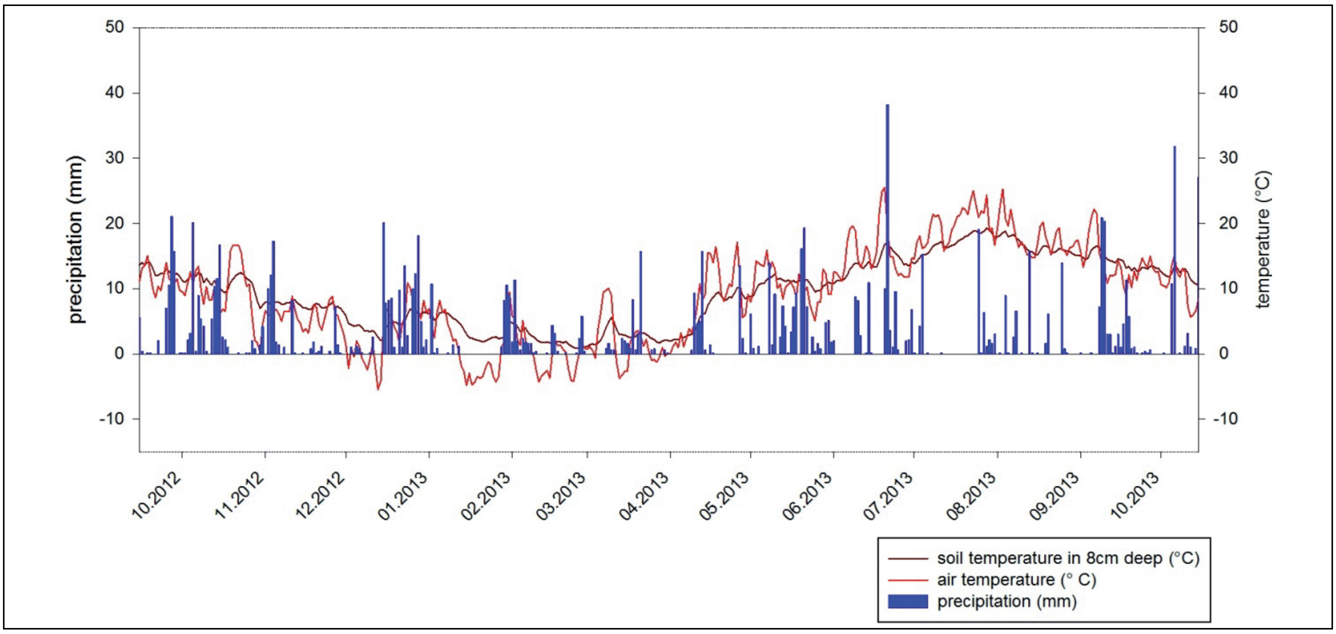

Fig. 2. Precipitation, air temperature and soil temperature at 8 cm depth in the vegetation period 2012/13 at the experimental site Karelshaff, Luxemburg (coordinates: 49°49'44,7" N, 6°03'42,4" E).

Table 8. Means (log transformed data) of previous crops' protein content and C:N ratio in straw in the first (2011/12) and second experimental sequence (2012/13), and average of the standard error of differences between two means (mean SED)

	Protein yield* (kg ha-1)		C:N ratio straw*	
	2011/12	2012/13	2011/12	2012/13
Winter pea	4.55 d	6.37 b	–	–
Winter pea in mixture**	5.67 c	6.66 ab	–	–
Winter faba bean	6.89 ab	7.08 a	3.80 bc	4.06 b
Winter triticale	4.90 c	4.71 d	4.61 a	4.98 a
Spring pea	6.69 ab	6.84 ab	3.22 e	4.07 b
Spring pea in mixture	6.48 ab	6.77 ab	3.62 de	4.13 b
Spring faba bean	6.95 a	6.87 a	4.04 cd	4.12 b
Blue lupin***	6.39 ab	5.65 c	3.81 b	3.68 b
Soybean****	6.36 b	6.87 a	3.80 bc	4.37 ab
Mean SED	*0.18*	*0.14*	*0.11*	*0.23*

Means followed by the same letter(s) within each column are not significantly different at $p \leq 0.05$
* means of log transformed data, ** technical problems at harvest in 2011/12, *** predation damage in 2012/13, **** predation damage in 2011/12

Yields of spring peas (pure stand and in mixture) tended to be higher than yields of winter peas, which contradicts findings by Urbatzka et al. (2011). These researchers also reported that the sensitivity to environmental conditions of spring peas is higher compared with winter peas. As weather conditions (Fig. 1 and Fig. 2) were favourable in both experimental sequences, which positively influenced soil moisture, there was little or no environmental stress and spring peas could perform well. Urbatzka et al. (2011) reported comparable protein content for winter and spring peas, whereas in the present study, protein content of winter peas (mixture and pure stand) was higher than spring peas in both experimental sequences. There was no clear trend visible for performance of winter

Table 9. Means (log transformed data) of winter wheat weed biomass yields at harvest after different previous crops in the second experimental sequence (2013/14), and average of the standard error of differences between two means (mean SED)

	Weed biomass yields at harvest* ($g\ m^{-2}$)
Winter pea	3.78 bc
Winter pea in mixture*	4.18 ab
Winter faba bean	3.48 c
Winter triticale	4.56 a
Spring pea	3.29 c
Spring pea in mixture	4.36 ab
Spring faba bean	3.70 bc
Blue lupin**	3.68 bc
Soybean***	3.27 c
Mean SED	*0.20*

Means followed by the same letter(s) within each column are not significantly different at $p \leq 0.05$
* means of log transformed data

and spring faba beans. The slightly better performance of winter faba bean in the second experimental sequence could be explained by the milder winter in that season and the resulting higher winter survival rate (99%) compared with the first experimental sequence (75%) (Fig. 1 and Fig. 2).

4.3 Previous crop impact on wheat

In both experimental sequences, winter wheat succeeding the non-legume winter triticale showed the lowest yield, which is in line with the findings of Chalk (1998), who reported lower previous crop values of monocropped cereals compared with cereals in rotations with grain legumes.

In the first experimental sequence, spring pea in pure stand clearly had the highest previous crop value. C:N ratio in the straw of spring pea in pure stand was significantly lowest and hence, immobilization of N during decomposition of the residues was low compared with the remaining cropping systems. Nevertheless, yield forming parameters of winter wheat such as tillering, plant density, Yara N, plant length at harvest and TKW, mainly influenced by N supply (Geisler, 1983), did not differ in the first experimental sequence. Impacts on soil structure and nutrient and water availability could have resulted in the observed differences in wheat yields. For example, peas use less water than other crops. Merrill et al. (2007) and Miller et al. (2002) reported a carry-over of available soil water following legumes as an important factor contributing to higher yields by the following wheat crops. The good performance of wheat succeeding blue lupin may also be explained by an increase of the access to water resources for wheat due to the tap-root penetration of lupin loosening the soil structure in deeper layers.

In the second experimental sequence, grain legumes in pure stand had a significantly higher previous crop value regarding wheat yield compared with grain legumes in mixtures and winter triticale. Neither C:N ratio in straw of the previous crops nor Nmin content after harvest of the previous crops explained the differences in wheat yield. Yield forming parameters such as tillering, plant density, Yara N, plant length at harvest and TKW are influenced by the N supply (Geisler, 1983) and were significantly lower for these three previous crops. Furthermore, weed biomass at harvest was higher for these three previous crops. Thus, the lower yields of winter wheat after winter triticale, winter pea in mixture and spring pea in mixture could be explained by a different mineralization of residues of these previous crops, and a resulting lower nitrogen supply compared with the other previous crops. Furthermore, the higher infestation rate of black head molds and *Puccinia striiformis* of winter wheat following these three crops may have been due to weakened plants caused by the lower nitrogen supply.

5 Conclusions

Overall, it was shown that with the exception of winter pea in pure stand, all tested grain legume cropping systems are suitable for cultivation as protein-rich animal fodder, even given poor soil conditions. When sufficient soil moisture is present, faba beans were shown to be most suitable for organic cultivation as protein-rich animal fodder on less favourable soil.

It was also observed that when deciding to cultivate peas in pure stand or not, it is important to consider the leaf type of the pea. Semi-leafless peas that can support themselves and are not prone to lodging reach a better yield when sown in pure stand, whereas full-leaf types should be cultivated with a cereal partner, as they need a supporting crop to achieve good yields. For the decision on whether to cultivate a winter or spring form of pea, it remains unclear whether the better performance of the spring form was due to the sowing time or the leaf type; here, further studies are necessary. For the tested winter pea variety, winter-kill is not a high risk, but it may be for the winter faba bean variety tested. Hence, the cultivation of the spring type should be preferred, at least until new winter hart varieties are available.

The reduced yields of mono-cropped cereals compared with cereals in rotation with grain legumes were confirmed. In the first experimental sequence, non-nitrogen related beneficial effects of grain legumes prevailed, with wheat succeeding spring pea in pure stand performing best. In the second experimental year, with the infestation of *Puccinia striiformis*, grain legumes grown in pure stand showed a higher previous crop value due to a difference in mineralization of residues and, consequently, a higher nitrogen supply compared with winter triticale or grain legumes grown in mixture with a cereal partner.

In summary, growing legume grain crops is a promising option for generating protein fodder, even under less favourable soil conditions in organic agriculture in Luxembourg.

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