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The Danish organic crop rotation experiment for cereal production 1997-2004

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1 Introduction

Consumer demands and politically determined subsidies increased certified organic farming in Denmark to 6.3 % of the agricultural land in 2003 (Plantedirektoratet, 2004). Most of these farms were traditional dairy farms, but since 1999, many farms with arable crops only, or farms with pigs or poultry, have converted to organic farming. In 2003, cattle farms (dairy or beef) constituted 39 % of the organic farms, farms with pigs or poultry constituted 20 % of the farms and the remaining 40 % of the farms were dominated by arable and vegetable crop production (Tersbøl et al., 2000; Plantedirektoratet, 2004).

The arable farms (excluding farms with vegetables as main crops), grow cereals for grain production in more than 50 % of the cultivated area, and have grass-clover or other N_2-fixing green manure crops in less than 20 % of the cultivated area. In contrast, the dairy farms typically have diversified crop rotations, with grass-clover in 40-60 % of the area, and cereals in less than 30 % of the area (Simmelsgaard et al., 1998; Kristensen et al., 2004). There are only few agronomic problems on organic farms with a large proportion of grass-clover ley in the crop rotation and a stock of ruminant animals (Askegaard et al., 1999; Mäder et al., 1999). Crop rotations comprising both grass-clover fields and arable crops have shown to be relatively robust in relation to most problems with weeds, pests and diseases (Dubois et al., 1999). Such rotations receive large N inputs from N_2-fixation by the grass-clover leys (Høgh-Jensen & Schjørring, 1994; Loges, 1998). Grass-clover leys have also been found to increase yields of succeeding cereal crops mainly as an effect of increased availability of N (Johnston et al., 1994).

More challenging agronomic problems exist in arable and vegetable organic farming systems. Such systems are necessary for the provision of sufficient organic raw and processed food for human consumption and feed for pig and poultry production (Fragstein von, 1996). The productivity of arable crop rotations for organic farming is often low due to the lack of N, and because use of artificial fertilizers is prohibited and availability of animal manure is limited on these farms (Olesen et al., 2002). Within arable organic systems, there is a trade-off between the inclusion of N_2-fixing crops, which may not have an economic value, and N demanding cash crops. These systems will tend to suffer from the lack of N and be less competitive against weeds due to the higher proportion of cash crops and small proportion of grass-clover as green manure. To retain nutrients in the arable organic farming systems, catch crops are widely used. These often include N_2-fixing species. Both catch crops and manure application can affect the crop/weed relationship (Gallandt et al., 1999). The optimal crop rotation and associated management will depend on soils and climate.

Weeds are more important in organic farming than in conventional systems, where weed problems can be remedied with herbicide applications. In organic farming, preventive measures, crop management and mechanical weed control are the only available options for weed management (Kropff et al., 2000). Interactions between weeds, weed management, nutrients, nutrient management and crop productivity are thus critical for weed control in arable organic farming.

The interactions between all these factors are difficult to study using the traditional field experiments, where the effects of a few factors are studied separately and isolated from the system as a whole in which they would eventually operate. Cropping system experiments provide knowledge with more relevance for the whole system (Gallandt et al., 1999). 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 (e.g. Bulson et al., 1996; Younie et al., 1996). Other factorial experiments have compared organic and integrated or conventional crop rotations (e.g. Besson et al., 1992; Drinkwater et al., 1998).

In 1997 a crop rotation experiment was initiated at three 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 experiment included three factors (proportion of grass-clover in the rotation, catch crop cultivation and manure application) in a randomised factorial design. The main indicators measured in the experiment were crop yield, nutrient leaching and weeds.

Table 1: Soil texture, organic C, total N, and pH in the top 25 cm of the soil at the three sites in autumn 1996 prior to the onset of the experiment, and mean annual precipitation; pH is taken as pH ($CaCl_2$)+0.5. Minerals, organic C and total N were measured in percent of dry soil (Olesen et al., 2000).

Site	Clay < 2 µm	Silt 2-20 µm	Fine sand 20-200 µm	Coarse sand 200-2000 µm	Organic C %	Total N %	pH	Annual precipitation mm
Jyndevad	4.5	2.4	18.0	73.1	1.17	0.085	6.1	964
Foulum	8.8	13.3	47.0	27.2	2.29	0.175	6.5	704
Flakkebjerg	15.5	12.4	47.4	22.9	1.01	0.107	7.4	626

2 Experimental design and site conditions

The Danish organic crop rotation experiment was designed as a three-factorial experiment with all crops in the rotations represented every year (Olesen et al., 2000). Results are presented for three sites representing different soil types and climatic regions in Denmark (Table 1), and for three rotations (R1, R2 and R4). Rotation 3 was only included at one location and with only one combination of treatments. Jyndevad is located in Southern Jutland on coarse sand, Foulum is located in Central Jutland on loamy sand and Flakkebjerg is located in Western Zealand on sandy loam. The plot gross size was 378, 216 and 169 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively. The three experimental sites have been thoroughly described by Djurhuus & Olesen (2000). Prior to the experiment, the experimental fields had been under conventional farming.

In 1999, a workshop was held in Denmark with the theme "Designing and testing crop rotations for organic farming" (Olesen et al., 1999). In this publication, further considerations on the design and testing of this experiment and many others can be found.

2.1. Experimental treatments

The following experimental factors were included in a fully factorial design: 1) crop rotation (fraction of grass-clover green manure in the rotation), 2) catch crop (with = +CC and without = -CC) and 3) manure (with = +M and without = -M) applied as slurry.

Three different four-year crop rotations were compared (Table 2). These rotations differed with respect to the use and duration of a grass-clover green manure crop, which was present in R1 and R2, but not in R4. The grass-clover crop was ploughed in spring in R1, and ploughed in autumn before sowing of winter wheat (*Triticum aestivum)* in R2. All crops in all rotations were represented every year.

The plots receiving manure (+M) 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 the Danish national standard (Plantedirektoratet, 1997). The N demands from grass-clover and from pea (*Pisum sativum*)/barley (*Hordeum vulgare*), lupin (*Lupinus angustifolius*) or lupin/barley were set to zero. The target rate for application of NH_4 is shown in Table 2.

Table 2: Treatments in the Danish Organic Crop Rotation Experiment 1997-2004; ^{CC} indicates crops with catch crop in the +CC treatment; ^{M} indicates crops with manure in the +M treatment, the number following ^{M} indicates slurry rate in kg NH_4-N ha^{-1} (Askegaard et al., 2004b).

	Rotation 1 R1	Rotation 2 R2	Rotation 4 R4
First cycle 1997-2000	Spring barley: ley^{1M50}	Spring barley:ley^{1M50}	Oats$^{CC\ M40}$
	Grass-clover	Grass clover	Winter wheat$^{CC\ M70}$
	Spring wheat$^{CC\ M50}$	Winter wheat$^{CC\ M50}$	Winter cereal$^{CC\ M70}$
	Lupin^{CC}	Pea/barley^{CC}	Pea/barley^{CC}
Second cycle 2001-2004	Spring barley:ley^{1M50}	Spring barley:ley^{1M50}	Winter wheat$^{CC\ M50}$
	Grass-clover	Grass-clover	Oats$^{CC\ M50}$
	Oats$^{CC\ M30}$	Winter cereal$^{CC\ M50}$	Spring barley$^{CC\ M50}$
	Pea/barley^{CC}	Lupin/barley^{CC}	Lupin/barley*
Locations	Jyndevad	Jyndevad Foulum Flakkebjerg	Foulum Flakkebjerg

[1]: The ley was undersown in the spring barley
*: Pure lupin at Foulum

Crop management: The experimental treatments were started in 1997. In 1996, a spring barley crop with undersown grass-clover was grown at all sites. The experiment was un-irrigated at all sites except at Jyndevad. All cereal and pulse crops were harvested at maturity. The grass-clover was used solely as a green manure crop, cut 2-5 times during the season, and the cuttings were left on the ground. Straw residues were incorporated in all treatments.

Ploughing was carried out in early spring for spring-sown crops at Jyndevad and Foulum, while this was carried out in late autumn/early winter at Flakkebjerg in most years. After ploughing, winter cereals were sown around

October 1st, except for autumn 2000 and 2001 where it was sown about a month earlier at Jyndevad and Foulum. From 2002, winter rye (*Secale cereale)* was sown in the end of October at Jyndevad. Manure was applied in the spring, either using trail hoses or worked into the soil prior to sowing.

The catch crop in R1 and R2 was either a non-nitrogen fixing crop, e.g. a pure stand of perennial ryegrass (*Lolium perenne*), or a mixture of non-nitrogen fixing and nitrogen fixing species, e.g. a mixture of ryegrass and clover species. The catch crop in R4 was the same as in R1/R2 or a pure nitrogen-fixing crop, e.g. white clover (*Trifolium repens*). The catch crops were undersown in the cereal or pulse crop in spring, except for the bi-cropped winter wheat in R4 in the first cycle. The undersown grass-clover ley in the spring barley was a mixture of perennial ryegrass (variety mixture, 21 kg ha^{-1}) and white clover (cv. Milo, 5 kg ha^{-1}) at Jyndevad and Foulum from 1997 to 2000 and at Jyndevad in unmanured (–M) plots from 2002 to 2004 and at Flakkebjerg 2000 to 2001. In all other years/treatments a mixture of perennial ryegrass (19 kg ha^{-1}), white clover (4 kg ha^{-1}) and red clover (*Trifolium pratense*) (cv. Rajah, 3 kg ha^{-1}) was used. Undersowing in a cereal crop is the usual way of establishing grass-clover and catch crops in Denmark.

In R4 during the first cycle (1997-2000), white clover was undersown in oat (*Avena sativa)*. After harvest of oat, 12 cm wide bands were rotavated, in which the winter wheat was sown at 24 cm row width. A brush hoe was used to inhibit the growth of clover and control weeds. The bi-cropping of wheat and white clover in R4 followed the principles of Clements et al. (1996), and the methodology is described by Olesen et al. (2000). This tested a new method of establishing the crop in the catch crop.

Annual weeds in cereals and pulses were mainly controlled by weed harrowing and row hoeing (Olesen et al., 2000). A reduced effort was used in the rotations with catch crops (+CC) as the catch crops were established by undersowing in spring. Perennial weeds were, if there was a problematic infestation, primarily controlled by stubble cultivation in autumn after cereal and pulse crops in treatments without undersown catch crops (-CC). For *E. repens* this was done when a threshold of 5 shoots m^{-2} was reached in the plot. This happened in most of the –CC plots at Jyndevad from 1998 to 2002. In most years, stubble cultivation was carried out by shallow ploughing (10-15 cm) in order to loosen the rhizomes, followed by repeated stubble harrowings alternating with rotavations, 2-8 treatments in all. No stubble cultivations were carried out in 2003. In 2001, the *E. repens* infestation in the +CC treatment of the pulse crops at Jyndevad was so severe that half of the plots were stubble cultivated. The rhizomes brought to the soil surface in these plots were removed manually. From 2000 to 2004, "summer fallow" was used at Jyndevad. The grass-clover was ploughed shallowly (10-15 cm) in late June and 2-10 cultivations, using the same implements as for stubble tillage, were carried out for 4-6 weeks. After this, deep ploughing (20-23 cm) and sowing of a winter cereal (in R2 in 2000 and 2001) or a catch crop (in R1 2000 to 2004 and before late sowing of winter cereal in R2 in 2002 to 2004) was carried out. *C. arvense* plants were pulled out in all plots at the time of budding, which coincided with anthesis of the cereals. At Flakkebjerg in 2000 to 2002, winter wheat was row hoed in the –CC treatments to control *C. arvense*. The decision whether to carry out stubble cultivation against *C. arvense* was made from visual evaluation of the infestation. One to four stubble cultivations were carried out with a stubble harrow with goosefoot shears, so wide that the whole area was cut through, at increasing depths from 5-15 cm in most of the -CC plots at Flakkebjerg from 1999 to 2002. No stubble cultivations were carried out in 2003.

2.2 Measurements

Each plot was sub-divided into three to five sub-plots. The grain yield of cereals and pulses were measured at harvest maturity in two sub-plots in each plot using a combine harvester. The net size of the harvest plots varied between sites from 16 to 24 m^2. The dry matter content of grains was determined after oven drying at 80 °C for 24 hours. Total N in the grains was determined using the Dumas method (Hansen, 1989).

Nitrate leaching was measured using ceramic suction cells installed at 0.8 m depth (Jyndevad) and at 1.0 m depth (Foulum and Flakkebjerg) in selected plots.

Samples of total aboveground biomass were taken in three or four quadrates of 0.25 m^2 sample areas in each plot with cereals and pulses at growth stage 59 according to the BBCH scale (Lancashire et al., 1991). Each sample was separated into different fractions: the crop, the undersown catch crop or ley, the three main annual weed species, the remaining annual weeds, and the perennial weeds. The weed fractions were counted and dry matter (above-ground biomass) of all fractions was determined after drying at 80 °C for 24 hours. *C. arvense* aboveground shoots were counted and weighed (fresh weight) in the whole plot at the time of anthesis of the cereals. Shoots of *E. repens* that extended above the crop were counted 2 weeks later in five 0.1 m^2 areas.

3 Key results

3.1 Soil

Negative nutrient balances for phosphorus (P), potassium (K) and magnesium (Mg) led to reduced soil availability of these nutrients during the period of 1996 to 2000. At Jyndevad (Askegaard et al., 2003), Foulum & Flakkebjerg (Askegaard et al., 2004a), there was a decline in exchangeable K (K_{ex}) in the plough layer during the first cycle of the crop rotation. At Jyndevad, this decrease was partly due to K leaching losses, which in the same period decreased from about 46 to 21 kg ha^{-1}. In spite of the decreasing K_{ex}, the K leaching losses remained fairly constant at Foulum and Flakkebjerg (Table 3).

Experiments with addition of potassium in 2000 and 2001 showed that pea, but not barley, responded positively to application of potassium fertilizer (Askegaard et al., 2003). It was subsequently decided to apply potassium in a KCl salt to the N_2-fixing crops and catch crops at Jyndevad, in the crop rotations without manure application.

Table 3: Leaching of K (K_{leach}, kg ha^{-1}) and K input in slurry (K_{slu}, kg ha^{-1}) and K_{ex} (mg kg^{-1}) in the topsoil (1996: 0-25 cm, 2000: 0-20 cm) of a four-cycle crop rotation (barley, grass-clover, winter wheat, pea/barley mixture) as affected by location and year (in Askegaard et al., 2004a).

	Jyndevad (5% clay)		Foulum (9% clay)		Flakkebjerg (16% clay)	
	K_{leach}	K_{slu}	K_{leach}	K_{slu}	K_{leach}	K_{slu}
Year	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1997	46	18	14	15	2	24
1998	41	34	16	20	2	12
1999	28	34	18	18		
2000	21	34	12	25		
Avg.	34	30	15	20	2	18
	K_{ex}(mg kg^{-1})					
1996	43		135		105	
2000	35		87		87	

Sulphate leaching decreased significantly ($p<0.001$) during the first three years after conversion to organic farming and per mm of drainage it was lowered 1.8-5.5 times in the third year (Eriksen et al., 2002). Similarly, the S-content of the crops decreased significantly over the years ($p<0.001$), reflecting lower soil S availability. Sulphur application in gypsum to small plots in spring barley at all sites in 1998, and at one site in 1999, increased straw yield by 23 %

(p<0.01) and grain yield by 13 % (not significant) on average. Significant fertilizer-S response was restricted to the sandy soils. Sulphate leaching was quantitatively the most important item of the S balance.

The effects of crop rotation and manure application on soil properties were investigated at Flakkebjerg in 2002 and 2003 (Schjønning et al., 2004). Comparing R4/-M/-CC and R4/+M/-CC showed the effect of manure application in similar systems, while the comparison of R4/-M/-CC and R2/-M/+CC contrasted a crop rotation dominated by small grain cereals to one with a versatile crop rotation including a grass-clover crop and the use of catch crops.

The results revealed a clear trend towards increased soil organic C for manuring as well as for the versatile crop rotation. Also the microbial biomass C was higher after manure application, and the versatile crop rotation yielded higher values than the cereal dominated system. Manure application as well as the versatile crop rotation led to increased soil porosity. Effects on the soil structural stability in terms of clay dispersibility and the stability of wet macro-aggregates could not be detected. Neither did tests of soil friability in the field give significant differences between the systems. Generally, the soil at the Flakkebjerg location has a poor workability and in 2002, a field soil drop test applied in the spring failed to induce any soil fragmentation at all. This is quite remarkable when compared to other studies making use of this methodology. In 2003 the field test generally was possible, and the resulting size distribution of aggregates showed a slight tendency (not statistically significant) of better fragmentation (increased friability/workability) for the systems receiving manure or having a versatile crop rotation. Taken together, the results indicate that application of animal manure and a versatile crop rotation may improve the tilth of a degraded soil. Organic C fractions may serve as early indicators of changes in soil health.

Table 4: Mineralised N (N_{min}), N uptake in crops (N_{up}), Total cumulated soil respiration ($Soil_{res}$) and Total N_2O-emission (N_2O_{em}) during March/April to August/September.

Crop rotation	Previous crop	N_{min}*, kg N ha^{-1}	N_{up}, kg N ha^{-1}	$Soil_{res}$*, kg CO_2-C ha^{-1}	N_2O_{em}*, kg N ha^{-1}
R2/-M/+CC	Pea/barley	87	89	5292	3.4
	Grass-clover	105	104	5260	3.1
R4/-M/-CC	Pea/barley	88	62	5430	2.7
	Winter wheat	71	61	4337	2.7

* March/April to August/September

The impacts of crop rotation and input of organic matter in the form of green manure crops, straw residues and incorporation of catch crops on crop yield, nitrogen uptake, microbial biomass and activity was studied in the experiment at Foulum in 2001 (Vinther et al., 2004). Measurements were carried out during one growing season in two cereal crops in each of two treatments: R2/-M/+CC and R4/-M/-CC.The pre-crops were pea/barley and grass-clover in R2, and pea/barley and winter wheat in R4. Mineralised N (N_{min}), N uptake in the crops (N_{up}), total cumulated soil respiration ($Soil_{res}$) and total N_2O emission (N_2O_{em}) were measured, N_{up} after harvest, the other three during the period from March/April to August/September (Table 4) N_2O emission factors, which were calculated as the emitted N_2O-N in proportion of mineralised N, ranged between 0.018 and 0.028. The more versatile crop rotation thus led to both increased productivity, but also to increased CO_2 and N_2O emissions.

3.2 Crops

Crop yields from the first cycle of the rotation (1997-2000) are reported in Olesen et al. (2002), and yields from the first two cycles of the rotation are reported in Askegaard et al. (2005a). There were limited problems with diseases, pests and annual weeds and increasing problems with perennial weeds during the two cycles. The average cereal yields of the manured crop rotations exceeded the yield level at Danish organic farms by 10 to 30 %. Fig. 1 shows the development of the average grain and seed yields for R2. The yield drop at Jyndevad in 2001 is explained by an exchange of pea by lupin in 2001 and a severe attack of grey mould (*Botrytis cinerea*) in the lupins at this location. The large average yield in 1998 at Foulum was due to optimal climatic conditions in the region that year. The yields in R2 at Flakkebjerg increased over time. This was due to an improvement in soil fertility from an initially low level (Schjønning et al., 2004). The yields were highest at Foulum and lowest at Jyndevad.

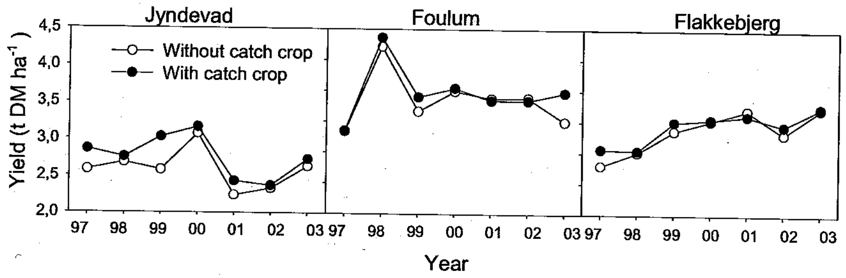

Fig. 1: Average annual dry matter (t DM ha^{-1}) yields of grain and pulses in crop rotation 2 with and without catch crops (Askegaard et al., 2005a).

The grain yields of all individual crops in the first cycle of the rotation were lowest at Jyndevad; yields of spring cereals were highest at Foulum, whereas winter cereals had similar yields at Foulum and Flakkebjerg. There were significant yield increases from catch crop in the spring cereals in R2 and R4, with the highest increases at Jyndevad and Foulum. There was also a significant yield increase from catch crop in pea/barley at Flakkebjerg. The yield of spring wheat in R1 and winter wheat in R2 was unaffected by catch crops. The bi-cropping of winter cereals and white clover reduced yields compared with a sole winter cereal crop. This yield reduction was highest at Foulum and in the second year of bi-cropping.

The rotational yield calculated as the sum of yields of all harvested crops over the four years of the first cycle of the rotation (1997-2000) varied considerably between sites and rotations (Olesen et al., 2002). The lowest yields were obtained at Jyndevad and the highest at Foulum, and R4 gave the highest yields. The effect of catch crop was only significant for R4 at Flakkebjerg, where a yield increase of 0.8 t ha^{-1} was obtained. The yield response to applied N was almost identical for all rotations and all sites, and it corresponded to about 2.4 t DM per 100 kg of ammonium N applied in slurry.

Table 5: Mean grain yield of cereal and pulse crops and mean yield increase from catch crops and manure application (t DM ha^{-1}) in the rotations R2 and R4 for two cycles of the rotations.

Cycle	Location	Rotation R2			Rotation R4		
		Mean Yield	Yield increase CC	Yield increase Manure	Mean Yield	Yield increase CC	Yield increase Manure
1st (1998-2000)	Jyndevad	2.87	0.20	0.65			
	Foulum	4.20	0.13	0.79	3.64	-0.23	1.01
	Flakkebjerg	3.34	0.06	0.50	3.06	0.21	0.90
2nd (2001-2004)	Jyndevad	2.42	0.06	0.96			
	Foulum	3.90	0.05	0.55	3.64	0.63	0.82
	Flakkebjerg	3.59	0.08	0.41	2.90	0.64	0.89

The effects of catch crops decreased from the first to the second cycle of R2 (Table 5). This was probably due to the influence of a buffering effect of the clover in the grass-clover crop. The positive yield effect of catch crops on the barley undersown with grass-clover resulted in less clover in the grass-clover green manure and in lower yield in the succeeding winter wheat (Askegaard et al., 2005a). Similarly, the effect of manure application decreased from the 1st to the 2nd cycle at Foulum and Flakkebjerg in both R2 and R4 (Table 5). This was probably mediated through an effect of the manure application on the proportion of clover in the grass-clover in R2 and the clover dominated catch crops in R4, where manure application reduced the development of the undersown clover crops.

3.3 Agroecological parameters

Nitrate leaching: Results for nitrate leaching in the first cycle of the rotation have been reported in Askegaard et al. (2005b). The nitrate leaching losses were highest at Jyndevad and lowest at Flakkebjerg (Table 6). Since the average nitrate concentrations did not differ substantially between the locations, this primarily reflected differences in the amount of drainage. There were no significant differences in nitrate leaching between crop rotations at each of the three locations except for the -CC treatments at Foulum, where the leaching was 42 % larger in R2 than in R4. There were no effects of manure application on the estimated nitrate leaching at the three locations. Conversely, there were significant effects of catch crops on nitrate leaching at Jyndevad in R1 and R2 and at Foulum in R2. Catch crops did not reduce nitrate leaching in R4 at Foulum in contrast to R2, where the catch crops reduced the nitrate leaching to the R4 level. Thus the catch crops could eliminate the effect of grass-clover on nitrate leaching. Catch crops did not reduce nitrate leaching significantly at Flakkebjerg, although a tendency was found in R2. When evaluating the effect of catch crops on nitrate leaching in R4, it should be kept in mind that white clover was the dominating catch crop in this crop rotation. This leguminous catch crop might have increased leaching.

Table 6: Effect of crop rotation and catch crop on nitrate leaching (kg NO_3-N ha^{-1} yr^{-1}) at the three experimental sites. Values with the same letter within a row are not significantly different ($p<0.05$) (Askegaard et al., 2005b).

Site	Rotation 1		Rotation 2		Rotation 4	
	– CC	+ CC	– CC	+ CC	– CC	+ CC
Jyndevad	106 [a]	56 [b]	104 [a]	65 [b]		
Foulum			54 [a]	38 [b]	37 [b]	39 [b]
Flakkebjerg			35 [a]	26 [a]	29 [a]	28 [a]

Annual flow-weighted mean nitrate-N concentration (nitrate leaching per volume of drainage) in R2/-CC showed similar values at the three locations, between 12 and 14 mg nitrate-N L^{-1} as an average of the rotation. The use of catch crops reduced the nitrate concentrations to below 10 mg nitrate-N L^{-1} in R1 and R2 at all locations. In comparison the WHO maximum value for drinking water is 11.3 mg nitrate-N L^{-1}. The annual flow-weighted mean nitrate-N concentration in R4/-CC was about 9 mg L^{-1} at Foulum and Flakkebjerg. The use of the legume catch crops maintained this level with a tendency to an increase.

Annual weeds: Results for annual weeds in the first cycle of the rotation (1997-2000) in R2 have been reported in Rasmussen et al. (2006). The weed biomass as well as the percentage weed biomass, as means over the four years, was highest at Foulum and lowest at Flakkebjerg.

At Jyndevad and Flakkebjerg there were equal levels of weed biomass in the +CC and –CC treatments as means over the four years, but at Foulum there was more weed biomass in the +CC than in the –CC (Table 7). The weed control scheme in the –CC plots was more intensive at Foulum than at the other locations. There was more weed biomass when manure was applied. However, manure application did not affect the percentage of weed biomass of the total biomass, indicating that the crop benefited as much from the manure as the weeds.

Table 7: Back-transformed means of weed biomass for each combination of location and catch crop in R2 1997-2000. From Rasmussen et al. (2006).

Location	Weed biomass (g m^{-2}) Catch crop	
	Without	With
Jyndevad	17	14
Foulum	17[a1)]	26[b]
Flakkebjerg	11	10

[1)] Different letters within a location indicate significant differences ($p<0.05$).

Weed biomass and percentage weed biomass varied between years, depending on locations and crops (Fig. 2). At Jyndevad, there were no differences between weed biomass in the different crops within a year, but the weed biomass in pea/barley and winter wheat decreased over time due to effective weed control. At Foulum the weed biomass increased in spring barley, where no weed control was carried out, and decreased in winter wheat. At Flakkebjerg, there was a tendency for increased weed biomass over the first three years in all crops, but in winter wheat it was lower in 2000 than in all other years, probably because row hoeing was used in winter wheat this year.

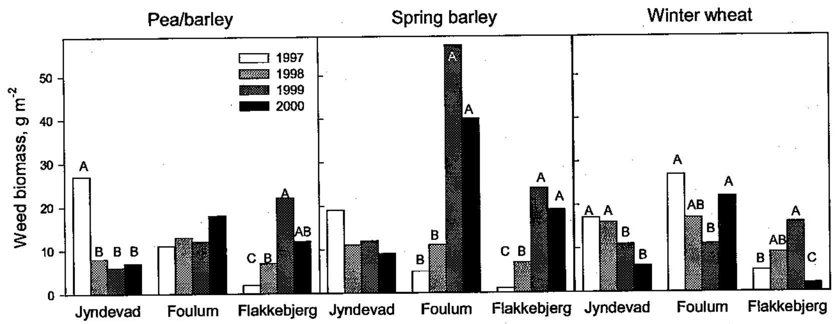

Fig. 2: Effect of location, year and crop on weed biomass in R2 1997-2000. Within each crop and location, bars with different letters are significantly different ($p<0.05$). Means of catch crop and manure treatments. From Rasmussen et al. (2006).

Effects of catch crop and manure varied between crops and locations. Generally, effects were more similar between different crops at each location than between the same crop at different locations. This could be caused by external factors such as weed seed bank in the soil, soil type and climate, as well as by management differences between locations.

There was a significant effect of the entry point of the rotation (which crop was grown the first year) on weed biomass and percentage weed biomass, but this effect varied between locations. At Foulum and Flakkebjerg, the greatest weed biomass occurred when the entry point of the rotation was grass-clover or winter wheat, but at Jyndevad no effect of entry point was detected. This information is significant for the interpretation of data. Conclusions might be influenced by how many entry points are included in an experiment – whether or not all crops are included every year.

Perennial weeds: Results on perennial weeds have been reported in Rasmussen et al. (2005). At Jyndevad, the *E. repens* infestation became an increasing problem during the first few years of the experiment. In 2001, the dry matter of rhizomes was found to be around 2 t ha^{-1} in the plots with highest infestation levels, and in several cases more than 100 shoots m^{-2} were found in plots. Stubble cultivation decreased *E. repens* infestation, but increased nitrate leaching (Askegaard et al., 2005b). The introduction of "summer fallow" increased the concentration of soil water nitrate-N from below 30 mg L^{-1} to above 100 mg L^{-1} in most years. Summer fallow reduced the amount of *E. repens* in the crop the following year, but no effect could be found in the second year after treatment. In spite of the high level of *E. repens* infestations in the +CC treatments at Jyndevad, average cereal and pulse yields where higher in the +CC than in the – CC treatments in the second cycle of the rotation, probably because of an improved nutrient supply.

At Flakkebjerg, there was a lower infestation level of *C. arvense* in R2 than in R4, with least biomass in the crop the year after grass-clover. There was no significant difference between the biomass of *C. arvense* in –CC and +CC treatments, in spite of the fact that stubble cultivations and row hoeing were carried out in the –CC and not in the +CC treatments. The reason most likely being that the nutrients retained in the topsoil by the catch crops benefited the crops, which became more competitive against the weeds. There was no significant difference in the nitrate leaching between the catch crop treatments at Flakkebjerg, but a yield increase in the +CC treatment in R4. Yields of spring cereals were consistently increased after catch crops.

3 Perspectives

The crop rotation experiment has shown significant effects of location, crop rotation, catch crops and manure on yields, weed infestation, soil fertility and nutrient losses (Olesen et al., 2002; Schjønning et al., 2004; Askegaard et al., 2005a, b; Rasmussen et al., 2005, 2006). There were indications of changes of some of these effects over time as a result of the 'buffering power' of grass-clover, where the N_2-fixation is affected by crop management and soil fertility. This buffering power will probably not only affect yields but also the risk of N losses, and there is a need to further investigate possibilities of controlling N supply to the crops better through improved use of green manure crops, catch crops and manure at the crop rotation level.

Perennial weed infestation (especially *C. arvense* and *E. repens*) has severely increased in the crop rotation experiment at two of the three locations within a short period of time, and these weeds may seriously reduce yields in organic arable farming. Direct control of perennial weeds is typically carried out by stubble cultivation in autumn, reducing the possibilities for growing catch crops. The energy use, as well as the elevated risk for nutrient leaching, jeopardizes the sustainability of this practice, and therefore cultivation should be avoided (Rasmussen et al., 2006). The crop rotation experiment has shown that the occurrence of these weeds is significantly affected by the choice of crops and catch crops, and by the addition of manure. However, this needs to be further substantiated, and the effects of weed infestation on yields, as well as the interaction with fertility level need to be quantified.

Crop production in organic farming systems relies to a large extent on soil fertility for nutrient supply. The soil fertility must be maintained via choice of crop rotation and (green) manuring practices. Fertility building by such means requires a long-term integrated approach, rather than the short-term and targeted solutions common in conventional agriculture (Watson et al., 2002). It follows that, for studies of management effects on soil fertility, long-term cropping experiments are indispensable.

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Soil properties, crop yield and quality with farmyard manure with and without biodynamic preparations and with inorganic fertilizers

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1 Introduction and experimental history

In the late 1970s in Germany and other European countries the issue of food quality was under public discussion, particularly whether it is normally better in organic than in conventional farming, and whether fertilization (organic vs. inorganic) may play a role in this context (Diehl & Wedler, 1978; Diercks, 1976; Schudel et al., 1979; Schuphan, 1974). Is food quality a matter of fertilizer type, or does the amount of fertilizer rather than its type affect quality? This discussion sometimes lacked scientific results. Thus, in 1980 a 4-year project was started at IBDF (Institute for Biodynamic Research) in Darmstadt (Germany) to investigate this subject. A field experiment compared farmyard manure in two treatments with and without biodynamic preparations and inorganic fertilizer, each type applied at three rates. From the beginning the experiment consisted of four identically structured fields to test the treatments with four crops per year cultivated in rotation. In the course of this trial interesting differences began to emerge with respect to soil development, appearing, for example, in visual characteristics like the colour of the (very sandy) soil. Its surface was darker in the organically fertilized plots (Abele, 1987).

Such observations were the reason why the experiment was continued beyond 1984. In order to study soil development, the 4-year project became a long-term fertilization experiment extending over more than 25 years and is still being continued today. An overview of the experiment over its entire life with its research topics and other main characteristics is given in Table 1.

After the 1st trial phase there were some years of a transitional period in which the four fields were cultivated according to the treatments, but without scientific investigations (because of lack of budget). Finally, in 1989-1992 a detailed soil biological project was carried out, focussing on the effects of fertilization upon carbon and nitrogen dynamics, enzyme activities and microbial biomass in the soil (Bachinger, 1996). For this purpose the crop rotation and the amounts of organic fertilizers applied were modified and oriented towards the usual conditions in organic farming.