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Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment

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SUMMARY

The possibilities for increasing total grain yield in organic cereal production through manipulation of crop rotation design were investigated in a field experiment on different soil types in Denmark from 1997 to 2000. Three experimental factors were included in the experiment in a factorial design: (1) proportion of grass-clover and pulses in the rotation, (2) catch crop (with and without) and (3) manure (with and without). Three four-course rotations were compared. Two of the rotations had 1 year of grass-clover as a green manure crop, either followed by spring wheat or by winter wheat. The grass-clover was replaced by winter cereals in the third rotation. Animal manure was applied as slurry in rates corresponding to 40% of the nitrogen (N) demand of the cereal crops.

Rotational grain yields of the cereal and pulse crops were calculated by summing yields for each plot over the 4 years in the rotation. The rotational yields were affected by all experimental factors (rotation, manure and catch crop). However, the largest effects on both dry matter and N yields were caused by differences between sites caused by differences in soils, climate and cropping history. The rotation without a green manure crop produced the greatest total yield. Dry matter and N yields in this rotation were about 10% higher than in the rotation with a grass-clover ley in 1 year in 4. Therefore, the yield benefits from the grass-clover ley could not adequately compensate for the yield reduction as a result of leaving 25% of the rotation out of production. There were no differences in dry matter and N yields in grains between the rotations, where either spring or winter cereals followed the grass-clover ley. The N use efficiency for ammonium-N in the applied manure corresponded to that obtained from N in commercial fertilizer. There were only very small yield benefits from the use of catch crops. However, this may change over time as fertility builds up in the system with catch crops.

INTRODUCTION

Organic farming in Denmark during the 1980s and 1990s has mainly been based on dairy farming systems with a high proportion of grass-clover and fodder crops in the rotation in combination with a stock of ruminant animals (Tersbøl & Fog 1995). This farm type has with proper management proved to sustain a stable crop production with negligible problems (Askegaard *et al.* 1999*a*). Such rotations receive large nitrogen (N) inputs from N_2-fixation by the grass-clover pastures (Høgh-Jensen & Schjørring 1994; Loges 1998).

In 1999 and 2000 some 482 Danish arable farms, equivalent to 18 863 ha, converted to organic farming in response to a high demand for, and high prices of, organic cereal grains (Offermann & Nieberg 2000; Tersbøl *et al.* 2000). Arable and vegetable organic farming systems are necessary for the provision of sufficient organic raw and processed food for human consumption and feed for pig and poultry production

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Table 1. *Soil texture, content of organic C and total N, and pH in the top 25 cm of the soil at the three experimental sites in autumn 1996 prior to the onset of the experiment. pH is taken as pH($CaCl_2$)+0·5. Soil minerals, organic C and total N are measured in per cent of dry soil* (*Olesen* et al. *2000*)

Location	Clay <2 μm	Silt 2–20 μm	Fine sand 20–200 μm	Coarse sand 200–2000 μm	Organic C	Total N	pH
Jyndevad	4·5	2·4	18·0	73·1	1·17	0·085	6·1
Foulum	8·8	13·3	47·0	27·2	2·29	0·175	6·5
Flakkebjerg	15·5	12·4	47·4	22·9	1·01	0·107	7·4

(von Fragstein 1996), which will be encouraged through increased trade via supermarkets (Hamm & Michelsen 2000).

Within arable organic systems there is a trade-off between the inclusion of N_2-fixing green-manure crops, which may not have a market value, and high N-demanding cash crops. These systems will tend to suffer from lack of N and be less competitive against annual weeds due to the higher proportion of cash crops and small proportion of grass-clover as green manure (Askegaard *et al.* 1999*b*). Some of the problems with N availability and with weed control may be solved through the judicious use of catch crops and any available animal manure (Masiunas 1998; Williams *et al.* 1998). The optimal crop rotation and associated management will depend on soils and climate.

The crop rotation effects may only manifest themselves after many years (Karlen *et al.* 1994). There have only been a few long-term studies under temperate conditions in Europe and North America, where different crop rotations have been compared under organic farming (Bulson *et al.* 1996; Younie *et al.* 1996). Other factorial experiments have compared organic and integrated or conventional crop rotations (Besson *et al.* 1992).

In 1997 a crop rotation experiment started at four sites in Denmark. The objective of the experiment was to explore the possibilities for both short-term and long-term increases in organic cereal production through manipulation of crop rotation design on different soil types. The current paper describes the effects of crop rotation in combination with the use of catch crops and manure on total crop rotation yields. The rotational yield is here taken to be the sum of the grain yields over a four-course rotation.

MATERIALS AND METHODS

The crop rotation experiment was designed as a factorial experiment with three factors (Olesen *et al.* 2000). Results are presented for three sites representing different soil types and climate regions in Denmark. Jyndevad is located in Southern Jutland and represents a coarse sandy soil with an average annual rainfall of 964 mm. Foulum is located in Central Jutland on a loamy sand with an annual rainfall of 704 mm. Flakkebjerg is located in Western Zealand on a sandy loam with an annual rainfall of 626 mm. The soil properties of the ploughing layer is shown for all sites in Table 1.

Experiment treatments

The experimental factors were (1) fraction of grass-clover and pulses in the rotation (crop rotation), (2) catch crop (with and without catch crop or bi-cropped clover) and (3) manure (with and without animal manure applied as slurry).

Four 4-year crop rotations were compared (Olesen *et al.* 2000). However, results are only presented here for the three rotations where all combinations with the other treatments were represented (Table 2). These rotations differ with respect to the use of a grass-clover green manure crop. This crop was present in rotations 1 and 2, but not in rotation 4. The grass-clover crop was followed by spring wheat in rotation 1, and by winter wheat in rotation 2. Crop rotation 1 is only represented at Jyndevad, and rotation 4 is only present at Foulum and Flakkebjerg. Rotation 4 was not included at Jyndevad, because the coarse sandy soil at Jyndevad was considered unsuitable for organic arable rotations without green manure crops. Two grass-clover green manure fields were used in crop rotation 1 in the first experimental year (see comments on 1997 in Table 2). All fields in all rotations were represented every year in two replicates resulting in a total of 64 plots at each site. Each block was subdivided into two sub-blocks. The three-way interactions between crop rotation, catch crop and manure treatments were confounded with the sub-blocks. The plots were completely randomized within each sub-block. The plot size was 378, 216 and 169 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively.

The undersown catch crops were either a pure stand of perennial ryegrass (*Lolium perenne*) or a mixture of perennial ryegrass and four clover species (hop medic *Medicago lupulina*, trefoil *Lotus corniculatus*, serradella *Ornithopus sativus* and subterranean clover *Trifolium subterraneum*). These catch crops were undersown in the cereal or pulse crop in spring. In the spring cereals the sowing took place on the same day as the cereal or pulse crop was sown, except for Jyndevad

Table 2. *Structure of the three different four-course crop rotations with and without catch crops. ' :' indicates that a grass-clover ley, a clover or a ryegrass/clover catch crop is established in a crop of cereals or pulses; '/' indicates a mixture of peas and spring barley or bi-cropping of winter cereals and clover*

	Course (field)	Rotation 1	Rotation 2	Rotation 4
Without catch crop	1	Spring barley : ley	Spring barley : ley	Spring oat
	2	Grass-clover	Grass-clover	Winter wheat
	3	Spring wheat*	Winter wheat	Winter cereal‡
	4	Lupin†	Peas/barley	Peas/barley
With catch crop	1	Spring barley : ley	Spring barley : ley	Spring oat : clover
	2	Grass-clover	Grass-clover	Winter wheat/clover
	3	Spring wheat : Grass*	Winter wheat : Grass	Winter cereal/clover‡
	4	Lupin : Grass-clover†	Peas/barley : Grass-clover	Peas/barley : Grass-clover

* Grass-clover in 1997.
† Winter wheat in 1997.
‡ Winter wheat except at Foulum in 1999 and 2000, where triticale was grown instead.

where sowing was delayed in order to permit weed harrowing in the rotations with catch crops. Delayed sowing was possible at Jyndevad as the use of irrigation ensured the germination of the catch crops. In the winter cereals the catch crop was sown in April just after the first weed harrowing.

The catch crop treatment in rotation 4 included a bi-crop of winter wheat in a pure stand of white clover. The white clover was undersown in oat. After harvest in the autumn, and a few days before sowing of winter wheat, the clover was cut as short as possible followed by rotary cultivation in 12-cm wide bands at double normal row spacing (25 cm). The winter wheat was drilled into these bands.

The plots receiving manure were supplied with anaerobically stored slurry at rates corresponding to 40% of the N demand of the specific rotation. The N demand was based on a Danish national standard (Plantedirektoratet 1997). The N demands from grass-clover and from peas/barley were set to nil. In rotations 1 and 2, spring barley, spring wheat and winter wheat each received slurry corresponding to a target of 50 kg NH_4-N/ha. In rotation 4, the target application rates were 40 and 70 kg NH_4-N/ha for spring oats and winter cereals, respectively. The actual average application rates are shown in Table 3. The average N rate in rotation 1 differs from a simple mean of the applied rates for the individual crops, because winter wheat was grown in 1997 and spring wheat in the other years.

Crop management

The experimental treatments were introduced in 1997. In 1996 a spring barley crop undersown with grass-clover was grown at all sites. No pesticides were applied in 1996. All locations were previously under conventional cropping. The crops during the 5 years prior to initiation of the experiment included different arable crops at Jyndevad and Flakkebjerg, and grass-clover and cereal crops at Foulum (Djurhuus & Olesen 2000).

Table 3. *Average rates of NH_4-N and total-N (kg/ha) in slurry to the individual crops in rotations R1, R2 and R4 at Jyndevad, Foulum and Flakkebjerg*

		Jyndevad		Foulum		Flakkebjerg	
Nutrient	Crop	R1	R2	R2	R4	R2	R4
NH_4-N	Spring barley	42	42	45		48	
	Spring wheat	43					
	Spring oat				38		35
	Winter cereals	33	42	46	64	46	67
	Average in rotation	20	21	23	41	24	40
Total-N	Average in rotation	40	39	34	61	35	58

The experiment was unirrigated at all sites except at Jyndevad. The amount of irrigation applied at Jyndevad was *c.* 100, 80, 20 and 90 mm in 1997, 1998, 1999 and 2000, respectively. All straw and grass-clover production was incorporated or left on the soil in all treatments. However, straw from the oat plots with catch crop at Foulum was removed in 1999 in order to promote growth of the undersown white clover.

The bi-cropping of wheat and white clover in crop rotation 4 followed the principles of Clements *et al.* (1996), and the methodology is described by Olesen *et al.* (2000). Weeds in cereals and pulses were mainly controlled by harrowing (Olesen *et al.* 2000).

The mean temperature during the main growing season (April to July) was around or above the normal

Table 4. *Temperature and rainfall in April to July at the three experimental sites during the 4 experimental years compared with average climate for 1961–90*

Location	1997	1998	1999	2000	Normal
Mean temperature (°C)					
Jyndevad	12·2	12·5	12·8	12·8	11·8
Foulum	11·4	11·3	11·8	11·9	11·4
Flakkebjerg	11·9	12·1	12·5	12·7	11·8
Rainfall (mm)					
Jyndevad	303	344	268	260	272
Foulum	284	228	261	188	219
Flakkebjerg	164	232	254	139	203

in all years (Table 4). The rainfall was highest at Jyndevad and lowest at Flakkebjerg, although the rainfall did not deviate substantially from the normal values. The driest conditions were experienced at Flakkebjerg in 2000.

Measurements

Each plot was subdivided into three to five subplots. The grain yield of cereals and pulses were measured at harvest in two subplots in each plot using a combine harvester. The size of the net harvest plots was 23, 24 and 16 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively. The dry matter content of grains was determined after oven drying at 80 °C for 24 h. Total N in the grains was determined on finely milled samples from each plot by the Dumas method (Hansen 1989).

Soil mineral N was determined from soil samples taken in March prior to soil cultivation in all plots with cereals or pulses. Eight samples were taken per plot using a soil auger (22 mm diameter) to a depth of 50 cm at Jyndevad and 100 cm at Foulum and Flakkebjerg. The soil samples from each plot were thoroughly mixed prior to taking a subsample, which was frozen prior to extraction and analysed for nitrate and ammonium N content, which was determined in 1 M KCl (1:5 w/v) soil extracts using flow injection and autoanalyser, respectively. The soil mineral N content was calculated by multiplying the N concentrations by the soil dry bulk density measured prior to onset of the experiment (Djurhuus & Olesen 2000).

Statistical analyses

The grain yields and soil mineral N contents for individual crops and locations were analysed using a linear mixed model with year, experimental treatments and their interactions as fixed effects and block, main plot and their interactions with year as random effects (Tables 5–7). The general form of the model thus

Table 5. *Mean soil mineral N (nitrate plus ammonium) (kg N/ha) measured in March prior to soil cultivation in cereals and pulses with and without catch crop (+/− CC). Soil mineral N was measured to 50 cm depth at Jyndevad, and to 100 cm depth at Foulum and Flakkebjerg. The presented values are averages over 4 years*

	Jyndevad		Foulum		Flakkebjerg	
Crop	−CC	+CC	−CC	+CC	−CC	+CC
Spring barley	15	16	32*	28	37*	32
Spring wheat†	25	25				
Spring oat			31	28	37*	32
Winter wheat after grass-clover	31	30	51	52	41	44
Winter wheat after oat			34	35	29	30
Winter wheat/triticale after wheat			34	34	31*	42
Peas/barley	16*	18	34	35	37	38
Lupin	19	19				

* Difference between catch crop treatments is significant at the 95% confidence level.
† Only means of 3 years, 1998–2000.

becomes

$$
\begin{aligned}
Y_{yrcmbh} = {} & \mu + \alpha_r + \beta_c + \gamma_m + (\alpha\beta)_{rc} + (\alpha\gamma)_{rm} \\
& + (\beta\gamma)_{cm} + \delta_y + (\alpha\delta)_{yr} + (\beta\delta)_{yc} + (\gamma\delta)_{ym} \\
& + (\alpha\beta\delta)_{yrc} + (\alpha\gamma\delta)_{yrm} + (\beta\gamma\delta)_{ycm} \\
& + E_b + F_{yb} + G_{bh} + H_{ybh} + J_{yrcmbh} \qquad (1)
\end{aligned}
$$

where Greek symbols denote fixed effects, and capital letters denote random effects. The indices y, r, c, m, b and h identify year, rotation, catch crop, manure, block and main plot. The random effects are assumed to be independent and normally distributed with zero mean and constant variance.

Logarithmic transformations of yield and soil mineral N were used to obtain variance homogeneity. It should be noted that when using log-transformed data in the analyses, when no interaction is detected, the effects on the measurement scale are multiplicative.

Total rotational grain yields were calculated for each plot by summing yields over all 4 experimental years. These rotational grain yields were calculated separately for all cereal crops and for all harvested crops (also including lupins and pea/barley) in the rotations (Tables 8–10). The rotational grain yields for each location were analysed using a linear mixed model with field, the experimental treatments and their interactions as fixed effects and block and main plot

Table 6. *Grain yields of individual crops* (*t DM/ha*) *for all treatments* (*without and with catch crops* (*−/+ CC*), *with/without manure* (*man*)) *and associated significance levels based on* F-*statistics*

Location	Crop (rotations)	−CC		+CC		Significance levels		
		−man	+man	−man	+man	man	CC	man × CC
Jyndevad	Spring barley (R1, R2)	1·7	2·4	2·3	3·0	<0·001	<0·001	0·412
	Spring wheat (R1)	2·5	3·2	2·4	3·0	0·002	0·563	0·887
	Winter wheat after grass-clover (R2)	2·3	3·0	2·2	3·1	0·025	0·963	0·449
	Peas/barley (R2)	3·5	3·2	3·1	3·9	0·105	0·284	0·349
	Lupin (R1)	1·6	2·1	1·8	1·6	0·083	0·129	0·007
Foulum	Spring barley (R2)	2·6	3·7	3·0	4·3	<0·001	0·003	0·952
	Spring oat (R4)	3·4	4·3	3·6	4·6	<0·001	0·044	0·698
	Winter wheat after grass-clover (R2)	3·4	4·8	3·4	5·0	<0·001	0·823	0·910
	Winter wheat after oat (R4)	2·4	4·5	2·2	3·6	<0·001	0·002	0·430
	Winter wheat/triticale after wheat (R4)	2·0	4·4	1·6	2·3	<0·001	<0·001	0·512
	Peas/barley (R2, R4)	4·1	3·8	4·1	4·0	0·001	0·178	0·160
Flakkebjerg	Spring barley (R2)	1·9	3·1	2·1	3·3	<0·001	0·013	0·855
	Spring oat (R4)	2·3	3·1	2·7	3·8	<0·001	<0·001	0·379
	Winter wheat after grass-clover (R2)	3·5	4·1	3·8	4·1	0·043	0·395	0·597
	Winter wheat after oat (R4)	2·4	3·7	2·3	3·8	<0·001	0·501	0·323
	Winter wheat after wheat (R4)	2·4	3·5	1·8	2·9	<0·001	<0·001	0·047
	Peas/barley (R2, R4)	2·7	2·9	3·2	3·3	0·093	<0·001	0·688

as random effects. The total amount of applied ammonium-N in the manure for each plot was used as a continuous variable in the model instead of the manure treatment effect. The field denotes the starting course of the crop rotation, i.e. the crop used in 1997 (Table 2). The general form of the model then becomes

$$\begin{aligned} Y_{rfcmbh} = {} & \mu + \alpha_r + \beta_c + \gamma x_{rfcmbh} \\ & + (\alpha\beta)_{rc} + \gamma_r x_{rfcmbh} \\ & + \gamma_c x_{rfcmbh} + \gamma_{rc} x_{rfcmbh} \\ & + \delta_f + (\alpha\delta)_{fr} + (\beta\delta)_{fc} + \gamma_f x_{rfcmbh} \\ & + (\alpha\beta\delta)_{frc} + \gamma_{fr} x_{rfcmbh} + \gamma_{fc} x_{rfcmbh} \\ & + \gamma_{frc} x_{rfcmbh} + E_b + F_{bh} + G_{rfcmbh} \end{aligned} \tag{2}$$

where α, β and δ denote fixed effects, and capital letters denote random effects. All terms with γ should be interpreted as slopes (t DM/kg N). x_{rfcmbh} is the amount of ammonium N in the applied manure (kg N/ha). The indices f, r, c, m, b and h identify effects of field number, rotation, catch crop, manure, block and main plot. The random effects are assumed to be independent and normally distributed with zero mean and constant variance.

One of the fields of rotation 1 at Jyndevad had grass-clover in 1997 instead of lupin, resulting in only 2 productive years compared with the 3 productive years of the other fields. The effect of 3 *v.* 2 productive years was estimated at 2·9 t DM/ha for dry matter yield and 46 kg N/ha for N yield in an analysis of variance, which included the effect of the treatments, their interactions and the number of productive years on rotational yields. The random effects were the same as shown in Eqn (2). The rotational yield data, which included all harvested crops for rotation 1, were corrected to 3 productive years in the estimates presented here.

The parameters of the models were estimated using the method of residual maximum likelihood (REML) (Searle *et al.* 1992) using the Newton–Raphson algorithm implemented in the MIXED procedure of SAS, Statistical Analysis System (SAS Institute 1996). In cases where more than one random effect had to be used for calculating the numerator of *F*-tests or standard error, the number of degrees of freedom were calculated approximately using Satterthwaites method (Satterthwaite 1946).

RESULTS

Soil mineral N contents in March varied between sites and crops (Table 5). The spring soil mineral N content was higher in winter wheat after grass-clover compared with the other crops, and the N content was lowest at Jyndevad. However, it should be noted that soil samples at Jyndevad were taken to a depth of 50 cm only, whereas samples at Foulum and Flakkebjerg were taken to a depth of 100 cm. The coarse sandy soil at Jyndevad restricts root growth to the upper 50–60 cm, whereas rooting depth of crops are 100 cm or more on the loamy sand and sandy loams

Table 7. *Nitrogen concentration in grain dry matter of individual crops (%) for all treatments (without and with catch crop (−/+ CC), with/without manure (man)) and associated significance levels based on* F*-statistics*

Location	Crop/manure	−CC		+CC		Significance levels		
		−man	+man	−man	+man	man	CC	man × CC
Jyndevad	Spring barley (R1, R2)	1·34	1·33	1·34	1·39	0·166	0·060	0·046
	Spring wheat (R1)	2·00	2·08	2·06	2·08	0·407	0·600	0·815
	Winter wheat after grass-clover (R2)	1·74	1·69	1·68	1·71	0·213	0·398	0·667
	Peas/barley (R2)	3·34	3·38	3·23	3·32	0·789	0·004	0·492
	Lupin (R1)	6·26	6·10	6·10	6·32	0·699	0·762	0·200
Foulum	Spring barley (R2)	1·26	1·37	1·30	1·41	<0·001	0·003	0·965
	Spring oat (R4)	1·55	1·57	1·47	1·64	0·005	0·805	0·035
	Winter wheat after grass-clover (R2)	1·68	1·70	1·66	1·63	0·594	0·004	0·395
	Winter wheat after oat (R4)	1·68	1·65	1·64	1·65	0·954	0·473	0·590
	Winter wheat/triticale after wheat (R4)	1·60	1·73	1·94	1·80	0·944	<0·001	0·209
	Peas/barley (R2, R4)	3·20	3·22	3·09	3·14	0·460	0·049	0·018
Flakkebjerg	Spring barley (R2)	1·29	1·31	1·27	1·31	0·225	0·648	0·503
	Spring oat (R4)	1·49	1·50	1·43	1·56	0·009	0·907	0·010
	Winter wheat after grass-clover (R2)	1·59	1·48	1·48	1·52	0·229	0·193	0·019
	Winter wheat after oat (R4)	1·40	1·49	1·56	1·57	0·044	<0·001	0·400
	Winter wheat after wheat (R4)	1·43	1·58	1·70	1·83	0·005	<0·001	0·743
	Peas/barley (R2, R4)	2·51	2·58	2·47	2·57	0·075	0·625	0·727

Table 8. *Effects of crop rotation without or with catch crop (−/+ CC) on rotational dry matter (t DM/ha) and nitrogen (kg N/ha) grain yields. The rotational yields were calculated either as the sum of all cereal crops or the sum of all crops in the rotations. The yields were estimated for each site separately at a N-rate of 0 kg N/ha*

Yield basis	Location	Rotation 1		Rotation 2		Rotation 4		S.E.D.	D.F.
		−CC	+CC	−CC	+CC	−CC	+CC		
Dry matter (t/ha)									
Cereals	Jyndevad	4·3	4·7	4·0	4·5			0·34	51
	Foulum			6·1	7·0	8·4	7·7	0·36	48
	Flakkebjerg			5·8	6·0	7·2	7·2	0·35	50
All harvested crops	Jyndevad	6·7	6·8	7·3	7·8			0·30	51
	Foulum			10·3	11·0	12·4	11·8	0·39	48
	Flakkebjerg			8·9	9·0	9·8	10·6	0·46	51
Nitrogen (kg N/ha)									
Cereals	Jyndevad	69	76	64	70			11	54
	Foulum			94	106	133	123	14	48
	Flakkebjerg			88	86	102	106	6	51
All harvested crops	Jyndevad	173	167	178	177			11	51
	Foulum			227	232	265	244	10	49
	Flakkebjerg			161	168	169	183	9	51

at Foulum and Flakkebjerg (Andersen 1986). Use of catch crops in some cases significantly reduced soil mineral N content in the spring cereals. At Jyndevad catch crops significantly increased soil mineral N for peas/barley. However, this effect was very small (2 kg N/ha). The second year of wheat and clover bi-cropping significantly increased soil mineral N at Flakkebjerg.

Grain yields of individual crops were lowest at Jyndevad, and highest for spring cereals at Foulum, whereas winter cereals had similar high yields at Foulum and Flakkebjerg (Table 6). There were significant yield increases from catch crop for spring barley and spring oat, with the highest increases in general at Jyndevad and Foulum. There was also a significant yield increase from catch crop for pea:barley at

Table 9. *Effects of the catch crop (+/−CC) on response of rotational dry matter and N grain yield to ammonium-N applied in manure. For N yield the response is equivalent to the N use efficiency. The responses were estimated for each site separately and for yields calculated either as the sum of all cereal crops or the sum of all crops in the rotations*

Yield basis	Location	−CC	+CC	S.E.D.	D.F.
Dry matter yield (t DM/kg N)					
Cereals	Jyndevad	0·019	0·019	0·0045	51
	Foulum	0·029	0·022	0·0030	48
	Flakkebjerg	0·020	0·023	0·0029	51
All harvested crops	Jyndevad	0·021	0·025	0·0039	51
	Foulum	0·027	0·021	0·0034	49
	Flakkebjerg	0·021	0·025	0·0037	51
N yield (kg N/kg N)					
Cereals	Jyndevad	0·28	0·29	0·079	54
	Foulum	0·49	0·39	0·054	49
	Flakkebjerg	0·33	0·42	0·044	51
All harvested crops	Jyndevad	0·45	0·49	0·143	51
	Foulum	0·41	0·41	0·078	48
	Flakkebjerg	0·39	0·49	0·068	51

Flakkebjerg. The yield of spring wheat in rotation 1 and winter wheat in rotation 2 was unaffected by catch crops. The bi-cropping of winter cereals and white clover reduced yields compared with a pure winter cereal crop. The yield reduction was highest at Foulum and in the second year of bi-cropping.

N concentration in the grains generally decreased in the order Jyndevad > Foulum > Flakkebjerg (Table 7). Manure application increased N concentrations for the spring cereals and the second year winter cereals at Foulum and Flakkebjerg. Catch crops in some cases increased N concentrations in grains of the spring cereals, especially with manure application. However, catch crops significantly reduced the N concentration of winter wheat in rotation 2 at Foulum.

The rotational grain yield calculated as the sum of grain yields of all harvested crops and of cereals only over all 4 years of the rotation varied considerably between sites and rotations (Table 8 and Fig. 1). The lowest yields were obtained at Jyndevad and the highest at Foulum. Rotation 1 gave the lowest and rotation 4 the highest yields. The effect of catch crop on rotational yield of all harvested crops was only significant for rotation 4 at Flakkebjerg, where a yield increase of 0·8 t/ha was obtained. For the rotational yield of cereal crops at Foulum there was a significant yield increase for the catch crop of 0·9 t/ha in rotation 2, but a significant yield decrease of 0·7 t/ha in rotation 4. Nitrogen yields were considerably higher when all crops were included compared with cereals only (Table 8). This is due to the higher N concentrations of the pulse crops (Table 7).

Table 10. *Effect of field (starting course) on dry matter (t/ha) and nitrogen (kg N/ha) grain yield for all harvested crops in rotation 2. The yields were estimated for all sites simultaneously at a N-rate of 0 kg N/ha using only data from crop rotation 2. The S.E.D. for dry matter yield was 0·40 t/ha (D.F. = 69) for comparisons within columns and 0·75 t/ha (D.F. = 6) for all other comparisons. The S.E.D. for N yield was 9·1 kg N/ha (D.F. = 69) for comparisons within columns and 14·7 kg N/ha (D.F. = 8) for all other comparisons*

Yield type	Field	Jyndevad	Foulum	Flakkebjerg
Dry matter (t/ha)	1	8·6	11·1	9·0
	2	8·2	10·9	8·5
	3	6·7	9·5	7·9
	4	6·8	11·3	10·2
Nitrogen (kg N/ha)	1	208	226	153
	2	175	223	155
	3	176	223	148
	4	153	247	201

The yield response to applied N was almost identical for all rotations and all sites (Table 9 and Fig. 1). This yield response corresponded to about 2·4 t DM per 100 kg of ammonium-N applied in slurry. The N-use efficiency defined as the increase in grain N content per applied amount of ammonium-N in slurry varied from 28 % to 49 % for grain N in cereal crops and from 39 % to 49 % for grain N from all harvested crops (Table 9).

There were highly significant effects of fields on the grain yields in rotation 2. The lowest grain yields were obtained for field 3 at all sites (Table 10). This field did not have a full grass-clover green manure prior to the winter wheat (Table 2). Field 4 at Jyndevad also gave moderately low yields.

DISCUSSION

Total grain yield of the cereal and pulse crops in the tested rotations was affected by all experimental factors (rotation, manure and catch crop). However, the largest effects on both dry matter and N yields were caused by differences between sites influenced by differences in soils, climate and cropping history. The lowest yields were obtained at Jyndevad on the coarse sandy soil, where losses of nitrogen due to leaching are high (Hansen *et al.* 2000). The experimental area at Flakkebjerg was previously grown with mainly cereals, whereas the area at Foulum was part of a mixed crop rotation that also included grass and grass-clover (Djurhuus & Olesen 2000). This is probably the reason for the higher yields at Foulum compared with Flakkebjerg.

Rotation 2 gave an increase in dry matter yield for all harvested crops of 12 % over rotation 1 at

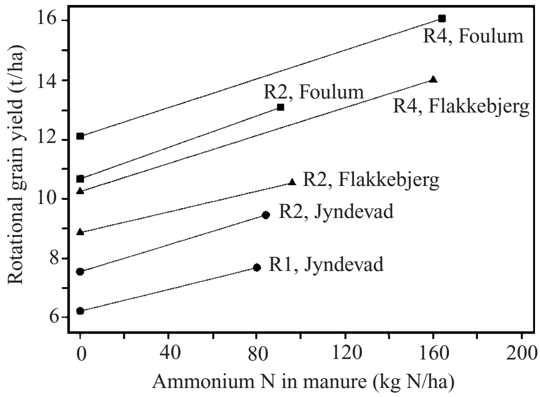

Fig. 1. Effects of total applied ammonium-N in manure on rotational grain yield of all harvested crops for the individual crop rotations and locations. R1, R2 and R4 refer to rotations 1, 2 and 4.

Jyndevad. However, this difference is mainly due to the higher yields of peas/barley in rotation 2 compared with the lupin yields in rotation 1. When a correction for the lower lupin yields is made, rotation 1 gives a benefit of 5% over rotation 2 in dry matter. The difference in N yield between rotations 2 and 1 was 4% in favour of rotation 2, and this was unaffected by the type of pulse crop.

Rotation 4 gave a dry matter yield increase for all crops of 13 and 15% over rotation 2 at Foulum and Flakkebjerg, respectively. For N, rotation 4 gave an increase of 11 and 7% for Foulum and Flakkebjerg, respectively. The yield increases would have been 33% if the grain yields of individual cereal and pulse crops had been the same in rotations 2 and 4 (increase from 3 to 4 productive years). Crop rotation 2 has a large N-input through the N fixation in the grass-clover green manure. The positive effects of this on yield of the following cereals were not enough to compensate for the lower overall yield from effectively leaving 25% of the rotational area out of production. This situation may, however, change over time as soil fertility builds up in rotation 2 and is depleted in rotation 4. This is also indicated in Table 10 where the rotation yield of field 3 was considerably lower than for the other fields, because the winter wheat of field 3 did not have grass-clover as a previous crop. The dry matter yield decreased from rotations 4 to 2 by 9 and 11% for Foulum and Flakkebjerg, respectively, when the yields were corrected for the lower yields of field 3.

Høgh-Jensen (1999) used a simulation model to estimate the effect of the ley proportion on yields in a stockless crop rotation for Danish climatic conditions. It was found that the rotational grain yield decreased by about 10% when increasing the ley proportion from 0 to 20% using approximately the same proportion of pulses in the rotation. This is nearly the same difference as found in the crop rotation experiment. However, the results were highly dependent upon the inclusion of pulses in the rotation, because the pulse crops also provide N input to the system through N fixation.

The effects of the catch crops on rotational grain yield were smaller than the effects of crop rotation and manure application. The effect of catch crop was significantly positive for dry matter yield in rotation 4 at Flakkebjerg only. At Foulum the catch crops in rotation 4 caused a small yield reduction. The cereal: clover bi-cropping system in rotation 4 was most prone to failure in the second year winter cereal (Table 6), partly due to problems with grass weeds and partly due to large incidences of take-all (*Gaeumannomyces graminis*), which in some cases were higher in the bi-cropping system compared with the ploughed system without catch crops. These problems suggest that crop rotation 4 can be optimized by reducing the proportion of winter cereals in the rotation and by avoiding a second year of bi-cropping.

The positive effects of catch crops on dry matter yields of spring cereals at Jyndevad and Foulum were not sufficient to significantly increase rotational yields (Tables 6 and 8). This is primarily caused by a dilution of the positive effects, because the yield benefits were only obtained in 3 of the 4 years (no catch crop treatment effect in 1997), and because the spring cereals only occupied one-quarter of the rotation. In addition, the undersown ryegrass catch crop may in some cases compete with the main crop for N. This is illustrated by the lower N concentration in the catch crop treatment in winter wheat in rotation 2 at Foulum (Table 7).

The effects of catch crops on dry matter yields of spring cereals were smaller at Flakkebjerg. On this sandy loam the catch crops may have reduced soil mineral N in spring, thus reducing the amount of N available for the spring cereal. The effect is called pre-emptive competition and most frequently occurs on soils with good N retention or under conditions with low winter rainfall (Thorup-Kristensen 1993). The low soil mineral N concentration in catch crop treatments at Foulum and Flakkebjerg before spring cereals indicates that pre-emptive competition may have played a role at both sites (Table 5). The average winter rainfall (November to March) during the four experimental years was 403, 259 and 238 mm at Jyndevad, Foulum and Flakkebjerg, respectively. The lower winter rainfall at Foulum and Flakkebjerg also indicates that pre-emptive competition may have occurred here.

The small effect of catch crops on crop yields was probably also an effect of the relatively short period that catch crops have been grown in the experiment. Only about 10–20% of the N returned in ryegrass residues are taken up in a following cereal crop (Jensen 1992; Thomsen & Jensen 1994). The remaining N in the catch crop will be available to following crops or lost by leaching. The effect of catch crops will therefore accumulate, and field experiments have shown that yield effects of catch crops over time may change from negative to positive (Hiitola & Eltun 1996).

The estimated response of grain yield to manure application of 2·4 t DM per 100 kg NH_4-N is about twice as high as the response estimated by Tersbøl & Kristensen (1997) using data from surveys on arable organic farms in Denmark. Their unfertilized yield on sandy loam soils was 2·7 t DM/ha for rotations with a low frequency of grass-clover crops, which is very similar to the yields obtained here (Table 6). The lower yield response to manure in the on-farm studies may have occurred partly because of lower utilization efficiencies under the on-farm conditions and partly because the effect of manure gets obscured by other interacting effects. The N use efficiency of grain for ammonium-N applied in manure was estimated at about 37% for cereal crops and about 44% for grain N based on all harvested crops (Table 9). A similar N use efficiency of 41% was found as an average for an application of 50 kg of fertilizer N to winter wheat in on-farm fertilizer experiments carried out during 1991–1998 (Knudsen *et al.* 1999).

The effect of leys on cereal yields was probably partly caused by effects on N fertility, and partly by other fertility effects. It should be noted that all grass-clover production was left in the field as a mulch, which probably has profound effects on soil N fertility. Grass-clover leys have been found to increase the yield potential of following cereals beyond that which can be compensated by N fertilization (Hanley & Ridgman 1979; Johnston *et al.* 1994; Uhlen *et al.* 1994; Eriksen 2001). Such fertility effects may be mediated through effects on soil quality, diseases, etc. (Karlen *et al.* 1994; Berzsenyi *et al.* 2000). Hanley & Ridgman (1979) found that the full benefits of the leys were obtained already during the first rotation cycle. However, other results have shown that soil fertility changes over time due to effects of crop rotation on both amount and quality of plant residues (Persson & Mattsson 1993; Drinkwater *et al.* 1998).

CONCLUSION

The results of the first course of this crop rotation experiment show large yield differences between the different sites. The largest rotation yields were obtained in the crop rotation without a green manure crop. This rotation gave an increase of rotational dry matter and N yields of about 10% over the rotation with grass-clover ley in one-quarter of the rotation. There were no differences in dry matter and N yields in grains between the rotations, where either spring or winter cereals followed the grass-clover ley. The N use efficiency for ammonium-N in the applied manure corresponded to that obtained from N in commercial fertilizer. There were only very small yield benefits from the use of catch crops.

The experiment is continuing, and further effects are expected to be caused by long-term changes in soil fertility and will therefore take longer time to manifest in the experiment. These further effects may increase the benefits from using catch crops and from the inclusion of grass-clover leys.

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