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Agronomic Effects of Underseeding Ribwort Plantain (*Plantago lanceolata* L.) in Organically Grown Potatoes

Pflanzenbauliche Auswirkungen einer Untersaat mit Spitzwegerich (*Plantago lanceolata* L.) in ökologisch angebauten Kartoffeln

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Summary

In a two year field experiment at Göttingen (Germany) organically grown potatoes were undersown with *Plantago lanceolata* L. (ribwort plantain) 44 (2002) and 21 (2004) days after potato planting. In the plots which were undersown, U(+), the weeds were suppressed by 59% (2002) and 70% (2004) compared to the plots without underseeding, U(-). Potato yield was only slightly affected by underseeding. However, in the undersown plots the portion of undersized tubers was increased by 15% in 2002 and 11% in 2004. At potato tuber harvest the average mineral soil N quantities (N_{min} = NO_3-N + NH_4-N) from the ridge and furrow zone (0-120 cm soil depth) were 62.4 kg N ha^{-1} in 2002 and 40.1 kg N ha^{-1} in 2004 in the U(-) plots vs. 44.6 kg N ha^{-1} (2002) and 12.5 kg N ha^{-1} (2004) in the U(+) plots. At the last sampling date in late autumn the reduction of the N_{min} quantities in the U(+) plots was 52% (2002) and 56% (2004). At the end of September 2004 the maximum total root length ranged between 2.21 km m^{-2} in U(-) and 6.37 km m^{-2} in U(+).

Key words: potatoes, underseeding, *Plantago lanceolata*, mineral soil N, weed suppression

Zusammenfassung

In zweijährigen Feldversuchen bei Göttingen wurden ökologisch angebaute Kartoffeln 44 (2002) bzw. 21 (2004) Tage nach dem Pflanzen mit *Plantago lanceolata* L. (Spitzwegerich) untergesät. In den untergesäten Parzellen (U+) wurden die Unkräuter zu 59% (2002) bzw. 70% (2004) zurückgedrängt, verglichen mit den Parzellen ohne Untersaat (U-). Die Kartoffelerträge wurden durch die Untersaat nur unwesentlich beeinflusst. Allerdings war der Anteil an Untergrößen an den geernteten Knollen in den untergesäten Parzellen um 15% (2002) bzw. 11% (2004) größer. In 0-120 cm Bodentiefe betrugen zur Kartoffelernte die N_{min}-Werte (NO_3-N + NH_4-N) im Mittel der Damm- und Furchenbereiche 62,4 kg N ha^{-1} im Jahr 2002 und 40,1 kg N ha^{-1} im Jahr 2004 in U(-) sowie 44,6 kg N ha^{-1} (2002) und 12,5 kg N ha^{-1} (2004) in U(+). Zum letzten Probenahmetermin im Spätherbst waren die N_{min}-Werte in den U(+)-Parzellen um 52% (2002) bzw. 56% (2004) reduziert. Ende September 2004 betrug die maximale Wurzellänge im Boden 2,21 km m^{-2} in U(-) und 6,37 km m^{-2} in U(+).

Schlüsselworte: Kartoffeln, Untersaat, *Plantago lanceolata*, N_{min}, Unkrautunterdrückung

Introduction

Potatoes (*Solanum tuberosum* L.) rank among those field crops which often leave substantial mineral soil N (N_{min}) residues after harvest (Goulding et al. 2000, Honisch et al. 2002, Webb et al. 2004). Remaining quantities of N_{min} after the potato harvest can mount to more than 100 kg N ha^{-1} (Vos & van Putten 2000). High N_{min} residues are associated with the hazard of the displacement of nitrate down to greater soil depths and to groundwater. It is widely accepted that organic farming contributes to the reduction of N-leakage potential of soils (Honisch et al. 2002). However, in individual cases organic potato growing as well as integrated management of potatoes may result in large N_{min} residues in the soil, e.g. when potatoes are cultivated after clover or alfalfa (Kainz et al. 1997, Zihlmann et al. 2004).

Little research work has been done so far to study to what extent surplus N_{min} residues in the soil can be retained by underseeding potato plants with catch crops (Kainz et al. 1997, Haas 2002). In these cases the undersown species were mainly annuals and the effect of the N_{min} reduction did not persist for longer periods.

The main objective of the present field experiment was to test *Plantago lanceolata* L. (ribwort plantain) as a catch crop sown under organically grown potatoes. *P. lanceolata* was chosen because it is known to show a very dense and deep root system associated with a considerable N uptake and N_{min} reduction in the soil profile (Reiter 2001). *P. lanceolata* is also a perennial rosette plant. From this feature it was expected that *P. lanceolata*, even with ample growth, will only compete moderately with the potato crop. Because of its perennial habit it was supposed that *P. lanceolata* would continue to grow after the potato harvest. Altogether, *P. lanceolata* could be classified as a promising candidate for undersowing in a potato stand. This should be true particularly if subsequent to the potato harvest no further tillage will be carried out which would cause an objectionable extra N mineralisation.

Underseeding catch crops has additional objectives, e. g. the accumulation of soil organic matter (Holmstrom et al. 2001), the lowering of wind and water erosion (Kainz et al. 1997) and the suppression of weeds (Kankanen et al. 2001). Weeds play a decisive role in organic farming systems (Welsh et al. 1999, Salonen et al. 2005). Therefore, from the additional objectives the weed suppressing potential of *P. lanceolata* undersown in potato stands was considered to be important.

Material and Methods

Location, design and treatments

The field experiments were conducted in 2002 and 2004 on a brown warp soil (Fluentic Eutrochrept) near Göttingen (51°32' N, 9°56' E), Germany. The topsoil (0-30 cm) of the experimental field was a silty loam with a composition of 24.8% clay, 61.5% silt and 13.7% sand. The bulk density was 1.33 g cm^{-3} (0-30 cm soil depth), 1.42 g cm^{-3} (30-60 cm), 1.49 g cm^{-3} (60-90 cm) and 1.48 g cm^{-3} (90-120 cm). Contents of P, K, Mg in the topsoil and the pH were similar in the two years. On average the extractable P (in H_2O), K (in $CaCl_2$) and Mg (in $CaCl_2$) in the soil were 121, 133 and 66 mg kg^{-1}, respectively. The pH (in 0.01 M $CaCl_2$) of the soil was 6.6. The annual precipitation at Göttingen (long-term average 1961-1990) is 648 mm, almost regularly distributed throughout the year. The experimental site is part of a cool-temperate zone characterized by a sub-oceanic climate with an annual mean long-term average temperature of 8.7°C. From April until the end of July the long-term average temperature is 13.4°C and precipitation 253 mm. In the two experimental years these values were 13.9°C (2002) or 12.8°C (2004), and 339 mm (2002) or 278 mm (2004). Between final harvest and final soil sampling in late autumn, precipitation was 72 mm in 2002 (44 days) and 151 mm in 2004 (84 days).

The agricultural land used for this field experiment had been managed organically since the end of 1994. The preceding crop in both experimental years was winter wheat which had followed a mixture of red clover (*Trifolium pratense* L.) and perennial ryegrass (*Lolium perenne* L.). In both experimental years the wheat stubble cultivation was carried out with a chisel plough in August after the winter wheat harvest. Tillage with a mouldboard plough to a depth of about 25 cm followed in early March (2002) and late February (2004). The seedbed was prepared with a rotary harrow and a ridge plough. The potatoes were planted 33 cm apart in 75 cm rows amounting to 40,400 potato plants ha^{-1}. The cultivar Linda was used in both years. This cultivar is characterised by a semi-erect spreading habit and long-oval yellow fleshed tubers with low mealiness. The seed tubers had been organically produced and were presprouted in a greenhouse for about 1 month.

The size of the plots ranged between 97 m^2 (2002) and 69 m^2 (2004). The field trial was arranged in a randomized block design with four replicates each year. Analysis of variance and estimation of least square means were performed using the General Linear Models (GLM) procedure of the software package SAS 8.01 (SAS Institute 2000). Residuals were checked for normal (Gaussian) distribution by PROC UNIVARIATE in SAS. The means were separated at P<0.001 (***), P<0.01 (**) and P<0.05 (*). All statistical analyses were done within individual procedures using arithmetical means of the original data.

Crop management

The potato crops were planted in the last decade of April in both experimental years. Rows were orientated east-west. Weeds were controlled by mechanical ridging and manual hoeing. Despite these procedures, many weeds survived until harvest like common lambsquarters (*Chenopodium album* L.) and cleavers (*Galium aparine* L.). Plant protection against Colorado beetle (*Leptinotarsa decemlineata* Say) was carried out successfully with *Bacillus thuringiensis* ssp. *tenebrionis*. The percentage of potato late blight (*Phytophthora infestans* (Mont.) de Bary) damage was estimated in 2002 and 2004 after Adler (2001) and Karalus (1995), respectively. Against *P. infestans* a cupriferous fungicide was used once in 2002 (26 June) and in 2004 (14 July). In both years the effectiveness was unsatisfactory because of frequent rainfall after application. No fertiliser was applied.

On 5 June 2002 and 18 May 2004, *P. lanceolata* was sown to a depth of 1-2 cm using a hand seeding machine (Sembdner HS, Germering, Germany). *P. lanceolata* seeds were sown in a narrow band of 3 cm width along the furrows at a density of 800 germinable seeds m^{-2} (circa 14 kg ha^{-1}). An undomesticated French *P. lanceolata* provenance, supplied by Conrad Appel, Darmstadt, Germany, was used. In both experimental years a rapid emergence of the *P. lanceolata* seedlings could be observed. Plots where no underseeding was carried out were denominated U(-) and plots with undersown *P. lanceolata* U(+).

Plants were sampled twice: at the maximum development of the potato foliage (BBCH 65; 11 July 2002 and 20 July 2004) and when the potato tubers in the soil had set their skins (BBCH 99; 28 August 2002 and 15 September 2004). At the first harvest 12 potato plants (=3 m^2) per plot were cut at the soil surface. Additionally, the above ground parts of the weeds (only in 2004 because of very low weed density in 2002) and of *P. lanceolata* were collected in the same area. The fresh weight and dry matter of all harvested plant parts were determined. At the second harvest the tubers of 60 potato plants (=15 m^2) per plot were lifted by hand. The marketable yield was defined as the medium sized tubers, i. e. 30-65 mm (2002) and 35-65 mm (2004). Harvesting of *P. lanceolata* and weeds was carried out according to the first harvest. Total C and N concentration of all samples were determined by the Dumas method (elementar vario EL, Heraeus).

The plots were harvested using a common potato harvester. The disc coulter which was attached to the machine ensured that in the U(+) plots the *P. lanceolata* plants survived in most instances but above ground plant material of *P. lanceolata* was partly cut off.

Root survey and N_{min} measurements

Root surveys were carried out in 2004 by means of the profile wall method (foil method, Böhm 1979). Wet root exposing was carried out by using a water sprayer and a toothed metal scraper. The frame used to count the exposed roots after removing a vertical soil layer of 0.5 cm was 150 × 150 cm and encompassed two potato rows. For evaluating the dots on the foil the software PLOTROOT, developed at our department, was used. It performs basic calculations such as the number of root units per line and column on the foil and the total number of root units. From this information root length (RL_{PW}, km m^{-2}) and root length density (RLD_{PW}, cm cm^{-3}) were calculated.

The U(-) and U(+) pits were situated in neighbouring plots. The zero line for root depth estimations was adjusted at the top of the ridges. The height of the ridges varied between 13 and 17 cm. Root length densities were determined for each 5 cm soil layer to a maximum depth of 120 cm. The root surveys were realised on 29 July (91 days after potato planting, DAP) and on 28 September (151 DAP).

In both experimental years at the beginning of the growing season and the three subsequent sampling dates the mineral nitrogen (N_{min} = NO_3-N + NH_4-N; 0-60 cm and 60-120 cm) was extracted from the soil using 0.01 M

$CaCl_2$. Nitrate and ammonium were quantified by means of a Perstorp analytical autoanalyser (Flow solution III). Soil cores had a diameter of 1.7 cm. At the beginning of the growing season six cores were taken per plot. At the later sampling dates eight cores were taken from each plot: four soil cores on the ridge and four in the furrow. The soil samples were immediately homogenized and then stored at -18°C until further analysis. At the sampling dates in July and at potato harvest time the zero line for the core sampling was at the top of the ridges. This implies that the upper cm of the soil cores taken in the furrows remained empty. The term "ridge" was maintained even at the last sampling date (11 October 2002 and 8 December 2004) when the ridges had been largely flattened by the preceding harvesting process. Nevertheless, the former ridge and furrow area were easily identified at this date particularly in the undersown plots where *P. lanceolata* exhibited successful regrowth.

Results

Growth of potato tops, P. lanceolata *and weeds; first harvest*

At the first harvest (11 July 2002 and 20 July 2004) dry biomass and N uptake of potato tops and above ground *P. lanceolata* were significantly higher in 2004 compared to 2002 (Tab. 1). In both experimental years, growth of potato tops and potato N uptake in the U(+) plots were lower than in the U(-) plots. However, these differences were not significant. Weeds grew faster in 2004 than in 2002 but substantial effects of *P. lanceolata* on weed growth could not be observed at this time. Likewise, the C:N ratios of the potato tops were similar (on average 16.6) for all treatments.

Both experimental years were characterised by relatively wet weather during spring and early summer. Additionally, in May and June 2002 the air temperature was slightly higher compared to the long time mean temperature. As expected, these weather conditions gave rise to a severe *P. infestans* attack (data not shown). In 2002 and 2004 the first symptoms emerged on 21 June and 7 July, respectively. There was no difference in *Phytophthora* ratings between the U(-) and the U(+) plots. On 30 July 2002 and 6 August 2004 the above ground potato tissue was completely destroyed in all plots.

Yield of potato tubers, P. lanceolata *and weeds; second harvest*

In 2002 the tuber yield was significantly lower than in 2004 (Tab. 2). As a mean of the treatments with and without *P. lanceolata* in 2002 only 168 dt ha^{-1} fresh tuber material could be harvested. In 2004 this value was 269 dt ha^{-1}. Similarly tuber dry matter yield was 37 dt ha^{-1} in 2002 and markedly higher in 2004 with 60 dt ha^{-1}. Uniformly, the dry matter content of the tubers was about 22%.

In both experimental years the tuber yield was only slightly lower in the U(+) plots. This applies to both fresh and dry tuber biomass. On average, the yield reduction was 6.8% but the differences between the treatments were statistically not significant. In both years weeds were clearly suppressed in the undersown plots. In 2002 the shoot dry biomass of *P. lanceolata* was 13 dt ha^{-1} and the weeds were reduced by 59%. In 2004 the shoot dry biomass of *P. lanceolata* was significantly higher (24 dt ha^{-1}) and the weed suppression was up to 70%, compared to the U(-) plots.

The DM yield total of tubers and above ground *P. lanceolata* and weeds averaged 55.5 dt ha^{-1} in 2002 and 86.5 dt ha^{-1} in 2004. The difference between the two years was statistically significant. In 2002 and 2004 the DM yield total did not differ significantly between the treatments.

The percentage of undersized (13%) and medium sized marketable tubers (86%) was similar in both experimental years. However, in 2002 the percentage of undersized tubers was higher in the U(+) plots. Inversely, in 2002 the percentage of medium sized tubers was lower in the U(+) plots. In 2004 the tendency for undersized and medium sized tubers was similar but the differences were only small. Oversized tubers were nonrelevant and contributed only to 1% (2002) and 0% (2004). The marketable tuber yield was significantly greater in 2004 compared to 2002. Underseeding *P. lanceolata* decreased marketable tuber yields. This effect was statistically significant in 2002 (-15%) and not significant in 2004 (-11%).

Tab. 1: First harvest (BBCH 65): Above ground biomass and N uptake of potato, *P. lanceolata* and weed; C:N-ratio of potato tops; *, ** differences statistically significant at the P=0.05 and 0.01 level, respectively; n.s. difference not significant at the P=0.05 level; n.e. not evaluated because of very low weed frequency. U(-) plots have not been undersown, U(+) plots have been undersown with *P. lanceolata*

Erste Ernte (BBCH 65): Oberidischer Aufwuchs und N-Aufnahme von Kartoffeln, P. lanceolata *und Unkräutern; C:N-Verhältnis des Kartoffelkrautes. *, ** Unterschiede sind statistisch signifikant bei P=0,05 bzw. P=0,01; n.s. Unterschiede nicht signifikant bei P=0,05; n.e. Daten nicht erhoben wegen sehr geringen Unkrautaufwuchses. U(-) Parzellen ohne Untersaat, U(+) Parzellen mit* P. lanceolata *untergesät*

	11 July 2002			20 July 2004			Difference between years
	U(-)	U(+)		U(-)	U(+)		
Potato tops dry biomass (dt ha^{-1})	12.9	11.8	n.s.	16.4	15.4	n.s.	*
P. lanceolata dry biomass (dt ha^{-1})	-	0.78	-	-	2.52	-	**
Weed dry biomass (dt ha^{-1})	n.e.	n.e.	-	0.97	0.63	n.s.	-
Potato tops N uptake (kg N ha^{-1})	26.3	24.6	n.s.	32.3	28.6	n.s.	**
P. lanceolata N uptake (kg N ha^{-1})	-	1.55		-	4.10		**
Weed N uptake (kg N ha^{-1})	n.e.	n.e.	-	2.28	1.31	n.s.	-
C:N-ratio of potato tops	16.2	17.2	n.s.	16.3	16.5	n.s.	n.s.

Tab. 2: Second harvest (BBCH 99): Potato tuber biomass, above ground biomass of *P. lanceolata* and of weed; size distribution of potato tubers, undersized in 2002: <30 mm, in 2004: <35 mm, medium sized in 2002: 30–65 mm, in 2004: 35– 65 mm, oversized >65 mm; <10 mm = cull; marketable tuber yield = medium sized tubers. *, **, *** differences statistically significant at the P=0.05, 0.01 and 0.001 level, respectively; n.s. difference not significant at the P=0.05 level. U(-) plots have not been undersown, U(+) plots have been undersown with *P. lanceolata*
Zweite Ernte (BBCH 99): Knollenerträge, oberirdischer Aufwuchs von P. lanceolata *und Unkräutern; Größenverteilung der Kartoffelknollen, Untergrößen im Jahr 2002: <30 mm, im Jahr 2004: <35 mm, Mittelgrößen im Jahr 2002: 30–65 mm, im Jahr 2004: 35–65 mm, Übergrößen >65 mm; <10 mm = Ausschuss; marktfähiger Knollenertrag = Mittelgrößen. *, **, *** Unterschiede sind statistisch signifikant bei P=0,05, 0,01 bzw. 0,001; n.s. Unterschiede nicht signifikant bei P=0,05. U(-) Parzellen ohne Untersaat, U(+) Parzellen mit* P. lanceolata *untergesät*

	28 August 2002			15 September 2004			Difference between years
	U(-)	U(+)		U(-)	U(+)		
Tuber fresh biomass (dt ha^{-1})	174	162	n.s.	278	259	n.s.	***
Tuber dry biomass (dt ha^{-1})	38	36	n.s.	62	57	n.s.	***
P. lanceolata dry biomass (dt ha^{-1})	-	13	-	-	24	-	**
Weed dry biomass (dt ha^{-1})	17	7	**	23	7	**	n.s.
Sum of DM of tuber, *P. lanceolata* and weed (dt ha^{-1})	55	56	n.s.	86	87	n.s.	***
Undersized tubers (%)	9.8	16.6	*	12.2	13.8	n.s.	n.s.
Medium sized tubers (%)	89.2	82.5	**	87.8	86.2	n.s.	n.s.
Oversized tubers (%)	1.0	0.9	n.s.	0.0	0.0	-	-
Marketable tuber yield (DM, dt ha^{-1})	34	29	*	55	49	n.s.	***

Tab. 3: Nitrogen uptake and DM N content of potato tubers, above ground parts of *P. lanceolata* and weed; C:N-ratio of *P. lanceolata* and weed. *, **, *** differences statistically significant at the P=0.05, 0.01 and 0.001 level, respectively; n.s. difference not significant at the P=0.05 level. U(-) plots have not been undersown, U(+) plots have been undersown with *P. lanceolata*
Stickstoffaufnahme und N-Gehalte (TM-bezogen) von Kartoffelknollen, oberidischem Aufwuchs von P. lanceolata *und Unkräutern; C:N-Verhältnis von P. lanceolata und Unkräutern. *, **, *** Unterschiede sind statistisch signifikant bei P=0,05, 0,01 bzw. 0,001; n.s. Unterschiede nicht signifikant bei P=0,05. U(-) Parzellen ohne Untersaat, U(+) Parzellen mit* P. lanceolata *untergesät*

	28 August 2002			15 September 2004			Difference between years
	U(-)	U(+)		U(-)	U(+)		
Tuber N uptake (kg N ha^{-1})	44.3	42.2	n.s.	61.9	54.9	*	**
P. lanceolata N uptake (kg N ha^{-1})	-	23.9	-	-	38.0	-	*
Weed N uptake (kg N ha^{-1})	28.9	9.3	**	62.2	10.8	**	**
Sum of N uptake of tubers, *P. lanceolata* and weed (kg N ha^{-1})	73.1	75.4	n.s.	124.1	103.7	**	**
Tuber N content (%)	1.17	1.15	n.s.	1.00	0.96	n.s.	***
P. lanceolata N content (%)	-	1.86	-	-	1.62	-	n.s.
Weed N content (%)	1.67	1.27	n.s.	2.64	1.65	**	*
C:N-ratio of *P. lanceolata*	-	18.1	-	-	25.2	-	*
C:N-ratio of weeds	16.1	20.9	*	15.2	23.4	***	n.s.

Nitrogen uptake of potato tubers, P. lanceolata *and weeds*

The N uptake by the potato tubers was markedly higher in 2004 compared to 2002 (Tab. 3). In 2002 differences between treatments were only small. However, in 2004 the N uptake of the tubers in the U(+) plots decreased compared to the U(-) plots. The N uptake in shoots of *P. lanceolata* totalled 38.0 kg N ha^{-1} in 2004. This value was significantly higher than in 2002 (23.9 kg N ha^{-1}). Likewise, the N uptake of the weeds was significantly higher in 2004 compared to 2002, especially in plots without *P. lanceolata* (significant interaction year × presence of *P. lanceolata*; P=0.006). In both years the N uptake of weeds was drastically reduced in the U(+) plots. This reduction amounted to 68% in 2002 and to 83% in 2004.

In 2002 there appeared only a small difference between treatments when the N uptake of tubers, *P. lanceolata* and weeds were added together. In 2004 the total N uptake of the U(-) plots exceeded the U(+) plots. Additionally, total N uptake was significantly higher in 2004 (mean 114 kg N ha^{-1}) than in 2002 (mean 74 kg N ha^{-1}).

Underseeding *P. lanceolata* influenced the N content (%, DM base) in the potato tubers only to a very small extent while N content values were significantly higher in 2002 (mean 1.16%) compared to 2004 (mean 0.98%). Similarly, the N content of above ground *P. lanceolata* was higher in 2002 but the difference was statistically insignificant. On average the N content in the *P. lanceolata* material came to 1.74%. Unlike *P. lanceolata*, the N content of the weeds was

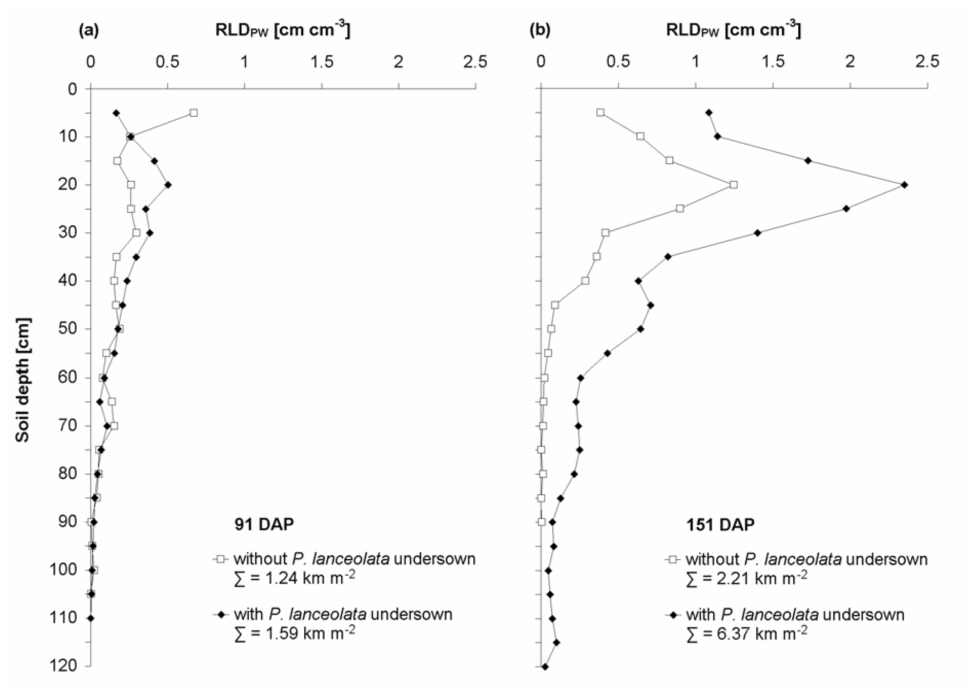

Fig. 1: Root length density (RLD_{PW}) and root length ($\Sigma = RL_{PW}$) in mixed stands of potatoes and weeds for two different underseeding treatments with *P. lanceolata*, (a) on 29 July 2004, 91 days after potato planting (DAP) and (b) on 28 September 2004, 151 DAP; profile wall method
Wurzellängendichte (RLD_{PW}) und Wurzellänge ($\Sigma = RL_{PW}$) in Mischbeständen aus Kartoffeln und Unkräutern bei zwei Untersaatvarianten mit P. lanceolata, *(a) am 29. Juli 2004, 91 Tage nach der Kartoffelpflanzung (DAP) und (b) am 28. September 2004, 151 DAP; Profilwandmethode*

significantly lower in the first year (mean 1.47%) compared to the second year (mean 2.14%). In both years the N content of the weeds was lower in the U(+) plots. This effect was statistically significant in 2004.

The C:N ratio of the above ground plant parts of *P. lanceolata* was higher in 2004. With respect to the weeds there was no significant difference between the two years. However, in 2002 and 2004 the C:N ratios of the weeds were markedly higher in the U(+) plots.

Root growth

The first root survey at the end of July 2004 displayed a maximum depth of rooting of 105 cm in the U(-) plot and 110 cm in the U(+) plot (Fig. 1). There was a slight increase of roots in the U(+) plot compared to the U(-) plot, particularly in the 10-45 cm soil layer. Here root length density (RLD_{PW}) averaged 0.22 cm cm^{-3} in the U(-) plot and 0.33 cm cm^{-3} in the U(+) plot. At this time the root length in the U(-) plot totalled RL_{PW} = 1.24 km m^{-2} and in the U(+) plot 1.59 km m^{-2}.

At the second root survey in the last decade of September 2004 the maximum depth of rooting was 90 cm in the U(-) plot and 120 cm in the U(+) plot. Root length density (RLD_{PW}) was always higher in the U(+) than in the U(-) plot. In the 0-30 cm soil layer the RLD_{PW} for the U(-) plot was 0.74 cm cm^{-3} and 1.61 cm cm^{-3} for the U(+) plot. In the 30-60 cm layer these values decreased to 0.14 and 0.58 cm cm^{-3} and in the 60-90 cm layer to 0.007 and 0.19 cm cm^{-3}, respectively. In the 90-120 cm soil depth no roots at all could be detected in the U(-) plot. However, RLD_{PW} in the U(+) plot was still 0.065 cm cm^{-3} in this deep soil layer. At the end of September total root length (RL_{PW}) ranged between 2.21 km m^{-2} in the U(-) plot and 6.37 km m^{-2} in the U(+) plot.

N_{min} in the soil

At the beginning of the growing season in early spring the N_{min} quantity in the soil (0-120 cm) was 59.0 kg N ha^{-1} in 2002 and 112.7 kg N ha^{-1} in 2004 (Tab. 4, footnote). This difference was statistically significant. In contrast to this in most cases the N_{min} quantities for the later sampling dates were lower in 2004 compared to 2002. At the first sampling date during the growing season the N_{min} quantities (0-120 cm) had fallen to 43.3 kg N ha^{-1} (2002) and 32.2 kg N ha^{-1} (2004; Tab. 4). At this time no significant differences between U(-) and U(+) plots could be observed.

At the second sampling date – directly before harvesting the potato tubers – the N_{min} quantities (0-120 cm) averaged 53.5 kg N ha^{-1} (29 August 2002) and 27.6 kg N ha^{-1} (16 September 2004). In 2002 no significant difference of the N_{min} quantities between the treatments could be detected in the ridge zone. However, in 2004 a marked difference was observed even underneath the ridges. The reduction of N_{min} in the U(+) plots attained 23.7 kg N ha^{-1} (68.5%) in the soil layer of 0-60 cm, and 5.1 kg N ha^{-1} (36.4%) in the soil layer of 60-120 cm. The N_{min} quantities underneath the furrow were lower in all cases in the U(+) plots compared to the U(-) plots. Underneath the furrow N_{min} per 60 cm soil layer was reduced to the range of 9.8 kg N ha^{-1} (0-60 cm; 16 September 2004) and 23.5 kg N ha^{-1} (0-60 cm; 29 August 2002) or between 55.5% (60-120 cm; 29 August 2002) and 75.2% (60-120 cm; 16 September 2004).

At the third sampling date the N_{min} quantities averaged 61.4 kg N ha^{-1} (11 October 2002) and 35.2 kg N ha^{-1} (8 December 2004; 0-120 cm). In the U(+) plots N_{min} was always lower compared to the U(-) plots. The N_{min} quantities (0-120 cm) were 66.0 kg N ha^{-1} in the U(-) plots and 30.6 kg N ha^{-1} in the U(+) plots (average for the two years). In seven of eight tested soil layers, 0-60 cm or 60-120 cm, the differences between U(-) and U(+) plots were statistically significant. The slightest effect occurred in 2002 in the ridge zone at a soil depth of 0-60 cm. The remaining significant reductions per 60 cm soil layer ranged between 5.7 kg N ha^{-1} (8 December 2004, ridge; 0-60 cm) and 33.6 kg N ha^{-1} (11 October 2002, furrow; 0-60 cm). Expressed as percentages these values ranged between 22.4% (8 December 2004, ridge; 0-60 cm) and 81.9% (11 October 2002, furrow; 60-120 cm).

At all six sampling dates for both years the N_{min} quantities underneath the ridge were compared to the N_{min} quan-

Tab. 4: Mineral soil nitrogen (N_{min}) at three times during the experimental years 2002 and 2004 as affected by the small scale arrangement (underneath the ridges or underneath the furrows), soil depth and presence of *P. lanceolata*. *, **, *** differences statistically significant at the P=0.05, 0.01 and 0.001 level, respectively; n.s. differences not significant at the P=0.05 level. N_{min} content at the beginning of the growing season see footnote. n.c. not calculated because of marked differences of the N_{min} recording dates between 2002 and 2004. Potato tuber harvesting on 28 August 2002 and 15 September 2004. No further soil cultivation took place after tuber harvest. U(-) plots have not been undersown, U(+) plots have been undersown with *P. lanceolata*

N_{min}-Vorrat im Boden zu drei Zeitpunkten der Versuchsjahre 2002 und 2004 in Abhängigkeit von der kleinräumigen Verteilung (unterhalb der Dämme oder unterhalb der Furchen), der Bodentiefe und der Gegenwart von P. lanceolata. **, **, *** Unterschiede sind statistisch signifikant bei P=0,05, 0,01 bzw. 0,001, n.s. Unterschiede nicht signifikant bei P=0,05. N_{min}-Vorrat im Boden zu Beginn der Vegetationszeit siehe Fußnote. n.c. nicht errechnet wegen starker Unterschiede in den Erfassungszeitpunkten der N_{min}-Vorräte zwischen 2002 und 2004. Kartoffelernten am 28. August 2002 und 15. September 2004. Keine weitere Bodenbearbeitung nach der Knollenernte. U(-) Parzellen ohne Untersaat, U(+) Parzellen mit* P. lanceolata *untergesät*

	Soil depth (cm)	Date (2002)	U(-) N_{min} (kg N ha^{-1})	U(+)		Date (2004)	U(-) N_{min} (kg N ha^{-1})	U(+)		Difference between years
Ridge	0 - 60	15 July	21.9	20.3	n.s.	21 July	24.0	21.0	n.s.	n.s.
	60 - 120		18.7	16.3	n.s.		15.6	13.0	n.s.	*
Furrow	0 - 60		20.3	19.9	n.s.		13.8	13.1	n.s.	***
	60 - 120		23.8	31.9	n.s.		15.3	13.0	n.s.	***
Difference between ridge and furrow (0 - 120 cm)			n.s.	*			**	*		
Ridge	0 - 60	29 August	35.0	41.5	n.s.	16 September	34.6	10.9	*	*
	60 - 120		26.8	24.9	n.s.		14.0	8.9	**	***
Furrow	0 - 60		33.0	9.5	*		16.3	6.5	*	**
	60 - 120		29.9	13.3	*		15.3	3.8	*	***
Difference between ridge and furrow (0 - 120 cm)			n.s.	**			*	**		
Ridge	0 - 60	11 October	46.6	37.1	n.s.	8 December	25.5	19.8	*	n.c.
	60 - 120		40.1	19.4	*		27.3	7.4	**	n.c.
Furrow	0 - 60		51.7	18.1	**		24.1	11.2	**	n.c.
	60 - 120		27.7	5.0	**		20.9	4.5	**	n.c.
Difference between ridge and furrow (0 - 120 cm)			n.s.	***			n.s.	***		

N_{min} content in the soil in early spring 2002, 0 - 60 cm: 39.0 kg N ha^{-1}, 60 - 120 cm: 20.0 kg N ha^{-1} and in early spring 2004, 0 - 60 cm: 80,5 kg N ha^{-1}, 60 - 120 cm: 32,2 kg N ha^{-1}; differences between years are significant for 0 - 60 cm (**) and 60 - 120 cm (*).

tities underneath the furrow (0-120 cm). This was done separately for the plots which had been and those which had not been undersown. At the first sampling date (15 July 2002) the results remained vague. At the other sampling dates in nine out of ten cases N_{min} was higher underneath the ridge compared to the furrow. In eight cases these differences were statistically significant. The differences in N_{min} between the ridge zone and the furrow zone were more pronounced in the U(+) plots. In 2004 the N_{min} quantities under the furrow compared to the ridge were smaller by 25.4% and 37.9% in the U(-) and U(+) plots, respectively (averages of the three sampling dates).

No clear trend could be observed when comparing the 0-60 cm and the 60-120 cm soil layers. In individual cases the reduction of the N_{min} (kg N ha^{-1} or %) in the undersown plots was similar in the upper soil layer compared to the lower soil layer, e.g. on 11 October 2002 (cf. 16 September 2004). At the last sampling date in 2004 (8 December) N_{min} in the U(+) plots decreased in the 0-60 cm layer on average by 9.3 kg N ha^{-1} (38.0%) compared to the U(-) plots. In the 60-120 cm soil layer the decrease was more pronounced and on average mounted up to 18.2 kg N ha^{-1} (75.7%).

Discussion

Plant growth

The N_{min} quantities in the soil at the beginning of the growing season were higher in 2004 compared to 2002, particularly in the 0-60 cm layer. Accordingly, the N uptake of the plants was markedly higher in 2004 than in 2002. Presumably this was the main reason for the better growth and higher above ground DM yields which were already apparent at the first harvest date in July 2004 when compared to July 2002. It is widely known that an increased N supply enhances overall plant growth, preferentially the shoot (SATTELMACHER et al. 1990). The growth of potatoes in organic farming is also often more limited due to the amount of available mineral soil nitrogen than by *Phytophthora* infestation (MÖLLER 2000). Additionally, the increased DM and N uptake of *P. lanceolata* in 2004 could also be due to the earlier seeding date of *P. lanceolata* in 2004 compared to 2002. The superior growth and stimulated N uptake in 2004 continued until the second harvest.

The evidence is that intercropping serves as a tool to suppress weeds (KIMPEL-FREUND et al. 1998, JØRGENSEN &

Møller 2000, Szumigalski & van Acker 2005). Competition for light and shading are important factors (Baumann et al. 2001). By underseeding potatoes similar intercropping effects can be attained. Rajalahti et al. (1999) succeeded in reducing the investment for herbicides by 70% when potatoes were undersown with different plant species, e. g. hairy vetch (*Vicia villosa* Roth). Comparably, in our experiments the weeds were substantially suppressed in the U(+) plots. Furthermore, the stronger shoot growth of *P. lanceolata* in the second experimental year resulted in an increased suppression of weeds compared to 2002.

Fresh and DM biomass of potato tubers were slightly reduced in the U(+) plots compared to the U(-) plots. Haas (2002) found similar effects on potatoes when sunflower (*Helianthus annuus* L.), maize (*Zea mays* L.) and white mustard (*Sinapis alba* L.) were undersown. However, the percentage of undersized tubers was higher in the U(+) plots compared to the U(-) plots. The results of the presented field experiments signal that the marketable tuber yield can be lowered through underseeding of *P. lanceolata*. This may happen when unfavourable growing conditions prevail like in 2002 or when potato cultivars are grown which genetically tend to produce rather small tubers like Linda.

Only little data is available which relates to potato tuber yield and tuber size with respect to underseeding. McKinlay (1985) investigated the influence of perennial ryegrass (*Lolium perenne* L.), undersown in potatoes, on potato aphid numbers. Similarly, he observed no significant potato yield reduction but more undersized tubers in the plots which had been undersown. The main effect of underseeding on the potato crop seems to be a reduction of the tuber size and only to a lesser extent the reduction of the tuber yield. Possibly, growing a potato cultivar which tends to form bigger tubers could make a contribution to lower the risk of harvesting more undersized tubers after underseeding. On the other hand, normally small-sized tubers are often preferred when seed potatoes are produced. Negative effects of underseeding plants like *P. lanceolata* on potato tuber size may also be reduced by retarding the time of underseeding. Finally, presprouting the seed potatoes helps to reduce the percentage of undersized tubers (Karalus & Rauber 1997).

In spite of a higher level of N_{min} in the soil at the beginning of the growing season in the second experimental year the N_{min} quantities recorded afterwards, in principle, were lower in 2004 than in 2002. Presumably the relatively high initial N_{min} quantity in 2004 induced the better growth of the potato tops as well as the tubers. Additionally, the *P. infestans* infestation clearly began later in 2004. In 2004 the green period of the potato canopy was about 16 days longer than in 2002. Ivins & Bremner (1964) demonstrated that an increased N supply, closely connected with greater leaf area duration, enhances the potato tuber yield significantly. Obviously, the better growth of the potato crop and of *P. lanceolata* in 2004 resulted in an extensive exhaustion of the mineral soil N and in low N_{min} quantities in the soil profile. Several investigations show the possibility that a healthy crop growth and a moderate or even high yield are related with low residual N_{min} quantities in the soil (Delgado et al. 2005).

The C:N ratio has a primary effect on net N mineralisation from plant residues (Nicolardot et al. 2001). The C:N ratio of the above ground potato material averaged 16.5 indicating a rather facile mineralisation (Whitmore & Handayanto 1997). *P. lanceolata* did not exercise a noticeable influence on the C:N ratio of the potato tops material. However, the C:N ratios of the weeds were significantly wider (> 20) in the U(+) plots than in the U(-) plots. Obviously, this was the consequence of competitive interference of *P. lanceolata*. Therefore weeds growing in the undersown plots were categorised as less decomposable than weeds growing in the U(-) plots.

Rooting and N_{min} quantities in the soil

The main intention of this study was to investigate the possibility of reducing N_{min} quantities in the soil by underseeding potatoes with *P. lanceolata*. This objective was clearly achieved. As expected, the reduction of the N_{min} quantities was more pronounced in the furrow zone where *P. lanceolata* had been planted. In many cases the decrease of N_{min} was up to 50% and more. Haas (2002) recorded nitrate-N quantities in a soil depth of 0-60 cm in November after potatoes. As a mean of three sites he found a decline in nitrate-N quantities of e. g. 15 kg N ha^{-1} when the potatoes had been undersown with maize or sunflower compared to the plots where no plants had been undersown but weeds were present. This value corresponded to an N_{min} reduction of about 31%. The reductions of N_{min} which we measured in the present study in potato plots which had been undersown with *P. lanceolata* were, on average, higher (0-120 cm). Striking percental reductions of N_{min} were found in the 0-60 cm soil layer but also in the subsoil (60-120 cm) which is prone to nitrate leaching (Beaudoin et al. 2005). At the last sampling date of the two experimental years the reduction of the N_{min} quantities in the soil layer of 60-120 cm averaged 20 kg N_{min} ha^{-1} or 68.7%.

The species undersown in potato stands by Haas (2002) were mainly annuals presumably showing only scant regrowth after being disturbed during the potato harvest. In contrast, the perennial *P. lanceolata* in this study largely survived the potato harvest procedure due to the position of the apex and leaf primordia near ground level. This feature obviously enabled extensive regrowth of *P. lanceolata* leaves and roots after the potato harvest.

Underseeding potatoes with *P. lanceolata* resulted in an N_{min} reduction which is known from intercropping systems of grain crops, e. g. mixtures of wheat with soybean or maize with faba bean (Zhang & Li 2003). Likewise, Zhou et al. (1997), in maize undersown with annual Italian ryegrass (*Lolium multiflorum* L.), found an N_{min} reduction in the 0-100 cm soil profile of 47% compared to the treatment without ryegrass.

Regrettably it was not possible to differentiate between the roots of potatoes, *P. lanceolata* and weeds. Nevertheless, the comparison of rooting without *P. lanceolata* and rooting in the presence of *P. lanceolata* confirmed the hypothesis of a superior root system of *P. lanceolata* even at the first root survey in July but mainly at the second survey in September. Stalham & Allen (2001) observed the root system of several potato cultivars mostly grown in ridges and summarised that "there was generally an increase in RLD between 10 and 20 cm in depth, with the peak at 20-30 cm depth followed by a rapid decrease". This is exactly the pattern which was found on 28 September 2004 in the experiment reported here. However, despite the fact that a large proportion of the roots ramified within the ploughed layer, the root system was less surface-orientated than data from literature suggest (Lesczynski & Tanner 1976). This holds although in addition to potatoes other species (*P. lanceolata* and weeds) were involved. Perhaps the characteristic root pattern in the soil profile results, firstly, from intermittent water shortage in the surface soil layer of the ridges. Secondly, permanently ploughed soils like that used in this research often form soil pans at the base of the top soil associated with mechanical impedance to root penetration (Tardieu 1994).

On 28 September 2004 the maximum depth of rooting in the U(+) plots was 120 cm. The roots in the U(-) plots only reached 90 cm depth. One should be careful not to over-interpret relations between species and root characteristics because of mutual interference of species in mixed stands (Berendse 1982, Hauggaard-Nielsen et al. 2006). However, in this study the root length density (cm cm^{-3}) in the U(+) plots was by far higher compared to the U(-) plots. Therefore it seems plausible to hold *P. lanceolata* directly or indirectly responsible for the reduction of the N_{min} quantities in the soil profile of the undersown plots.

At the September sampling 2004 the N_{min} quantities in the soil averaged circa 49 kg N ha^{-1} and 22 kg N ha^{-1} in the U(-) and U(+) plots respectively (0-120 cm). Thus, the N_{min} quantity in the U(+) plots was 27 kg N ha^{-1} lower than in the U(-) plots. The N uptake of above ground parts of *P. lanceolata*, weeds and potato tubers (second harvest) totalled 124.1 kg N ha^{-1} in the U(-) plots and 103.7 kg N ha^{-1} in the U(+) plots. The increased N uptake in the U(-) plots mainly resulted from the profuse growth of the weeds which obviously could benefit from the lack of competing *P. lanceolata* and the high N_{min} quantity in the 0-60 cm soil layer at the beginning of the growing season. Otherwise this comparison shows that the attempt fails to explain the lower N_{min} quantities in the soil of the U(+) plots by referring to the N uptake of above ground plant parts and potato tubers.

If the N_{min} quantities and the N uptake of the potato tubers, above ground *P. lanceolata* and weed are added together for the September 2004 sampling date, then the N quantity in the U(+) plots was in fact 47 kg N ha^{-1} lower than in the U(-) plots. At the root survey in September 2004 the estimated root length in the U(-) and U(+) plots was 2.21 km m^{-2} and 6.37 km m^{-2}, respectively. Probably, the difference in root length between the U(-) and U(+) plots can mainly be attributed to *P. lanceolata* roots.

According to the results of Schmidtke (2001), obtained at the same site, the 38 kg N ha^{-1} in the *P. lanceolata* shoots of the U(+) plots (2004) correspond approximately to *P. lanceolata* root N in the range of 9.5 and 14.8 kg N ha^{-1}. This is not enough to explain the difference of the N quantity between the U(-) and U(+) plots in this study. Even if some N leaching occurred in 2004 there is no reason to suppose more leaching in the U(+) plots compared to the U(-) plots. The opposite should be true. We presume other unknown factors which caused the decline in N_{min} to these low values which were observed in the undersown plots. Perhaps the *P. lanceolata* specific iridoid glycosides aucubin and catalpol affect soil microorganisms. More research work in this field seems to be necessary.

Conclusion

This study offers a practical possibility to grow potatoes organically by using *P. lanceolata* as an undersown species to lower the risk of nitrate leaching markedly without exerting severe competitive disadvantages with respect to the potatoes. Underseeding *P. lanceolata* appears to make a contribution to the reduction of environmental hazards as one of the outstanding principles of organic farming.

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References

Adler, N., 2001: Untersuchungen zum Befall von Kartoffeln mit *Phytophthora infestans* (Mont.) de Bary mittels visueller Bonituren und PCR-Methoden. Diss. TU München-Weihenstephan, Germany.

Baumann, D.T., L. Bastiaans & M.J. Kropff, 2001: Effects of intercropping on growth and reproductive capacity of late-emerging *Senecio vulgaris* L., with special reference to competition for light. Ann. Bot. **87**, 209-217.

Beaudoin, N., J.K. Saad, C. van Laethem, J.M. Machet, J. Maucorps & B. Mary, 2005: Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. Agric. Ecosyst. Envir. **111**, 292-310.

Berendse, F., 1982: Competition between plant populations with different rooting depths. III. Field experiments. Oecologia **53**, 50-55.

Böhm, W., 1979: Methods of Studying Root Systems. Springer, Berlin, Heidelberg, New York.

Delgado, J.A., R. Khosla, W.C. Bausch, D.G. Westfall & D.J. Inman, 2005: Nitrogen fertilizer management based on site-specific management zones reduces potential for nitrate leaching. J. Soil Water Conserv. **60**, 402-410.

Goulding, K.W.T., P.R. Poulton, C.P. Webster & M.T. Howe, 2000: Nitrate leaching from Broadbalk wheat experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and the weather. Soil Use and Management **16**, 244-250.

Haas, G., 2002: Grundwasserschutz im organischen Landbau – Untersaaten in Kartoffeln zur Minderung hoher Restnitratmengen im Boden. Köster, Berlin.

Hauggaard-Nielsen, H., M.K. Andersen, B. Jornsgaard & E.S. Jensen, 2006: Density and relative frequency effects on competitive interactions and resource use in pea-barley intercrops. Field Crops Res. **95**, 256-267.

Holmstrom, D.A., H.T. Kunelius & J.A. Ivany, 2001: Forages underseeded in barley for residue management for potatoes. Can. J. Plant Sci. **81**, 205-210.

Honisch, M., C. Hellmeier & K. Weiss, 2002: Response of surface and subsurface water quality to land use changes. Geoderma **105**, 277-298.

Ivins, J.D. & P.M. Bremner, 1964: Growth, development and yield in the potato. Outlook Agric. **4**, 211-217.

Jørgensen, V. & E. Møller, 2000: Intercropping of different secondary crops in maize. Acta Agric. Scand., Section B: Soil Plant Sci. **50**, 82-88.

Kainz, M., G. Gerl & K. Auerswald, 1997: Verminderung der Boden- und Gewässerbelastung im Kartoffelanbau des Ökologischen Landbaus. Mitt. Deutsch. Bodenkundl. Ges. **85**, III, 1307-1310.

Kankanen, H.J., H.J. Mikkola & C.I. Eriksson, 2001: Effect of sowing technique on growth of undersown crop and yield of spring barley. J. Agron. Crop Sci. **187**, 127-136.

Karalus, W., 1995: Einfluß der Pflanzgutvorbereitung auf den Krankheitsbefall und Ertragsaufbau bei Kartoffeln (*Solanum tuberosum* L.) im ökologischen Landbau. Diss. Univ. Gießen, Germany.

Karalus, W. & R. Rauber, 1997: Effect of presprouting on yield of maincrop potatoes (*Solanum tuberosum* L.) in organic farming. J. Agron. Crop Sci. **179**, 241-249.

Kimpel-Freund, H., K. Schmidtke & R. Rauber, 1998: Einfluß von Erbsen (*Pisum sativum* L.) mit unterschiedlichen morphologischen Merkmalen in Reinsaat und Gemenge mit Hafer (*Avena sativa* L.) auf die Konkurrenz gegenüber

Unkräutern. Pflanzenbauwiss. **2**, 25-36.

LESCZYNSKI, D.B. & C.B. TANNER, 1976: Seasonal variation in root distribution of irrigated field-grown Russet Burbank potato. Amer. Potato J. **53**, 69-78.

MCKINLAY, R.G., 1985: Effect of undersowing potatoes with grass on potato aphid numbers. Ann. Appl. Biol. **106**, 23-29.

MÖLLER, K., 2000: Estimation of probable yield losses by *Phytophthora infestans* depending on nitrogen supply of organic maincrop potatoes. In: SCHEPPERS, H. & E. BOUMA (eds.): Proc. workshop on the European network for development of an integrated control strategy of potato late blight. Oostende, Belgium, 29 September - 2 October 1999, 201-211.

NICOLARDOT, B., S. RECOUS & B. MARY, 2001: Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C:N ratio of the residues. Plant Soil **228**, 83-103.

RAJALAHTI, R.M., R.R. BELLINDER & M.P. HOFFMANN, 1999: Time of hilling and interseeding affects weed control and potato yield. Weed Sci. **47**, 215-225.

REITER, K., 2001: Einfluss langjährig differenzierter Bodenbearbeitung auf die N_2-Fixierungsleistung von Erbse und Rotklee, ermittelt mit Hilfe einer großflächigen ^{15}N-Spurenanreicherung. Diss. Univ. Göttingen, Germany.

SAS, SAS/STAT 2000: User's Guide, Release 8.01. Cary, NC, USA.

SALONEN, J., T. HYVONEN & H. JALLI, 2005: Weed flora and weed management of field peas in Finland. Agric. Food Sci. **14**, 189-201.

SATTELMACHER, B., F. KLOTZ & H. MARSCHNER, 1990: Influence of nitrogen level on root growth and morphology of two potato varieties differing in nitrogen acquisition. Plant Soil **123**, 131-137.

SCHMIDTKE, K., 2001: Umweltgerechter Anbau von Leguminosen – Entwicklung und Anwendung eines Verfahrens zur Quantifizierung der N-Flächenbilanz, Final Report. Deutsche Bundesstiftung Umwelt, Osnabrück.

STALHAM, M.A. & E.J. ALLEN, 2001: Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. J. Agric. Sci. (Camb.) **137**, 251-270.

SZUMIGALSKI, A. & R. VAN ACKER, 2005: Weed suppression and crop production in annual intercrops. Weed Sci. **53**, 813-825.

TARDIEU, F., 1994: Growth and functioning of roots and of root systems subjected to soil compaction. Towards a system with multiple signalling? Soil Till. Res. **30**, 217-243.

VOS, J. & P.E.L. VAN PUTTEN, 2000: Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus and potassium. Nutr. Cycl. Agroecosyst. **56**, 87-97.

WEBB, J., S. ELLIS, R. HARRISON & R. THORMAN, 2004: Measurement of N fluxes and soil N in two arable soils in the UK. Plant Soil **260**, 253-270.

WELSH, J.P., L. PHILIPPS, H.A.J. BULSON & M. WOLFE, 1999: Weed control strategies for organic cereal crops. The 1999 Brighton Conf. – Weeds, 945-950.

WHITMORE, A.P. & E. HANDAYANTO, 1997: Simulating the mineralization of N from crop residues in relation to residue quality. In: CADISH, G& K.E. GILLER (eds.): Driven by nature, plant litter quality and decomposition, 337-348. Wallingford, UK, CAB International.

ZHANG F. & L. LI, 2003: Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil **248**, 305-312.

ZHOU, X., A.F. MACKENZIE, C.A. MADRAMOOTOO, J.W. KALULI & D.L. SMITH, 1997: Management practices to conserve soil nitrate in maize production systems. J. Envir. Qual. **26**, 1369-1374.

ZIHLMANN, U., P. WEISSKOPF & W. JOSSI, 2004: DOK-Versuch: Stickstoffdynamik im Boden beim Kartoffelanbau. Agrarforschung **11**, 298-303.

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