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Timing incorporation of different green manure crops to minimize the risk of nitrogen leaching

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Seven field trials at four research sites were carried out to study the effect of incorporation time of different plant materials on soil mineral N content during two successive seasons. Annual hairy vetch (*Vicia villosa* Roth), red clover (*Trifolium pratense* L.), westerwold ryegrass (*Lolium multiflorum* Lam. *var. westerwoldicum*) and straw residues of N-fertilized spring barley (*Hordeum vulgare*) were incorporated into the soil by ploughing in early September, late October and the following May, and by reduced tillage in May.

Delaying incorporation of the green manure crop in autumn lessened the risk of N leaching. The higher the crop N and soil NO_3-N content, the greater the risk of leaching. Incorporation in the following spring, which lessened the risk of N leaching as compared with early autumn ploughing, often had an adverse effect on the growth of the succeeding crop. After spring barley, the NO_3-N content of the soil tended to be high, but the timing of incorporation did not have a marked effect on soil N. With exceptionally high soil mineral N content, N leaching was best inhibited by growing westerwold ryegrass in the first experimental year.

Key words: Avena sativa, decomposition, *Hordeum vulgare*, legumes, *Lolium multiflorum*, mineralization, mulching, nitrate nitrogen, *Trifolium pratense, Vicia villosa*

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Introduction

The rapid increase in Finland’s set-aside area in the late 1980s and early 1990s caused concern due to results suggesting high rates of leaching from bare fallows (Turtola & Känkänen 1992). Reducing leaching by growing N-absorbing crops on a set-aside field, green fallow, was recommended (Jaakkola 1984). Experiments with several different green fallow crops showed that delayed ploughing in autumn markedly decreased the risk of nitrate N leaching (Känkänen 1993).

The net N mineralization from an incorporated green manure crop is highly dependent on the species grown in the crop (Smith and Sharpley 1990), and the chemical composition and phenological stage of the crop (Wivstad 1997). There are considerable differences in N mineralization rates and amounts of legumes (Marstorp and Kirchmann 1991), and the mineralization rate of non-leguminous crops increases with decreasing C:N ratios (Vinther 1994).

Low temperatures slow down the decomposition of plant material and nitrification in soil (Anderson 1960), suggesting low mineralization and leaching during the winter in Finland, when the temperature is near or below 0°C and the soil is usually frozen. On the other hand, mineralization at low temparatures is not negligible (Van Schöll et al. 1997), and Müller and Sundman (1988) found a high release of N from buried plant material during the period when the soil was frozen most of the time (5 months of 6.5). DeLuca et al. (1992) found that freeze-thaw treatment of soil resulted in a significant increase in the N mineralization rate and mineral-N flush. In any case, delayed incorporation in autumn has been found to be a promising way of reducing the risk of N leaching (Gustafson 1987, Kyllingsbaek 1989). If spring-sown crops are grown after green manure crops, a further benefit may possibly be derived from delaying incorporation until the spring. In some cases, however, incorporation in spring immediately before the next crop is sown can lead to a net N mineralization that occurs too late for optimum utilization of green manure N by the succeeding crop (Thorup-Kristensen 1996).

Our aim here was to investigate how the incorporation time (early or late autumn ploughing, and spring incorporation by ploughing or reduced tillage) of green manure crops with different N contents (hairy vetch, red clover and westerwold ryegrass) affects the risk of N leaching. Green manure yields and soil mineral N contents were measured. Incorporation of spring barley straw was compared with that of green manures.

Material and methods

The experiments were established in 1991 and 1993 at the Institute of Crop and Soil Science in Jokioinen (60°49’N, 23°28’E), the Häme Research Station in Pälkäne (61°20’N, 24°13’E) and the South Ostrobothnia Research Station in Ylistaro(52°56’N, 22°30’E). At the Central Ostrobothnia Research Station in Toholampi (63°49’N, 24°10’E) the experiment was established in 1991 only. Abbreviations of trials are as follows: Jokioinen 1991–1993 = J1, Jokioinen 1993–1995 = J2, Pälkäne 1991–1993 = P1, Pälkäne 1993–1995 = P2, Ylistaro 1991–1993 = Y1, Ylistaro 1993–1995 = Y2 and Toholampi 1991–1993 = T.

The experimental soils were tentatively classified according to the Soil Taxonomy (Soil Survey Staff 1998) as follows (the conventional abbreviations of the Finnish names of the soil types are given in parentheses):

J1 and J2: very fine Typic Cryaquept (J1: As, J2: Hts)
P1 and P2: coarse-loamy Oxyaquic Eutrocryept (HHt)
Y1 and Y2: fine-silty Aquic Dystrocryept (LjS)
T: coarse-loamy Aquic Dystrocryept (KHt)

The Toholampi soil was probably an Aquic Haplocryod but, owing to relatively deep plough-

Table 1. Incorporation and barley sowing dates at the experimental sites. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

	Ploughing			Reduced	Barley
	Early autumn	Late autumn	Spring	tillage	sowing
J1	September 9	October 30	May 12	May 11	May 21
J2	September 3	October 25	May 10	May 10	May 13
P1	September 11	November 5	May 20	May 20	May 20
P2	October 11	October 22	May 19	May 19	May 25
Y1	September 7	October 24	May 19	May 19	May 22
Y2	September 2	October 27	May 17	May 17	May 20
T1	September 5	October 10	May 21	May 21	May 22

ing, the E horizon and also the upper part of the Bhs horizon had been mixed with the Ap horizon. The fields at Ylistaro differ from the others in the high organic matter content of the plough layer (4–10% and 10–17% in Y1 and Y2, respectively).

Hairy vetch (*Vicia villosa* Roth), red clover (*Trifolium pratense* L.), westerwold ryegrass (*Lolium multiflorum* Lam. *var. westerwoldicum*) and straw residues of spring barley (*Hordeum vulgare*) were incorporated into the soil by ploughing in early autumn (beginning of September), late autumn (end of October) and spring (May) and by reduced tillage in spring (Table 1). Vetch, clover and ryegrass were grown as annual, spring-sown green fallows except in 1993 at Pälkäne and Ylistaro where red clover was undersown the previous year in spring barley. The green fallows grew without chemical fertilizer. Spring barley was sown at the same time as green manure crops in the spring of the first experimental year, and with normal rates of NPK fertilizer (60 to 100 kg N ha^{-1} depending on soil fertility).

The dates of spring ploughing and reduced tillage were chosen carefully to ensure that soil moisture was appropriate and that the succeeding crop was sown at the same time as autumn ploughed plots. A cultivator was used for reduced tillage at Jokioinen and Ylistaro, and a PTO-driven rotary cultivator (vertically rotating blades) at Pälkäne and Toholampi.

Spring barley was sown as the succeeding crop in May in the second experimental year. It was fertilized with 0, 40 and 80 kg N ha^{-1} after legumes and with 40, 80 and 120 kg N ha^{-1} after non-leguminous crops. These rates were chosen, as earlier results suggested that the average residual N effect of legume crops in Finland is 40 kg ha^{-1} (Kauppila & Kurki 1992). Phosphorus and potassium were applied separately, irrespective of N fertilization. The growth of barley was satisfactory except in J1, where the grain yield was < 1000 kg ha^{-1} because of drought. After barley had been harvested in August in the second experimental year, the experimental area was ploughed down in September or early October. Oats (*Avena sativa*) was sown in the following spring and fertilized with N rates 20 kg ha^{-1} below normal. The experiments were designed as split-split-plot trials with preceding crop as the main plot (size 16 m x 24 m), tillage as the subplot (4 m x 24 m) and rate of fertilizer N in the second year as the sub-subplot (4 m x 7 m), and with three replicates.

Plant samples (0.25 m^2 per plot) and root samples from the 0–25 cm soil layer (12.5 cm x 12.5 cm surface area) were taken in the first autumn and second spring immediately before the tillage treatment of each plot. Plants were cut with scissors at the base. The root samples were taken manually, washed with a hydropneumatic root washer (Smucker et al. 1982), and separated from other organic matter with tweezers. Plant

Table 2. First and last date of snow cover and soil frost, and maximum depth of soil frost in winter after the growing season of the first experimental year. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

	Snow cover		Soil frost		
	First date	Last date	First date	Last date	Max. depth
J1	December 19	March 23	December 5	March 12	25 cm
J2	November 14	April 10	November 10	April 27	101 cm
P1	December 16	April 27	December 4	April 27	13 cm
P2	November 24	April 7	October 21	May 13	85 cm
Y1	December 5	April 19	December 4	May 4	29 cm
Y2	November 15	April 6	November 15	May 16	61 cm
T	December 7	April 27	November 20	May 7	18 cm

and root samples were dried in an oven (2 hours at 105°C and overnight at 60°C), and dry matter and nitrogen contents and yields were measured.

The soil samples were taken from the 0–30 cm and 30–60 cm layers by mixing 16 cores in topsoil or six cores in subsoil samples. The soil samples were taken four times: 1) in the first year in late autumn as near soil-freezing as possible, 2) in the second spring before sowing of barley, 3) in autumn after harvesting of barley and 4) in the third spring before sowing of oats. The first sampling was carried out in six trials, and the others in all seven trials. After the plots had been divided into different N levels for the succeeding barley, samples 3 and 4 were taken from the low-N plots. The soil samples were extracted with 2 M KCl. The nitrate (NO_3-) and ammonium (NH_4^+) nitrogen contents of the extracts were analysed with a scalar autoanalyser (air segmented flow analyser, photometric detection) and converted into kg ha^{-1}.

September and October were exceptionally cool in the first experimental years, 1991 and 1993: in 1993 the air temperature was 4–5°C below normal. November 1991 was 5°C warmer than normal. Late autumn 1993 was dry after a rather wet August, and precipitation in both September and November was 35–50 mm below normal. May 1992 was unusually warm and dry.

The first date of permanent soil frost in the growing seasons of green manure occurred between late October and early December. The soil frost lasted from 3 to 6 months, and the snow cover from 3 to 5 months (Table 2). The dates of incorporation, soil freezing and thawing, and barley sowing were considered critical with regard to N-leaching risk. The temperature sum between early and late autumn ploughing was at least as high as the temperature sums between late autumn ploughing and soil freezing, and soil thawing and spring incorporation put together (Table 3.). Precipitation, too, was highest during the first period. The number of days between spring incorporation and barley sowing ranged from 0 to 10, and the temperature sum from 0 to 100. Only in one trial, P2, did it rain (28 mm) between spring incorporation and barley sowing.

The number of days between the first soil sampling and soil freezing ranged from 10 to 40. Late autumn ploughing was done at about the same time as soil sampling in four trials, a week earlier in one trial and three and a half weeks earlier in one trial. This might obscure the comparison of effects of ploughing time on the N leaching risk in differerent trials. However, the temperature from late autumn ploughing to soil freezing was so low (Table 3) that only minor mineralization and changes in soil N would be expected. At Pälkäne early autumn ploughing was mistakenly delayed in 1993, resulting in an 11-day period and a very low temperature sum between early and late autumn ploughing. This

Table 3. Air temperature (°C) and precipitation (mm) values between critical days. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

	Mean air temperature			Temperature sum, > 0			Precipitation sum		
	period 1	period 2	period 3	period 1	period 2	period 3	period 1	period 2	period 3
J1	6,7	2,2	2,0	354	97	154	128	82	91
J2	4,6	0,1	9,4	249	14	131	55	1	4
P1	6,6	1,9	8,2	365	70	197	112	53	8
P2*	2,7	–	6,9	30	0	48	26	0	4
Y1	6,6	2,1	8,1	322	105	129	117	52	9
Y2	4,0	–0,1	4,7	234	15	9	104	3	0
T	6,4	2,2	7,5	224	118	105	142	55	4

Period 1 is between early and late autumn ploughing, period 2 between late autumn ploughing and the beginning of soil frost and period 3 between the end of soil frost and spring incorporation.
*In Pälkäne 1993, early autumn ploughing was delayed by mistake.

trial also differed from the others in that the soil was frozen at about the same date as the late autumn ploughing was done, and that the first soil samples were not taken.

The data from the seven different experimental sites were analysed separately. The main effects of preceding crop and incorporation treatment, and their interactions, were tested statistically by analysis of variance according to the split-plot design. If an interaction between preceding crop and incorporation treatment was found, the effects of incorporation treatments were determined separately for the preceding crops. The differences between incorporation treatments were examined in pairs. The means were compared by Tukey's HSD methods. If there was no interaction, but the main effect of preceding crop or incorporation treatment was significant, it was examined by making paired comparisons.

Before the analysis of variance was performed, the consistency of data from different examinations with the assumptions of equality of group variances were checked by Box-Cox diagnostic plots, on the basis of which the variables were transformed. Square root, logarithm and reciprocal transformations were used. In addition, the normality of errors was assessed by steam and leaf display and by normal probability plot. All analyses were performed with the SAS statistical package. MIXED (SAS 1992), UNIVARIATE (SAS 1990) and GPLOT (SAS 1991) procedures were used.

The soil nitrogen data presented here are medians of the treatments. The differences between treatments are presented as differences between medians. The medians and differences between medians indicate better the practical importance of treatment differences than do means and differences of means based on transformed variables. However, the analyses of variance were based on transformed variables.

Results

Crop N

The N yields of green manure crops for incorporation varied, depending on site, year, species and sampling date (Table 4). In autumn, hairy vetch had often produced over 200 kg N ha^{-1}, but after the succeeding winter there was considerably less N in material left on the soil

Table 4. Mean values of above-ground, root and total N yields (kg ha^{-1}) of annually grown crops for incorporation. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, T = Toholampi 1991–1993.

	Above-ground biomass N			Root N, 0–20 cm depth		
	V. villosa	*T. pratense*	*L. multiflorum*	*V. villosa*	*T. pratense*	*L. multiflorum*
J1						
Early autumn	216	157	40	4	38	6
Late autumn	236	83	46	4	135	10
Spring	40	35	21	6	20	8
Reduced tillage	50	32	20	5	55	10
J2						
Early autumn	199	82	52	23	38	27
Late autumn	188	115	69	19	87	18
Spring	60	99	31	5	75	14
Reduced tillage	106	70	38	14	70	15
P1						
Early autumn	188	45	23	12	13	22
Late autumn	197	53	25	29	78	22
Spring	82	58	32			
Reduced tillage	113	49	23			
T						
Early autumn	123	36	45	4	4	8
Late autumn	153	36	12	11	24	15
Spring	48	16	15	6	28	28
Reduced tillage	45	23	17	5	27	32

surface. The decrease was marked, although the small sample size (0,25 m^2 per plot) caused some variation in results. In red clover, the same phenomenom was found clearly only in J1. The N yield of red clover in autumn varied more than did that of vetch (40 to 220 kg ha^{-1}). A great proportion of the red clover N was in roots, and the amount of N in the roots of red clover grown annually increased sharply between samplings before early and late autumn ploughing. The small size of the root samples caused some uncertaintity in the root yield results. The N of vetch occurred mainly in above-ground plant material. The N yield of westerwold ryegrass ranged from 30 to 90 kg ha^{-1}. The average of the above-ground N content incorporated in plant material varied between trials from 2.1 to 3.1%, 1.2 to 3.4%, 0.9 to 1.8% and 0.8 to 1.4% in vetch, red clover, ryegrass and barley straw, respectively. The root N content ranged from 1.5 to 3.0%, 1.3 to 2.8%, 0.8 to 1.7% and 1.1 to 1.9%, respectively.

Soil mineral N

The level of soil mineral N differed greatly both between and within the experimental sites. In the trial with the lowest NO_3-N levels (J1), the minimum and maximum values of all samples at 0–60 cm depth in the first soil sampling after barley were 2 and 14 kg NO_3-N ha^{-1} and in the trial with the highest NO_3-N levels (Y2), 50 and 88 kg NO_3-N ha^{-1}, respectively. Similarly, in the trial with the lowest NH_4-N levels (Y1), the values were 8 and 13 kg NH_4-N ha^{-1} and in the trial with the highest NH_4-N levels (Y2), 15 and 50 kg NH_4-N ha^{-1}. Unless otherwise mentioned, only

Table 5. Main effect of preceding crop and incorporation treatment on soil NO3-N (kg ha^{-1}) in late autumn of the first experimental year. Medians of crop and incorporation treatment and statistical significance of F values by analysis of variance (P values). Within columns, medians followed by the same letter are not significantly different at $P < 0.05$. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

		J1	J2[1)]	P1[1)]	P2[2)]	Y1[1)]	Y2	T
0–30 cm	crop							
	V. villosa	8^{b}	51^{b}	14^{b}	8	29^{c}	28^{b}	11^{c}
	T. pratense	3^{a}	5^{a}	2^{a}	4	5^{ab}	14^{a}	4^{b}
	L. multiflorum	3^{a}	4^{a}	1^{a}	5	3^{a}	16^{a}	2^{a}
	H. vulgare	4^{a}	6^{a}	3^{a}	5	12^{b}	35^{b}	7^{b}
	P value	*0.011*	*<0.001*	*<0.001*	–	*<0.001*	*0.006*	*<0.001*
	incorporation							
	Early autumn	6^{b}	12^{b}	7^{b}	6	19^{b}	26^{b}	9^{b}
	Late autumn	3^{a}	6^{a}	2^{a}	4	6^{a}	17^{a}	6^{a}
	Spring	4^{a}	5^{a}	2^{a}	5	7^{a}	23^{a}	5^{a}
	P value	*0.002*	*<0.001*	*<0.001*	–	*<0.001*	*0.013*	*<0.001*
30–60 cm	crop							
	V. villosa	2	15^{b}	13^{b}	–	11^{b}	29^{b}	5^{b}
	T. pratense	1	5^{ab}	1^{a}	–	8^{b}	12^{a}	1^{a}
	L. multiflorum	1	2^{a}	2[3)]	–	2^{a}	13^{a}	1^{a}
	H. vulgare	2	6^{ab}	10^{b}	–	18^{b}	33^{b}	9^{b}
	P value	–	*0.017*	*<0.001*	–	*0.004*	*<0.001*	*<0.001*
	incorporation							
	Early autumn	2	8^{b}	11^{b}	–	17^{b}	26^{b}	7^{b}
	Late autumn	1	5^{a}	7^{a}	–	9^{a}	17^{a}	5^{a}
	Spring	1	6^{a}	5^{a}	–	10^{a}	18^{a}	3^{a}
	P value	–	*<0.001*	*<0.001*	–	*<0.001*	*0.003*	*0.003*

1) There was an interaction between preceding crop and incorporation treatment in trials J2, P1 and Y1. The interaction is presented in Table 8.
2) No replicates in 0–30 cm and no samples taken from 30–60 cm.
3) The treatment was not included in the analysis because too many observations were lacking.

statistically significant ($P < 0.05$) differences between treatments are examined below.

Only in some cases did treatments affect the NH$_4$-N content in the upper soil layer (0–30 cm). For example, hairy vetch increased the NH$_4$-N content in late autumn of the first experimental year in two trials (J2, Y1) by 4–7 kg ha^{-1} (4–7 kg differences between medians) as compared with barley and westerwold ryegrass. In one trial (Y1), early ploughing of hairy vetch increased the NH$_4$-N content by 20 kg ha^{-1} as compared with other incorporation treatments, but the other trials did not confirm this effect. In the following spring, red clover increased the NH$_4$-N content by 5–9 kg ha^{-1} as compared with barley in three trials (J1, P2, Y2) and slightly also in other trials. The NH$_4$-N content of the deeper soil layer (30–60 cm) was unaffected by the treatments.

Effect of green manure crop and barley residues on soil NO$_3$-N

The crops of the first experimental year affected the NO$_3$-N content of the upper soil layer in the

Table 6. Main effect of preceding crop and incorporation treatment on soil NO3-N (kg ha^{-1}) in the spring of the second experimental year. Medians of crop and incorporation treatment and statistical significance of F values by analysis of variance (P values). Within columns, medians followed by the same letter are not significantly different at $P < 0.05$. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

		J1	J2	P1	P2$^{1)}$	Y1	Y2	T$^{1)}$
0–30 cm	crop							
	V. villosa	8	21^{b}	5	32^{c}	30^{b}	47^{b}	16^{b}
	T. pratense	6	10^{a}	5	6^{a}	10^{a}	33^{a}	5^{a}
	L. multiflorum	4	7^{a}	7	5^{a}	12^{a}	34^{a}	1^{a}
	H. vulgare	6	8^{a}	5	9^{b}	12^{a}	38^{ab}	6^{a}
	P value	*0.29*	*0.016*	*0.63*	*<0.001*	*0.005*	*0.027*	*0.002*
	incorporation							
	Early autumn	6^{a}	10^{b}	5	10^{c}	21^{c}	79^{c}	8^{c}
	Late autumn	5^{a}	8^{ab}	7	8^{b}	17^{b}	39^{b}	6^{b}
	Spring	7^{b}	8^{a}	5	7^{a}	10^{a}	34^{a}	5^{a}
	P value	*0.018*	*0.028*	*0.17*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
30–60 cm	crop							
	V. villosa	3	11	4	17^{c}	27	45^{b}	11^{c}
	T. pratense	2	11	3	4^{a}	16	28^{a}	3a^{b}
	L. multiflorum	1	7	4	3^{a}	10	30^{a}	3^{a}
	H. vulgare	2	8	3	7^{b}	21	44^{b}	6^{b}
	P value	*0.09*	*0.88*	*0.83*	*<0.001*	*0.19*	*0.002*	*<0.001*
	incorporation							
	Early autumn	3^{b}	10	3	8^{b}	25^{b}	60^{b}	5^{b}
	Late autumn	2^{a}	9	7	5^{a}	18^{a}	39^{a}	4^{a}
	Spring	2^{a}	9	4	5^{a}	16^{a}	31^{a}	5^{a}
	P value	*0.014*	*0.15*	*0.45*	*<0.001*	*<0.001*	*<0.001*	*0.014*

1) There was an interaction between preceding crop and incorporation treatment in trials P2 and T. The interaction is presented in Table 9.

first autumn in all sampled trials, in the following spring in five trials and in the following autumn in three trials. In the deeper soil layer, the crops affected NO_3-N content in the first autumn in five trials, in the following spring in three trials and in the following autumn in five trials. In the second spring after incorporations, the crops of the first experimental year no longer affected soil NO_3-N.

In late autumn of the first experimental year there was clearly more soil NO_3-N in both soil layers after vetch than after the other green manure crops (Table 5). The NO_3-N contents after barley were similar to those after ryegrass and red clover in the upper soil layer, except in three trials (Y1, Y2, T) in which they were higher. In the deeper soil layer, the NO_3-N contents after barley were similar to those after vetch.

In the following spring, soil NO_3-N was higher after vetch than after other crops in five trials out of seven (Table 6): the difference between the medians of vetch and other crops was 9–26 kg ha^{-1} in the upper layer. In the deeper soil layer, the NO_3-N content was higher after vetch in two trials (P2, T) and lower after ryegrass and clover in three trials (P2, Y2, T) than after barley.

In the third sampling, the differences between crops were small in the NO_3-N content of the upper soil layer (Table 7). In spite of statistically significant differences in the deeper layer in five trials, the differences between the crops were

Table 7. Main effect of preceding crop and incorporation treatment on soil NO3-N (kg ha^{-1}) after harvest of spring barley in the second experimental year. Medians of crop and incorporation treatment and statistical significance of F values by analysis of variance (P values). Within columns, medians followed by the same letter are not significantly different at $P < 0.05$. J1 = Jokioinen 1991–1993, J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, P2 = Pälkäne 1993–1995, Y1 = Ylistaro 1991–1993, Y2 = Ylistaro 1993–1995, T = Toholampi 1991–1993.

		J1	J2	P1	P2 1)	Y1	Y2	T
0–30 cm	crop							
	V. villosa	5^{ab}	7	4	7^{b}	9	14	3^{b}
	T. pratense	8^{b}	8	2	4^{ab}	8	9	1^{a}
	L. multiflorum	4^{a}	8	2	4^{a}	9	16	1a^{b}
	H. vulgare	6^{ab}	8	4	6^{ab}	9	17	2a^{b}
	P value	*0.053*	–	–	*0.039*	*0.91*	*0.09*	*0.02*
	incorporation							
	Early autumn	6^{ab}	8	3	8^{c}	9^{ab}	15	2
	Late autumn	6^{a}	7	3	7^{bc}	11^{b}	14	2
	Spring ploughing	8^{b}	9	4	5^{ab}	10^{ab}	9	2
	Reduced tillage	4^{a}	7	3	4^{a}	7^{a}	14	1
	P value	*0.01*	–	–	*<0.001*	*0.025*	*0.08*	*0.25*
30–60 cm	crop							
	V. villosa	4^{ab}	2	5^{b}	3^{b}	11^{b}	43^{ab}	1
	T. pratense	5^{b}	2	3^{a}	2^{ab}	9^{ab}	31^{a}	<1
	L. multiflorum	3^{a}	3	2^{a}	2^{a}	7^{a}	37^{a}	1
	H. vulgare	5^{ab}	3	6^{b}	3^{ab}	10^{ab}	100^{b}	1
	P value	*0.019*	–	*0.013*	*0.031*	*0.043*	*0.014*	–
	incorporation							
	Early autumn	5^{a}	3	4	3^{b}	15^{b}	54^{b}	1
	Late autumn	4^{a}	2	4	3^{ab}	9^{ab}	63^{b}	1
	Spring ploughing	7^{b}	3	4	3^{ab}	10^{ab}	38^{ab}	1
	Reduced tillage	3^{a}	2	4	2^{a}	7^{a}	33^{a}	<1
	P value	*<0.001*	–	*0.54*	*0.031*	*0.006*	*0.005*	–

1) There was an interaction between preceding crop and incorporation treatment in trial P2.
The interaction is presented in Table 10.

small except in one trial (Y2), in which the amount of NO_3-N after barley was exceptionally high (100 kg ha^{-1}). At the fourth sampling, the crop of the first experimental year had no significant effects on soil NO_3-N.

Effect of incorporation treatments on soil NO_3-N

The effect of incorporation treatment on the NO_3-N content of the upper soil layer in the first autumn was statistically significant in all sampled trials, in the following spring in six trials and in the next autumn in three trials. In the deeper soil layer, incorporation treatment affected NO_3-N content in the first autumn and following spring in five trials and in the following autumn in four trials. In the spring of the third experimental year, the incorporation treatment no longer affected soil NO_3-N. The timing and method of incorporation generally had a similar effect on soil NO_3-N, irrespective of the preceding crop, but in some cases there was an interaction between incorporation treatment and the crop incorporated. These interactions are mentioned in the context of the

Table 8. Effects of incorporation treatments of different preceding crops on soil NO3-N (kg ha^{-1}) in late autumn of the first experimental year in trials with interactions. Medians of incorporation treatment in different crops, and statistical significances of interaction between crop and incorporation treatment by analysis of variance (P value). Within columns, medians followed by the same letter are not significantly different at P < 0.05. J2 = Jokioinen 1993–1995, P1 = Pälkäne 1991–1993, Y1 = Ylistaro 1991–1993.

	0–30 cm				*30–60 cm*			
	V. villosa	*T. pratense*	*L. multiflorum*	*H. vulgare*	*V. villosa*	*T. pratense*	*L. multiflorum*	*H. vulgare*
J2	*P=0.003*				*P=0.034*			
Early autumn	56^{c}	16^{b}	9^{b}	10^{b}	22^{b}	8^{b}	7^{b}	5^{a}
Late autumn	30^{a}	4^{a}	3^{a}	6^{ab}	14^{a}	4^{a}	2^{a}	7^{a}
Spring	51^{b}	4^{a}	4^{a}	5^{a}	12^{a}	5^{a}	2^{a}	6^{a}
P1	*P<0.001*				*P=0.009*			
Early autumn	13^{a}	7^{b}	3^{b}	6^{b}	22^{b}	9^{b}	4 1)	14^{a}
Late autumn	17^{b}	2^{a}	1^{a}	3^{a}	8^{a}	1^{a}	–	9^{a}
Spring	14^{ab}	2^{a}	1^{a}	2^{a}	9^{a}	1^{a}	<1	10^{a}
Y1	*P=0.016*				*P=0.15*			
Early autumn	48^{b}	18^{b}	12^{b}	19^{b}	No interaction			
Late autumn	21^{a}	4^{a}	2^{a}	10^{a}				
Spring	24^{a}	5^{a}	2^{a}	12^{a}				

1) The treatment was not included in the analysis because too many observations were lacking.

main effects of each sampling, and the values are shown in Tables.

Early ploughing in autumn increased the upper soil layer NO_3-N content in the late autumn of the first experimental year in all trials. Compared with other incorporation treatments, which differed only slightly from each other, the increase varied mainly from 2 to 13 kg ha^{-1} (Table 5). In trials J2, P1 and Y1, an interaction was also found between preceding crop and incorporation treatment (Table 8). All exceptions refer to cases in which hairy vetch was the preceding crop: in Y1, the increase in NO_3-N content due to early autumn ploughing was greater after vetch than after other crops. In J2, late ploughing after vetch resulted in by far the lowest NO_3-N content, contrary to P1. In the deeper soil layer, early ploughing distinctly increased the NO_3-N content in five trials out of six, and slightly so also in the sixth trial (J1) (Table 5). In J2 and P1 an interaction was found between the preceding crop and the incorporation treatment: early ploughing after barley did not cause a clear increase in the NO_3-N content (table 8).

In the following spring, the soil NO_3-N content was highest in five trials out of seven in both layers when ploughing was done in early autumn although, from a practical point of view, the difference was small except in Y1 and Y2 (Table 6). In Y1 and Y2, the soil NO_3-N content was higher in both soil layers after late autumn ploughing than after incorporation in spring, although the difference was statistically significant only in the upper layer. In P2 and T, from a practical point of view, significant differences were found in values after hairy vetch and red clover, but those after westerwold ryegrass and barley incorporation treatments did not differ clearly (interaction, Table 9).

In the third sampling, the timing and method of incorporation had only a minor effect on the NO_3-N content of the upper soil layer (Table 7). In the deeper soil layer, marked differences in NO_3-N contents were found only in trials at Ylis-

Table 9. Effects of incorporation treatments of different preceding crops on soil NO3-N (kg ha^{-1}) in spring of the second experimental year in trials with interactions. Medians of incorporation treatment in different crops, and statistical significances of interaction between crop and incorporation treatment by analysis of variance (P value). Within columns, medians followed by the same letter are not significantly different at P < 0.05. P2 = Pälkäne 1993–1995, T = Toholampi 1991–1993.

	0–30 cm				*30–60 cm*			
	V. villosa	*T. pratense*	*L. multiflorum*	*H. vulgare*	*V. villosa*	*T. pratense*	*L. multiflorum*	*H. vulgare*
P2	*P=0.003*				*P=0.007*			
Early autumn	59^{b}	9^{c}	6^{b}	10^{a}	22^{b}	8^{b}	4^{b}	$7a^{b}$
Late autumn	38^{a}	6^{b}	7^{b}	7^{a}	15^{a}	3^{a}	2^{a}	6^{a}
Spring	30^{a}	4^{a}	4^{a}	9^{a}	15^{a}	3^{a}	2^{a}	9^{b}
T	*P=0.021*				*P=0.012*			
Early autumn	17^{a}	10^{b}	6^{b}	8^{a}	18^{b}	4^{a}	4^{b}	$6a^{b}$
Late autumn	18^{a}	6^{b}	3^{b}	6^{a}	10^{a}	3^{a}	3^{ab}	4^{a}
Spring	14^{a}	2^{a}	1^{a}	6^{a}	10^{a}	2^{a}	2^{a}	8^{b}

taro (Y1, Y2). In Y1, the NO_3-N content was lower after reduced tillage than after early autumn ploughing. In Y2, both early and late autumn ploughing resulted in a higher NO_3-N content than did reduced tillage, the medians being 54, 63 and 33 kg ha^{-1}, respectively. After spring ploughing the NO_3-N content (median 38 kg ha^{-1}) was lower than after autumn ploughing treatments, although the difference was not statistically significant. In P2, the effect of incorporation varied, depending on the preceding crop: with early autumn ploughing after hairy vetch the NO_3-N content was 4–6 kg ha^{-1} higher than with other treatments (Table 10).

Discussion

The N content of incorporated plant material had a crucial effect on mineral soil N content after incorporation, as shown also in earlier experiments (Smith and Sharpley 1990, Marstorp and Kirchmann 1991, Vinther 1994). After hairy vetch, the NO_3-N content of the soil was clearly higher than after other green manure crops with lower N contents. Likewise the effect of timing of the incorporation was greatest after vetch. After N-fertilized spring barley, the NO_3-N content of the soil was often high in spite of a low N

Table 10. Effects of incorporation treatments of different preceding crops on soil NO3-N (kg ha^{-1}) in autumn of the second experimental year in trial P2 with interactions. Medians of incorporation treatment in different crops, and statistical significances of interaction between crop and incorporation treatment by analysis of variance (P value). Within columns, medians followed by the same letter are not significantly different at P < 0.05. P2 = Pälkäne 1993–1995.

	0–30 cm	*30–60 cm*			
		V. villosa	*T. pratense*	*L. multiflorum*	*H. vulgare*
P2	*P=0.39*	*P=0.004*			
Early autumn	No interaction	8^{b}	2^{a}	2^{a}	3^{a}
Late autumn		3^{a}	3^{a}	2^{a}	3^{a}
Spring		4^{a}	3^{a}	2^{a}	3^{a}
Reduced tillage		2^{a}	1^{a}	1^{a}	3^{a}

content in the straw residues incorporated, but the timing of incorporation did not have a marked effect on soil N.

The N content of incorporated plant material was most important to the effect of timing of the incorporation. The higher the N content of incorporated material, the greater the increase in the NO_3-N content in soil after early autumn ploughing as compared with later incorporations. Lindén and Wallgren (1993) also found that early ploughing caused a greater accumulation of mineral N in the soil during the autumn after clover and grass-clover leys than after cereals. In addition to the higher quantity of N, this finding may be explained by the more rapid mineralization of N-rich materials (Jensen 1992).

As shown by the soil NO_3-N content before winter, delaying incorporation of the green manure crop in autumn as much as possible, while taking into consideration the appropriate soil moisture, lessens the risk of N leaching. The same conclusion was reached in Canada by Sanderson and Mac Leod (1994), who incorporated lupin in autumn at dates very close to those in this study. Because of the high soil NO_3-N content after hairy vetch, as was also observed by Goffart et al. (1992), early autumn ploughing of vetch should be avoided. Even with red clover, delayed ploughing was clearly beneficial. When cereal stubble was tilled, the timing of autumn ploughing had less effect on the soil NO_3-N, even though the NO_3-N content in the 30–60 cm soil layer was about the same in late autumn after barley as it was after N-rich crops. The beneficial effect of delaying the incorporation of a growing green manure crop is pronounced due to the prolonged N uptake. In addition, the growing green manure crop keeps the soil drier than does stubble, resulting in less downward water flow and a better capacity to carry machines.

Tilling in late autumn did not generally increase the soil NO_3-N content in the spring of the second experimental year as compared with spring incorporations, except in two trials at the Ylistaro experimental site, where the soil had a high mineral N content. There, late autumn ploughing made for a slight increase in the NO_3-N flowing down to the deeper soil layer as compared with spring tillage; the effect became even more pronounced in Y2 after the succeeding spring barley. This can be interpreted as an increased leaching risk, although the following crops may be able to use N from soil layers deeper than those sampled here (Thorup-Kristensen 1996). At other sites with moderate soil mineral N contents, the period between late autumn incorporation and winter was short enough to inhibit N mineralization. The decomposition rate could be influenced by soil mineral N content, as shown in the experiment by Mary et al. (1996), where low soil mineral N slowed down the decomposition rate of wheat straw residues.

Because of the higher soil NO_3-N content in the spring of the second experimental year, in most of the trials more N was potentially available for spring barley after early autumn ploughing than after late autumn ploughing. In addition, at Ylistaro more N was available after late autumn ploughing than after ploughing or reduced tillage in spring. However, the grain yield of spring barley did not correlate with these soil N figures, as shown in an article to be published later.

Postponing the tillage of barley stubble to the spring on light soils caused a slight increase in the NO_3-N content in the deeper soil layer just before the tillage as compared with late autumn ploughing. A possible explanation is the immobilization associated with straw decomposition (Christensen 1986 and Mary et al. 1996) after autumn ploughing, which inhibits the leaching of N on sandy soils (Kolenbrander 1969). When barley stubble is incorporated in spring, immobilization by straw decomposition cannot occur before the leaching period caused by snow melt. We may therefore conclude that although late autumn ploughing may increase N leaching as compared with spring tillage in some cases of high soil NO_3-N content, it may, after N poor crops, even lessen the leaching risk as compared with spring tillage. However, both late autumn and spring incorporations lessen the risk of N leaching as compared with early autumn ploughing. This is in accordance with the finding of

Breland (1994) that clover decomposed rapidly even at 5°C, and that N losses from plant residues rich in N could be reduced by ploughing in the residues late in the autumn or by leaving them on the soil surface until the spring.

Christensen (1986) noted similar decomposition rates for straw buried at depths of 5, 10 and 15 cm. The present study provides weak evidence that reduced tillage decreased the soil NO_3-N content in the autumn following spring tillages, mainly in the presence of N-rich soil.

Soil type has a bearing on the effect of tillage timing on the growth of the succeeding crop and must therefore be taken into account when considering spring instead of autumn tillage. Spring ploughing is not suitable for heavy clay soil (Mikkola 1989), but, as we found here, reduced tillage with a cultivator in spring leads to good growth of spring barley. On other soil types, reduced tillage in spring often causes poor growth of spring barley. As shown by the present study, reduced tillage of red clover, a perennial that strongly competes with cereal crops by regrowth, is particularly unsuitable.

Conclusions

Owing to its beneficial effect on the risk of nitrogen leaching and its suitability for cereal sowing in the succeeding spring, ploughing in late autumn is a recommended procedure for incorporating green manure crops. The importance of delaying incorporation increases with the increase in the crop nitrogen content and soil NO_3-N content. Spring ploughing can be used on all but clay soils. Reduced tillage in spring also reduces N leaching, but its suitability is impaired by the adverse effects on the growth of the succeeding crop. In fields with an exceptionally high soil mineral N content, the simplest way to inhibit N leaching is to avoid N fertilization and crops with a high N content.

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SELOSTUS

Viherlannoituskasvuston kynnön viivyttäminen vähentää typen huuhtoutumista

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Kun viherlannoituskasvusto muokataan maahan, voi kasvusto sisältää suuria määriä typpeä. Etenkin palkokasveja sisältävien kasvustojen typpipitoisuus on korkea, jolloin typen vapautuminen on edullisissa olosuhteissa nopeaa. Viherlannoituksen typen saaminen tehokkaasti seuraavan kasvin käyttöön on paitsi taloudellisesti kannattavaa, suotavaa myös typen huuhtoutumisen vähentämiseksi.

Tutkimus sai alkunsa viherkesantoalan voimakkaasti kasvaessa 1990-luvun alussa, ja perustuukin erilaisiin viherkesannon toteuttamisvaihtoehtoihin tavanomaisessa viljanviljelyssä. Aiempien tutkimustulosten mukaan viherlannoitteen muokkausajankohta vaikuttaa typen vapautumiseen ja huuhtoutumiseen. Tässä tutkimuksessa haettiin parhaita ajankohtia typpipitoisuuksiltaan erilaisten kasvustojen muokkaamiseen.

Seitsemässä kokeessa MTT:n neljällä tutkimusasemalla yksivuotisena viherkesantona kasvaneet ruisvirna, puna-apila ja westerwoldin raiheinä sekä tuleentuneena korjatun ohran sänki ja puintijäte kynnettiin maahan aikaisin tai myöhään syksyllä (vaihdellen syyskuun alusta marraskuun alkuun) tai keväällä ennen kylvömuokkausta. Kyntöjen vaihtoehtona kasvustot muokattiin maahan kyntämättä keväällä ennen varsinaista kylvömuokkausta.

Viherkesannon syyskynnön viivyttäminen vähensi typen huuhtoutumisriskiä. Kynnön viivyttämisestä oli sitä enemmän hyötyä, mitä typpipitoisempaa kasvusto oli. Etenkin virnan aikainen kyntäminen aiheutti suuren huuhtoutumisriskin, sillä kasvimassan korkean typpipitoisuuden lisäksi virnakasvuston kokonaistyppimäärä oli suuri. Ohran sängen kyntöajankohta vaikutti melko vähän typen huuhtotumisriskiin. Niinpä maatilan syyskynnöt kannattaa aloittaa sängiltä ja päättää typpipitoisimpiin viherkesantoihin.

Kevätkyntöä voidaan käyttää myöhäisen syyskynnön ohella huuhtoutumisen hillitsemiseen savimaita lukuunottamatta. Myös kyntämätön perusmuokkaus keväällä vähensi typen huuhtoutumista, mutta haittasi usein seuraavan viljan kasvua. Niissä kokeissa, joissa maan typpipitoisuus oli poikkeuksellisen korkea, typen huuhtoutumista hillittiin parhaiten kasvattamalla kesantovuonna typpilannoittamatonta westerwoldin raiheinää.