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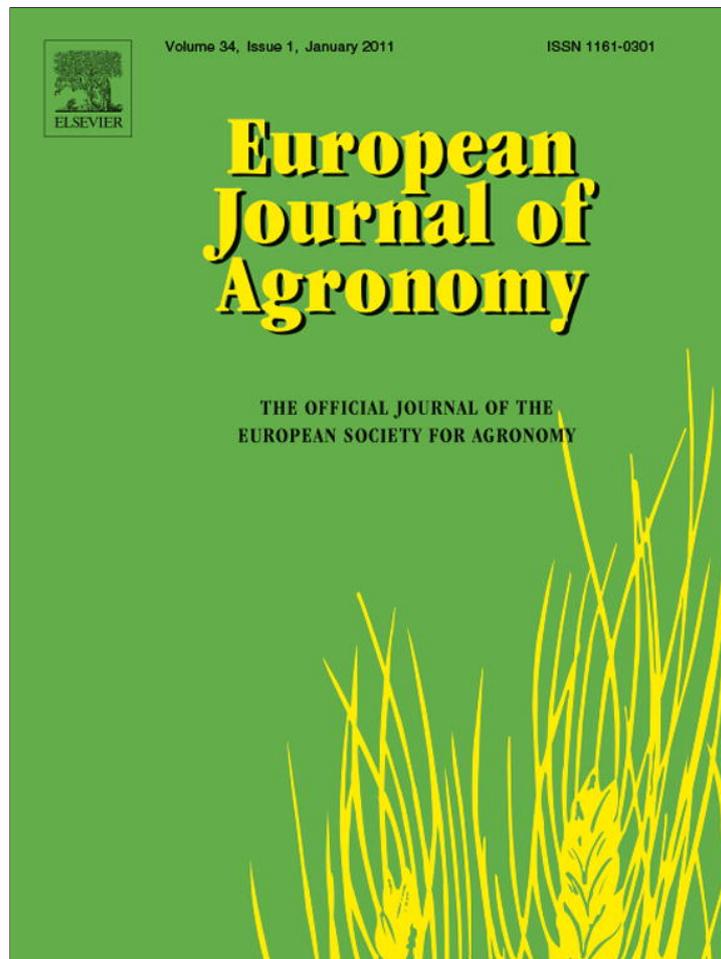
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Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops

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ABSTRACT

One of the core ideas behind organic production is that cropping systems should be less dependent on import of resources, and minimize negative effects on the surrounding environment compared to conventional production. However, even when clearly complying with regulations for organic production, it is not always obvious that these goals are reached. As an example, strong dependence on import of manure is often seen in current organic production, especially in systems producing high value crops such as vegetable crops.

The aim of the present study was to test novel approaches to organic rotations, designed to reduce the reliance on import of external resources significantly. We compared a conventional system (C) and an organic system relying on manure import for soil fertility (O1) to two novel systems (O2 and O3) all based on the same crop rotation. The O2 and O3 systems represented new versions of the organic rotation, both relying on green manures and catch crops grown during the autumn after the main crop as their main source of soil fertility, and the O3 system further leaving rows of the green manures to grow as intercrops between vegetable rows to improve the conditions for biodiversity and natural pest regulation in the crops. Reliance on resource import to the systems differed, with average annual import of nitrogen fertilizers of 149, 85, 25 and 25 kg N ha⁻¹ in the C, O1, O2 and O3 systems, respectively.

As expected, the crop yields were lower in the organic system. It differed strongly among crop species, but on average the organic crops yielded c. 82% of conventional yields in all three organic systems, when calculated based on the area actually grown with the main crops. In the O3 system some of the area of the vegetable fields was allocated to intercrops, so vegetable yields calculated based on total land area was only 63% of conventional yields.

Differences in quality parameters of the harvested crops, i.e. nutrient content, dry matter content or damages by pests or diseases were few and not systematic, whereas clear effects on nutrient balances and nitrogen leaching indicators were found. Root growth of all crops was studied in the C and O2 system, but only few effects of cropping system on root growth was observed. However, the addition of green manures to the systems almost doubled the average soil exploration by active root systems during the rotation from only 21% in C to 38% in O2 when measured to 2.4 m depth. This relates well to the observed differences in subsoil inorganic N content (N_{inorg}, 1–2 m depth) across the whole rotation (74 and 61 kg N ha⁻¹ in C and O1 vs. only 22 and 21 kg N ha⁻¹ in O2 and O3), indicating a strongly reduced N leaching loss in the two systems based on fertility building crops (green manures and catch crops). In short, the main distinctions were not observed between organic and conventional systems (i.e. C vs. O1, O2 and O3), but between systems based mainly on nutrient import vs. systems based mainly on fertility building crops (C and O1 vs. O2 and O3).

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1. Introduction

It is often discussed and studied whether organic production methods are better for the environment (e.g. Birkhofer et al., 2008; Aronsson et al., 2007) or produce higher quality food than conventional methods (e.g. Dangour et al., 2009). However, answering such questions is difficult for several reasons. One is that organic and conventional productions are not well defined methods; they

can both be performed in very different ways. In any comparison a specific approach to organic production is compared to a specific approach to conventional production. In some studies the focus has been to compare conventional with organic livestock-based and biodynamic systems as in the DOK trials (Mäder et al., 2002; Bosshard et al., 2009). Here a main difference was that fresh and composted animal manures were used in the organic and biodynamic systems, respectively, whereas mineral fertilizer was used in the conventional. Another recent approach is the Nafferton organic rotation experiment (e.g. Leifert et al., 2007; Eyre et al., 2009), where comparisons were made not only between organic and conventional systems, but between all combinations of organic vs. conventional plant protection, nutrient management and rotations optimized for organic or conventional production, in order to investigate which of these factors are primarily responsible for differences in productivity, environmental effects or product quality. Other studies of organic cereal rotations have focused on the use of animal vs. green manures (Torstensson et al., 2006; Aronsson et al., 2007; Doltra et al., 2011). However, though these experiments were very different in their approach, they were all aimed to investigate methods that were already in common use in organic production. Thus, there is a need to investigate new methods to improve organic production.

In practical farming, there is a tendency that organic production methods become more like conventional methods with increased reliance on input factors. In some countries it is allowed to use animal manure from conventional farms and other nutrient rich residues originating from conventional farming systems. This way the reliance on fertility building crops and diversified crop rotations for proper nutrient husbandry is decreased in the organic systems, but this decouples the biogeochemical cycles of carbon and N (i.e. less co-flow of C and N cycles) with possible increase of N losses from the production (Tonitto et al., 2006; Gardner and Drinkwater, 2009). While such a development may in the short term help organic farms to supply the market demand and to be commercially viable, it may in the longer term undermine consumer confidence if organic farming is not seen to deliver the really different, sustainable, and environmentally friendly alternative to conventional farming. In addition, national regulations may change so that less conventional input is allowed in to organic production, which will lead to an increased demand for improved nutrient management and robust growing systems.

Conventional farming is developing production methods with focus on quality and environment (e.g. Jayasundara et al., 2007), and for organic farming to continue to differentiate from that of conventional, organic farming needs to develop too to ensure high quality products and sustainable cropping systems. In addition the productivity needs to increase in order to be commercially viable and to meet the increasing global demands for food production.

Fertility building crops are management tools to reduce the need for external N inputs and losses to the environment, like legume green manures that increase N input through atmospheric N fixation (Thorup-Kristensen et al., 2003), and autumn N catch crops that increase N re-cycling by uptake and mineralization at optimized management strategies (Thorup-Kristensen, 2006b; Tonitto et al., 2006; Thorup-Kristensen and Dresbøll, 2010). A major problem is that green manure crops often are grown the whole growing season and thereby reduce the possibility to grow main crops. Short term green manure strategies using only the autumn after main crop harvest may be quite effective (Thorup-Kristensen, 2006b; Sørensen and Thorup-Kristensen, 2003), and they allow green manures to be grown much more frequently in the rotation and at lower cost. Intercrops are living mulches that are grown together with the main crops. Intercrops may have positive effects on pest and weed management (Vanek et al., 2005; Jones and Sieving, 2006), and on nutrient cycling when main crop/intercrop competition is

controlled (Liedgens et al., 2004; Bãth et al., 2008). The question is how the combined and optimized use of these fertility building crops affects the performance of an organic crop rotation in terms of crop yields and nutrient dynamics?

In this study we aimed at a new approach to organic vegetable crop production, with reduced need for external inputs, decreased nutrient losses to the environment and improved natural pest regulation in the field, while also maintaining high crop yields. Two such systems were developed, and compared to a conventional system and an organic system mimicking modern organic production systems which rely on high conventional nutrient import. The main crop rotation was identical in the four systems, but they varied strongly in nutrient import and in the use of fertility building crops like autumn N catch crops, green manures and intercrops.

A number of factors in terms of crop growth, product quality, nutrient dynamics, and insect pest dynamics in the experiment were studied as part of the interdisciplinary project VegQure (http://www.icrofs.org/Pages/Research/darcofIII_vegquire.html). This paper concerns the agronomic and environmental results from the experiment in terms of crop shoot and root growth, yield, pest and disease damage to vegetable products, nutrient uptake and nitrogen dynamics measured to 2.5 m soil depth. Results concerning the other factors will be published elsewhere.

2. Materials and methods

2.1. Field site

Four cropping systems were grown at the Research Centre Aarslev (10°27'E, 55°18'N) in Denmark in the period 2006–2009. The soil was a sandy loam (Typic Agrudalf) with the 0–0.5 m soil layer containing 1.0% C, 13% clay, 15% silt and 70% sand; the 0.5–1 m layer containing 0.2% C, 18% clay, 13% silt and 68% sand and the 1–2.5 m layer containing 0.1% C, 18% clay, 14% silt and 68% sand. The pH_{CaCl2} was 6.7, 5.9 and 7.3; the content of phosphorous (P) was 23, 19 and 16 mg kg⁻¹ and of potassium (K) was 115, 98 and 105 mg kg⁻¹ in the 0–0.5, 0.5–1 and 1–2.5 m layers, respectively (P extracted with 0.5 M NaHCO₃, K extracted with CH₃COONH₄). Weather conditions were recorded at a meteorological station at the research centre. During the period from 2006 to 2009 the average annual precipitation at the site was 754 mm and the average air temperature was 9.2 °C.

The fields had been managed according to organic farming practice with no use of pesticides or inorganic fertilizers since 1996 prior to the initiation of the crop rotation experiment. In 2005 spring barley with undersown clovergrass was grown across all the fields, but after harvest, the clover grass was killed by spraying with glyphosate in system C, and by repeated autumn tillage in system O1 (system identification is outlined in Table 1). In the O2 system the clover grass was incorporated late autumn before winter rye and in the spring before the other crops. The same procedure was followed in the O3 system except before the vegetables, where row intercrops were established according to the method described below.

2.2. Experimental design and the four cropping systems

The experiment included four cropping systems (Table 1) grown in a randomized complete block design with three replicates. The rotations in the four cropping systems were identical in terms of rotation of main crops of cereals and vegetables, but varied in the growing of green manure and catch crops in the autumn after main crop harvest, in management, and in the import and use of fertilizers and pest management (Table 2).

Table 1
Rotation and fertilization of the four cropping systems, the conventional system (C), the import based organic system (O1), the organic system with autumn soil cover (O2) and the organic system with autumn soil cover and intercrops (O3).

		C	O1	O2	O3
System		Conventional	Organic – Import based	Organic – Autumn soil cover	Organic – Autumn soil cover and intercrops
Fertilizer		NPK fertilizer	Slurry	Slurry	Slurry
Mean N addition (kg N ha ⁻¹)	149	88	26	26	
Field 1	Oats				
	Autumn crop	–	–	Green manure	Green manure
	N addition (kg N ha ⁻¹)	90	47	0	0
Field 2	Carrot				
	Autumn crop	Winter rye	Winter rye	Winter rye	Winter rye
	N addition (kg N ha ⁻¹)	120	56	0	0
Field 3	Winter rye				
	Autumn crop	–	–	Green manure	Green manure
	N addition (kg N ha ⁻¹)	120	47	0	0
Field 4	Lettuce				
	Autumn crop	–	–	Radish catch crop	Radish catch crop
	N addition (kg N ha ⁻¹)	170	112	0	0
Field 5	Oats				
	Autumn crop	–	–	Green manure	Green manure
	N addition (kg N ha ⁻¹)	90	47	0	0
Field 6	Onion				
	Autumn crop	Winter rye	Winter rye	Winter rye	Winter rye
	N addition (kg N ha ⁻¹)	170	112	70	70
Field 7	Winter rye				
	Autumn crop	–	–	Green manure	Green manure
	N addition (kg N ha ⁻¹)	120	47	0	0
Field 8	White cabbage				
	Autumn crop	–	–	Re-sprouting cabbage	Re-sprouting cabbage
	N addition (kg N ha ⁻¹)	310	234	140	140

One of the systems was grown according to conventional farming methods (C) and the three others according to organic farming methods, but with different approaches. The organic systems were all grown as stockless rotations, but in the first (O1) the crop nutrient supply was based on import of slurry, whereas in O2 and O3 most of the nutrient supply came from fertility building crops with a much reduced reliance on imported slurry compared to O1. In O2 and O3 a catch crop of fodder radish (*Raphanus sativus* L. var. *oleiformis* Pers.) was grown after lettuce harvest, and the white cabbage stubble was left growing as a catch crop after cabbage harvest. Furthermore green manures with legumes were sown into the two cereal crops in the spring in O2 and O3, and left to grow in the field during the autumn after cereal harvest. In O2 these green manures were then ploughed into the soil in the early spring prior to establishment of vegetable crops. In O3 parts of the green manures were left to grow as a row intercrop together with the vegetables. This was done by rotovating 1.3 m wide bands of green manure into the soil in November to make room for vegetable rows in the next year, but leaving bands of green manure 0.3 m wide to continue growth in between next year's vegetable crops. Before establishment of the vegetable crops, the bands of green manure were root pruned according to Båth et al. (2008) to remove most of the extensive root system developed by the intercrop in the previous season, and thereby to reduce its competitive effect against the newly established vegetable crops. This was done by a device 0.35 m wide and working to a depth of c. 0.22 m which was drawn through the soil. The legumes under sown in oats (*Avena sativa* L. 'Fredy') were in system O2 *Anthyllis vulneraria* L., *Medicago lupulina* L., *Trifolium repens* L., *Trifolium pratense* L. and *Lolium perenne* L.; and in system O3 *Sanguisorba minor* Scop. and *Lotus corniculatus* L. The legumes under sown in winter rye (*Secale cereale* L. 'Recrut') were in system O2 *Medicago sativa* L. and *Trifolium pretense* L.; and in system O3 *Lotus corniculatus* L. and *Lolium perenne* L.

In C, O1 and O2 all four vegetable crops were grown at a row distance of 0.5 m. In system O3 every third row was an intercrop. The distance between two neighbouring vegetable rows was 0.5 m,

whereas a bit more space was allowed for the intercrop giving a distance of 1.1 m between two vegetable rows across the intercrop. The vegetable crops were carrot (*Daucus carota* L. 'Bolero'), lettuce (*Lactuca sativa* L. 'Ar dinas'), onion (*Allium cepa* L. 'Hytech') and white cabbage (*Brassica oleracea* L. convar. *capitata* (L.) Alef. var. *alba* DC 'Impala').

Three replicate blocks were established, each block containing four plots representing the four cropping systems. The plot size was 10 by 130 m. This area was split up into eight fields (10 by 12.5 m) representing one replicate crop rotation of each cropping system. The eight fields were kept together in pairs, making four pairs of fields each 25 m long, kept apart by three areas of 10 m each for field operations. The four plots (cropping systems) within each replicate block were arranged side by side, separated by 8 m of land again used for field operations and as border area between the cropping systems.

In short, the crops were managed according to best practice within organic and conventional production. Regarding pest management and fertilization (Table 2) we maintained differences between conventional and organic systems as strictly as possible, as it was exactly the effects of different pest management and fertilization we wanted to study. However, in other aspects of crop management we made a few compromises to avoid that the differences observed were due to factors such as sowing time or planting method where these tend to differ between organic and conventional practice. Thus carrots in all the four systems were sown relatively late as recommended in organic production to avoid the first generation of the carrot root fly, and all onions were established as speedlings with 4–7 plants per pot transplanted into the field, which is normal practise in organic production in Denmark, as opposed to direct sowing used in conventional production.

The crop rotation was an 8-year rotation of oats–carrot–winter rye–lettuce–oats–onion–winter rye–white cabbage. To simplify management, it was organized as a 4-year rotation in the field where the two oat fields were kept together as one larger field, and the same was done with winter rye. Following oat, the field was

Table 2
Agricultural management of the crops grown in the four cropping systems (C, the conventional system; O1, the import-based organic system; O2, the organic system with autumn soil cover; O3, the organic system with autumn soil cover and intercrops). Unless indicated for each year, the time point was the same in 2007, 2008 and 2009.

Crop	Treatment		Cropping system			
			C	O1	O2	O3
Oats	Soil	Ploughing ^a	November	November		
		Incorporation ^a			March	March
	Establishment	Rotovator	Mid April	Mid April	Mid April	Mid April
		Sowing	Mid April	Mid April	Mid April	Mid April
	Green manure	Sowing			Mid April	Mid April
Fertilizer		Slurry		Early April		
Pests	NPK	Tribenuron-methyl + fluroxypyr (w) ^b	April			
		MCPA (w) ^c	Mid May (07–08)			
		Cyprodinil + Propiconazol + Azoxystrobin (f)	Early June (07–08)			
Harvest		August	August	August	August	
Carrot	Soil	Harrow	3 times August/September	3 times August/September		
		Ploughing	November	November	March	
	Fertilizer	Incorporation in rows				Late November
		Loosening of soil				March/April/May
		Rotovator				May
	Soil	Slurry		April		
		NPK				
	Establishment	Root pruning				April
		Sowing		May	May	May
	Pests	Linuron (w)	June	May/June	May/June	May/June
Burn (w)						
Winter rye	Soil	Glyphosat (w)	May/June (08–09)			
		Linuron + Aclonifen (w)	June (07)			
	Establishment	Azoxtstrobin (f)	August/September (08–09)			
		Pyraclostrobin + Boscalid (f)	August/September (08–09)			
	Green manure	Alpha-cypermethrin (i)	4–5 times July/August (08–09)			
		Harvest	October	October	October	October
	Fertilizer	Ploughing + rotovator	October	October	October	October
		Sowing	Mid October	Mid October	Mid October	Mid October
	Pests	NPK	Twice March and April		April	April
		Slurry		Early April		
Lettuce	Soil	Tribenuron-methyl (w)	Late March (07)			
		MCPA (w)	April (08–09)			
	Harvest	August	August	August	August	
Lettuce	Soil	Harrow	3 times August/September	3 times August/September	August	August
		Ploughing	November	November	March	
	Establishment	Incorporation in rows				Late November
		Root pruning				Mid April
		Loosening of soil				April/May
	Fertilizer	Rotovator				May
		Planting	Mid May	Mid May	Mid May	Mid May
	Pests	NPK	Early May			
		Slurry		April		
	Soil	Alpha-cypermethrin (i)	June (07), May/June (08)			
Harvest		July	July	July	July	
Catch crops	Incorporation		July	July	July	
	Fodder radish, sowing			Early August	Early August	
	Harrow	3 times August/September	3 times August/September			

again in mid November to determine the level of unused soil N at risk of being lost by leaching during winter. To reduce the work load and cost, a reduced sampling plan was made. During 2007 and 2008 soil sampling was made in all fields in the C and O2 systems to 2 m depth, to get results on soil availability and depletion by all crops in the rotations. During 2007, 2008 and 2009 sampling was made to 2.5 m depth in the lettuce, oat following lettuce and onion fields in all four cropping systems. These three crops were chosen to compare effects of the four systems during the part of the crop rotation where the highest leaching risk was expected. Soil was sampled using a soil piston auger with an inner diameter of 14 mm. Nine replicate samples were combined into one bulk sample for each soil layer and plot. The samples were divided into 0.5 m depth intervals. The soil samples were frozen until analysis then thawed and subsamples of 100 g fresh weight were extracted in 1 M KCl for 1 h (soil/solution ratio 1:2). The soil extract was centrifuged and the supernatant was analyzed for NH_4^+ and NO_3^- content by standard colorimetric methods using an AutoAnalyzer 3 (Bran + Luebbe, Germany). The N_{inorg} was determined as the sum of nitrate-N and ammonia-N.

2.5. Statistical analysis

Statistical significance of differences in yields and nutrient uptake were averaged over the 3 years and tested by analysis of variance (*F*-test). Multiple comparisons were based on values of least significant difference (LSD) derived from analyses of variance (Proc GLM, SAS Institute Inc., Cary, NC). The results of pests, diseases and damages were transformed before analysis by the function $y = \log(x + 0.8)$ to obtain homogeneity of variance. The value 0.8 was added to avoid observations equal to zero. In assessing differences between results, tests with $P < 0.05$ were considered statistically significant.

3. Results

3.1. Yield

Generally, all plants grew well in all four systems, and the total crop biomass determined as t ha^{-1} dry matter was only moderately lower in the organic systems than in the conventional system (Fig. 1). On average across all crops, the biomass production of O1, O2 and O3 was 83%, 81% and 63% of that in C. All the vegetables in the O3 system had lower total biomass due to the reduced number of vegetable rows, though the difference between O3 and the two other organic systems was only significant for carrot and white cabbage. However, if the O3 biomass was corrected to biomass m^{-1} crop row rather than biomass ha^{-1} the yield did not differ significantly from C, O1 or O2 except in onion. When corrected in this way, the biomass production of O3 was at the same level as in O1 and O2, and only 81% of that in C.

Determined as fresh weight of harvest product, the total yield of carrot and white cabbage was similar in the C, O1, and O2 system (Table 3). For the onions the conventional system had significantly higher yield than the other systems whereas in lettuce no significant differences were found between C and O1 but between C and the organic systems with catch crops. The marketable yield was higher in the conventional system when growing white cabbage whereas similar marketable yields among systems were seen in carrot and onion (Table 3). In lettuce the marketable yield did not differ between the C and O1 system, whereas the C system differed from O2 and O3. The percentage of crops discarded was identical between the cropping systems as was the dry matter percentage when comparing the four cropping systems in any of the crops examined (Table 3). The two cereals reacted quite differently, oats

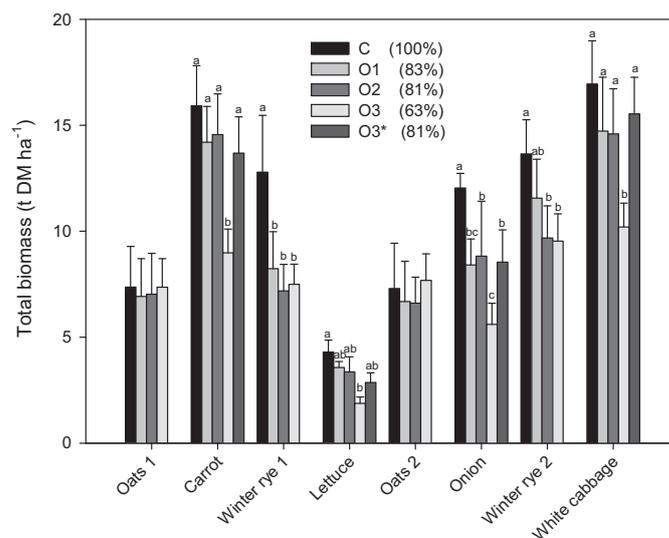


Fig. 1. Total biomass produced in the four cropping systems determined as t ha^{-1} dry matter. O3* shows the total biomass of the O3 system when adjusted to identical row meters ha^{-1} . Results are means of 3 years and bars show standard deviation. Bars with different letters within each crop are significant different ($P < 0.05$).

showed no yield effects, whereas yield of winter rye was substantially higher in C than in the O1, O2 and O3, and the yield reduction in the organic systems was stronger when winter rye followed carrot than when it followed onion (Table 3).

3.2. Quality

There was no effect of cropping system on the grading of vegetables in size categories in onion, carrot or white cabbage (Fig. 2). However, in lettuce more large lettuces were produced in the conventional system compared to O2 and O3. The O1 system produced significantly more large lettuces than the O3 system as well.

The vegetable crops were examined for pests, diseases and damages, and a selection of these is presented in Table 4. Within each of the years significant differences between the systems could be found in some of the parameters determined (Table 5), but when compared as averages over the 3-year period no effect of the variable pest, soil and crop management in the different cropping systems was seen. In some cases the vegetables from the organic systems were more damaged than the conventional vegetables, e.g. damages by rot, slugs, and cabbage white butterfly in white cabbage, watery scales in onion and by scab in carrot. In other cases the conventional vegetables showed higher levels of damages than organic vegetables such as thrips in white cabbage, decay in onion, and branches and green necks in carrots (Table 5).

3.3. Nutrients

Differences in nutrient concentrations in the products were quite few, though some effects were observed (Table 6). In carrot, winter rye and oats after white cabbage the crops in the conventional system had significantly higher N concentration compared to the other systems. In addition, there was a tendency towards a lower N concentration in all crops in the O3 cropping system; however, this was only significant for the carrots. No effect of the systems on P, K and S concentrations was found but the concentrations varied considerable between the crops. The total N uptake in the entire plant was generally also higher in the conventional system than the other systems (Table 3).

The effect of cropping system on nutrient uptake in the harvested crop was limited, however, where differences in uptake

Table 3
The total and marketable yield (fresh weight for vegetables, cereal grain yield is determined at 85% dry matter), total N uptake in the whole plant, dry matter percentage and percentage discard determined in the four cropping systems. O3* show the results from cropping system O3 when it has been corrected to the same m crop row. Results are means of 3 years and numbers in brackets show the standard deviations. Means followed by different letters within a row are significantly different at $P < 0.05$.

	Cropping system				
	C	O1	O2	O3	O3*
Oats after white cabbage					
Grain yield ($t\ ha^{-1}$)	4.5 (1.0)	4.6 (0.9)	4.6 (1.0)	4.8 (0.8)	
Total N uptake ($t\ ha^{-1}$)	94.3 (14.2)	77.3 (15.8)	75.1 (10.2)	77.4 (4.4)	
Carrot					
Total yield ($t\ ha^{-1}$)	103.6 (7.6)a	93.5 (7.9)ab	95.1 (7.8)ab	58.7 (5.2)c	89.4b
Marketable yield ($t\ ha^{-1}$)	70.0 (20.5)a	66.2 (11.7)a	58.6 (9.2)ab	38.5 (3.3)b	57.2ab
Total N uptake ($kg\ ha^{-1}$)	183 (38.0)a	138.4 (18.1)b	152.4 (17.6)ab	80.4 (7.2)c	
Dry matter (%)	11.9 (0.7)	11.9 (1.0)	11.9 (1.0)	12.0 (1.0)	
Total discard (%)	33.3 (16.1)	29.7 (7.5)	38.5 (7.4)	35.9 (3.8)	
Winter rye after carrot					
Grain yield ($t\ dw\ ha^{-1}$)	7.8 (2.0)a	4.9 (1.0)b	4.5 (0.9)b	4.6 (0.6)b	
Total N uptake ($t\ ha^{-1}$)	144.2 (23.6)a	76.0 (8.7)b	70.2 (8.7)b	69.3 (4.5)b	
Lettuce					
Total yield ($t\ ha^{-1}$)	43.4 (13.6)a	36.2 (12.2)ab	32.4 (7.7)b	20.0 (5.0)c	30.2a
Marketable yield ($t\ ha^{-1}$)	39.0 (7.4)a	32.9 (12.7)ab	29.1 (8.7)b	18.6 (6.3)c	27.2b
Total N uptake ($kg\ ha^{-1}$)	114.2 (19.5)a	93.9 (9.4)ab	86.0 (9.3)b	54.9 (16.3)c	
Dry matter (%)	4.3 (0.3)	4.5 (0.3)	4.7 (0.4)	4.6 (0.4)	
Total discard (%)	9.0 (13.0)	9.3 (13.7)	10.2 (15.5)	7.5 (9.9)	
Oats after lettuce					
Grain yield ($t\ dw\ ha^{-1}$)	4.5 (1.1)	4.3 (1.0)	4.4 (0.7)	4.8 (0.6)	
Total N uptake ($t\ ha^{-1}$)	87.8 (22.9)	69.0 (9.0)	67.0 (8.3)	81.7 (15.2)	
Onion					
Total yield ($t\ ha^{-1}$)	73.8 (13.7)a	51.8 (8.1)bc	54.0 (9.6)b	34.8 (3.6)c	52.6a
Marketable yield ($t\ ha^{-1}$)	63.0 (18.3)	42.1 (9.2)	45.6 (13.6)	30.7 (3.1)	46.8
Total N uptake ($kg\ ha^{-1}$)	173.2 (33.9)a	106.7 (21.9)b	112.3 (39.2)b	68.4 (13.4)b	
Dry matter (%)	12.8 (0.6)	12.4 (0.7)	12.5 (0.5)	12.7 (0.5)	
Total discard (%)	15.1 (12.6)	19.1 (10.6)	17.0 (14.5)	9.8 (6.1)	
Winter rye after onion					
Grain yield ($t\ dw\ ha^{-1}$)	8.4 (1.5)	6.6 (1.0)	6.0 (0.9)	5.7 (0.8)	
Total N uptake ($t\ ha^{-1}$)	157.5 (17.8)a	111.1 (13.8)b	101.7 (18.5)b	90.5 (8.2)b	
White cabbage					
Total yield ($t\ ha^{-1}$)	98.1 (9.2)a	80.7 (12.4)a	82.0 (11.8)a	56.1 (7.7)b	85.4a
Marketable yield ($t\ ha^{-1}$)	95.9 (7.7)a	77.2 (11.1)b	74.4 (11.5)b	47.9 (8.2)c	73.0b
Total N uptake ($kg\ ha^{-1}$)	379.3 (40.1)a	309.8 (42.9)b	305.3 (32.2)b	205.6 (25.4)c	
Dry matter (%)	9.9 (0.3)	9.9 (0.4)	10.0 (0.4)	10.2 (0.5)	
Total discard (%)	2.2 (2.6)	4.1 (4.0)	9.2 (4.9)	15.0 (13.1)	

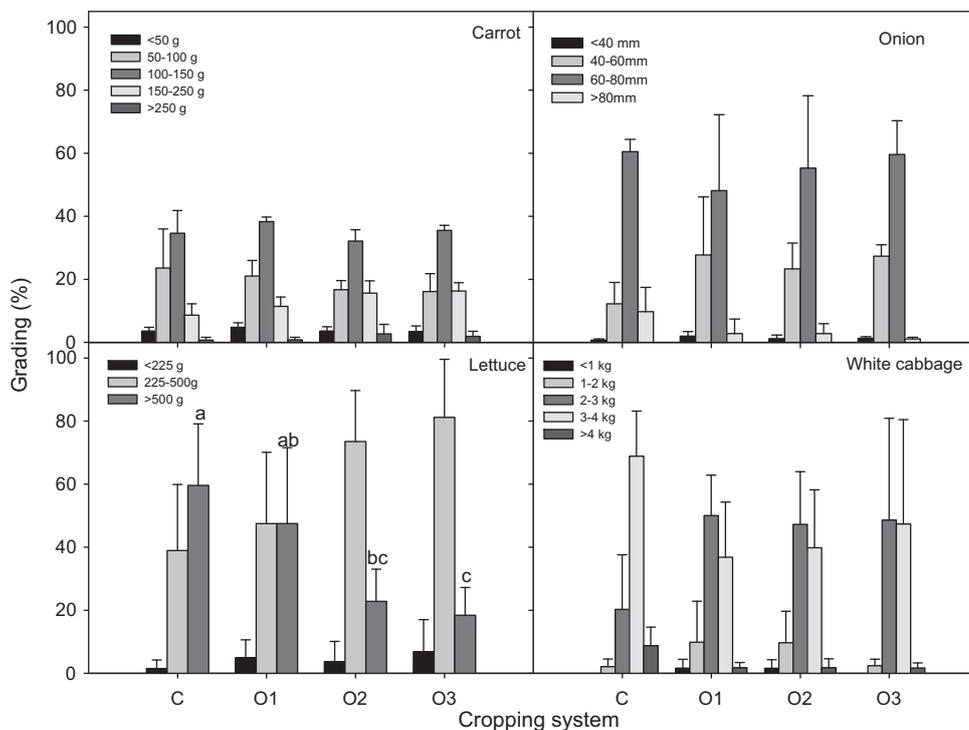


Fig. 2. Size distribution of carrot, onion, lettuce and white cabbage from the four different cropping systems. Results are means of 3 years and bars show standard deviation. Bars with different letters within each size interval are significant different ($P < 0.05$).

Table 4

Pests, diseases and damages observed in the four vegetable crops. The pests, diseases and damages are only listed if it was observed on more than 1% of the crops. Results are means of 3 years and numbers in brackets are standard deviations.

Pests, diseases and damages	Cropping system			
	C (%)	O1 (%)	O2 (%)	O3 (%)
Carrot				
Cavity spot	1.8 (2.8)	1.8 (2.7)	1.6 (2.5)	1.9 (2.9)
Scab	0.8 (0.5)	0.7 (0.4)	1.0 (0.5)	1.7 (1.3)
Other diseases	2.3 (2.7)	1.4 (1.5)	1.5 (1.2)	3.0 (4.4)
Carrot root fly	4.8 (5.4)	3.6 (2.9)	5.1 (5.7)	2.5 (2.3)
Cutworms	1.0 (0.5)	1.2 (0.6)	1.6 (1.4)	1.8 (0.6)
Mice	1.7 (1.2)	1.5 (1.5)	1.9 (0.9)	1.6 (1.3)
Branched roots	6.6 (6.5)	4.2 (0.7)	5.2 (1.3)	3.9 (1.3)
Split roots	3.9 (4.6)	3.2 (2.7)	3.9 (3.6)	2.9 (2.3)
Cracked roots	1.4 (2.2)	0.6 (1.0)	0.6 (0.8)	0.7 (1.1)
Broken roots	2.9 (1.1)	1.9 (0.7)	2.8 (2.1)	2.6 (1.8)
Deform roots	4.4 (1.2)	5.9 (1.8)	5.0 (1.8)	6.3 (0.8)
Green neck	5.7 (8.9)	1.2 (1.0)	1.8 (1.1)	0.8 (0.1)
Lettuce				
Tipburn (inside)	0.6 (1.1)	0	0	2.5 (4.3)
Cracks in leaves	3.1 (5.3)	1.2 (2.1)	1.2 (2.1)	0.3 (0.5)
Rot (bottom)	3.7 (3.7)	3.7 (4.9)	5.2 (7.5)	2.5 (2.8)
Undeveloped	1.5 (2.7)	4.9 (5.7)	3.7 (6.4)	6.8 (10.2)
Ticks	33.3 (57.7)	33.3 (57.7)	29.0 (50.3)	31.5 (54.5)
Lice (severe)	4.6 (8.0)	13.9 (24.1)	24.7 (42.8)	9.3 (16.0)
Lice (total)	24.7 (42.8)	32.7 (56.7)	33.0 (57.2)	29.0 (50.3)
Slugs	0	0.6 (1.1)	0	1.5 (2.7)
Onion				
Decay	12.2 (16.4)	5.6 (4.9)	2.5 (2.2)	2.3 (2.7)
Watery scales	1.0 (1.1)	8.1 (11.7)	9.8 (15.6)	3.6 (5.3)
Dry scales	1.3 (1.2)	3.4 (5.1)	2.8 (3.8)	2.1 (2.9)
White cabbage				
Rot	2.1 (2.5)	3.2 (4.1)	7.9 (5.8)	13.2 (15.4)
Cracks in leaves	0	1.1 (0.9)	1.6 (1.6)	2.1 (2.4)
Thrips (severe attack)	11.6 (10.9)	6.9 (6.3)	11.6 (7.9)	2.6 (4.8)
Thrips (total)	70.4 (15.9)	67.7 (20.1)	72.0 (20.4)	51.9 (24.3)
Cabbage root fly (total)	2.1 (2.4)	1.6 (1.6)	2.6 (3.3)	2.6 (3.3)
Cabbage white butterfly (severe attack)	1.1 (2.1)	4.2 (4.4)	7.4 (10.1)	2.6 (6.3)
Cabbage white butterfly (total)	32.8 (21.9)	41.8 (11.1)	38.1 (22.1)	51.9 (13.5)
Slugs	0.5 (0.9)	1.6 (2.7)	0.5 (0.9)	7.9 (13.7)

Table 5

Examples of year to year variation in selected crops and selected pests or diseases. Results are means of 3 replicates and numbers in bracket show standard deviation. Means followed by different letters within a row are significantly different at $P < 0.05$.

Crop	Pest/disease/damage	Year	Cropping system				
			C	O1	O2	O3	
White cabbage	Rot in the top	2007	0a	1.6 (2.7)a	3.2 (2.7)a	0a	
		2008	4.8 (0)a	4.8 (4.8)a	11.1 (7.3)a	11.1 (11.0)a	
		2009	1.6 (2.7)b	3.2 (5.5)b	9.5 (4.8)ab	28.6 (14.3)a	
	Slugs	2007	1.6 (2.7)b	4.8 (4.8)ab	1.6 (2.7)b	23.8 (14.3)a	
		2008	0a	0a	0a	0a	
		2009	0a	0a	0a	0a	
	Thrips (severe)	2007	11.1 (7.3)a	6.3 (2.7)a	14.3 (8.2)a	6.3 (7.3)a	
		2008	22.2 (9.9)a	1.6 (2.7)b	4.8 (4.8)b	0b	
		2009	1.6 (2.7)b	12.7 (7.3)a	15.9 (7.3)a	1.6 (2.7)b	
	Cabbage white butterfly	2007	49.2 (2.7)a	42.9 (8.2)a	49.2 (11.0)a	57.1 (9.5)a	
		2008	7.9 (5.5)b	30.2 (12.0)a	12.7 (2.7)b	36.5 (9.9)a	
		2009	41.3 (19.2)a	52.4 (12.6)a	52.4 (9.5)a	61.9 (19.0)a	
Onion	Decay	2007	0a	0a	0a	0a	
		2008	5.8 (2.4)a	8.3 (4.4)a	3.8 (0.5)a	5.2 (2.5)a	
		2009	30.9 (14.8)a	8.6 (6.1)b	3.7 (1.1)bc	1.9 (0.6)c	
	Watery scales	2007	2.1 (1.1)c	21.6 (6.1)a	27.7 (3.2)a	9.7 (4.4)b	
		2008	0.7 (0.2)a	2.8 (2.8)a	1.6 (1.1)a	1.1 (0.7)a	
		2009	0a	0a	0a	0a	
	Carrot	Scab (<i>Streptomyces scabies</i>)	2007	1.3 (1.5)a	1.1 (1.0)a	1.2 (0.5)a	1.2 (0.9)a
			2008	0.8 (0.9)b	0.4 (0.2)b	0.5 (0.4)b	3.1 (0.7)a
			2009	0.3 (0.1)a	0.6 (0.9)a	1.4 (0.7)a	0.7 (0.3)a
Green neck		2007	16.0 (8.2)a	1.8 (1.1)b	1.9 (0.8)b	0.4 (0.2)b	
		2008	0.8 (0.7)a	1.8 (1.4)a	2.8 (3.1)a	1.8 (2.2)a	
		2009	0.3 (0.1)a	0a	0.7 (0.9)a	0.2 (0.4)a	
Split roots		2007	9.0 (1.9)a	5.6 (6.0)a	4.2 (1.3)a	5.1 (2.4)a	
		2008	2.4 (0.2)b	3.8 (1.4)b	7.3 (2.6)a	3.2 (1.3)b	
		2009	0.2 (0.1)a	0.3 (0.2)a	0.2 (0.2)a	0.6 (0.5)a	
Branched roots	2007	14.0 (2.0)a	4.7 (4.3)b	3.7 (2.1)b	2.5 (0.8)b		
	2008	3.8 (0.4)a	4.4 (1.8)a	5.9 (1.2)a	4.8 (1.5)a		
	2009	2.1 (1.2)a	3.5 (1.1)a	6.0 (2.9)a	3.6 (1.1)a		

Table 6
N and S concentration in the main crop of the 8 crops in the crop rotation. S concentration is only determined in white cabbage. Results are means of 3 replicates in 3 years and statistical significant differences between the four cropping systems are marked with different letters.

	C	O1	O2	O3
N (%)				
Oats after white cabbage	2.00a	1.63b	1.61b	1.55b
Carrot	0.97a	0.82b	0.89bc	0.75c
Winter rye after carrot	1.77a	1.47b	1.52b	1.48b
Lettuce	3.09	2.91	2.84	2.56
Oats after lettuce	1.89	1.59	1.47	1.60
Onion	1.60	1.35	1.35	1.32
Winter rye after onion	1.78a	1.53b	1.61b	1.52b
White cabbage	2.15	2.12	2.09	2.03
S (%)				
White cabbage	0.69	0.68	0.61	0.64

were observed, the conventional system was superior to the organic systems. In the vegetable crops some variation in the N uptake was seen whereas no differences between the systems was observed in P and K uptake, with the exception of K uptake in lettuce where the conventional system provided more K than the organic systems with fertility building crops. In winter rye more N and K were taken up in the conventional system as well (Fig. 3).

Differences in nutrient balances (fertilizer input minus crop removal) were mainly governed by differences in fertilizer strategies, as the differences in nutrient removal with harvested products were not large (Table 7). The O3 and especially O2 showed clear negative balances for N, P and K. These two systems had the same fertilizer application, but the yields and thereby nutrient removals were higher in O2. The O1 also showed negative balance values for P and K, but not for N. System C was close to balance, but slightly negative for K and positive for N and P.

3.4. Root distribution and growth

There were large differences in root distribution under the different crops, from onion which had practically no roots below 0.5 m to white cabbage and fodder radish which had high root densities all the way to 2.5 m (Fig. 4). The total root density among main crops increased in the order onion < lettuce < oats < carrot < winter rye < white cabbage. The fodder radish catch crop grown after lettuce in O2 showed the highest root intensity of all crops in the rotation, and showed high root intensity also in the deepest observed soil layers (Fig. 4a). Green manure growing after harvest of winter rye in O2 showed root intensities much as those measured on the winter rye crop (Fig. 4d), whereas the root intensity observed on the green manure growing after oats tended to be lower than the root intensity observed on the oats itself (Fig. 4c) and lower than observed on the green manure grown after winter rye.

Differences in root growth between the C and O2 systems were limited. Winter rye showed significantly higher root intensity in the O2 system than in C whether it was grown after onion or carrot (Fig. 4d), whereas there was a tendency to increased root intensity of white cabbage in the subsoil in the C system compared to O2, though this was not significant (Fig. 4a). Winter rye also showed significantly higher root intensity when grown after onions than after carrots.

Table 7
Nutrient application by fertilization and nutrient balance calculated as the difference between what was added with fertilizer and removed by harvested products.

	C (kg nutrient ha ⁻¹ year ⁻¹)	O1 (kg nutrient ha ⁻¹ year ⁻¹)	O2 (kg nutrient ha ⁻¹ year ⁻¹)	O3 (kg nutrient ha ⁻¹ year ⁻¹)
N application	149	85	25	25
N balance	32	1	-58	-38
P application	28	6	2	2
P balance	8	-10	-15	-11
K application	70	31	9	9
K balance	-27	-50	-70	-48

The average soil exploitation by roots (Table 8) showed that most of the soil within the studied soil layer (0–2.4 m) was unexploited by roots most of the time, but the exploitation was almost twice as extensive in O2 (38%) as in C (21%). The difference between the two systems was strongest in the deeper soil layers between 1 and 2.4 m where O2 had 27% root exploitation compared to 12% in C. As differences in root growth among crops grown in the two systems were quite small, the differences between the systems were due almost exclusively to the presence of fertility building crops in the autumn in O2, fertility building crops which were not present in C (Fig. 5).

3.5. Inorganic nitrogen

Spring N_{inorg} values in the topsoil did not tell much about the functioning of the system, mainly because there was a lot of variation in fertilization and crop activity at the time of soil sampling (Fig. 6). Winter rye had been growing strongly since the early spring, and also oats had some growth prior to the May soil sampling, whereas among the vegetables only the onions had already been planted but not grown much yet. In O1 all crops had already received the full amount of slurry, in O2 and O3 slurry had been applied to onion and white cabbage plots. In C all but the carrot plots had received fertilizer at the time of the May soil sampling, but some crops had only received part of their fertilizer at the sampling time (Table 2). In the case of carrot no fertilizer had been added to the C, O2 or O3 systems, so the effect of green manure in O2 can be directly compared with the not yet fertilized plots in C (Fig. 6), which shows that topsoil N_{inorg} was approximately doubled and below 0.5 m N_{inorg} was reduced in the O2 system.

The subsoil N_{inorg} in May provide more information about the functioning of the systems, as it was less affected by recent fertilization and early crop growth. In the winter rye plots early growth was likely to have reduced subsoil N_{inorg} already, and there were some indications in the results that the application of slurry to the topsoil had already increased subsoil N_{inorg} . Subsoil N_{inorg} was clearly higher before onion than before carrot in O2 (Fig. 6), even though the pre-crops were identical, and subsoil N_{inorg} before white cabbage was much higher than before lettuce in O2 again after identical pre-crops.

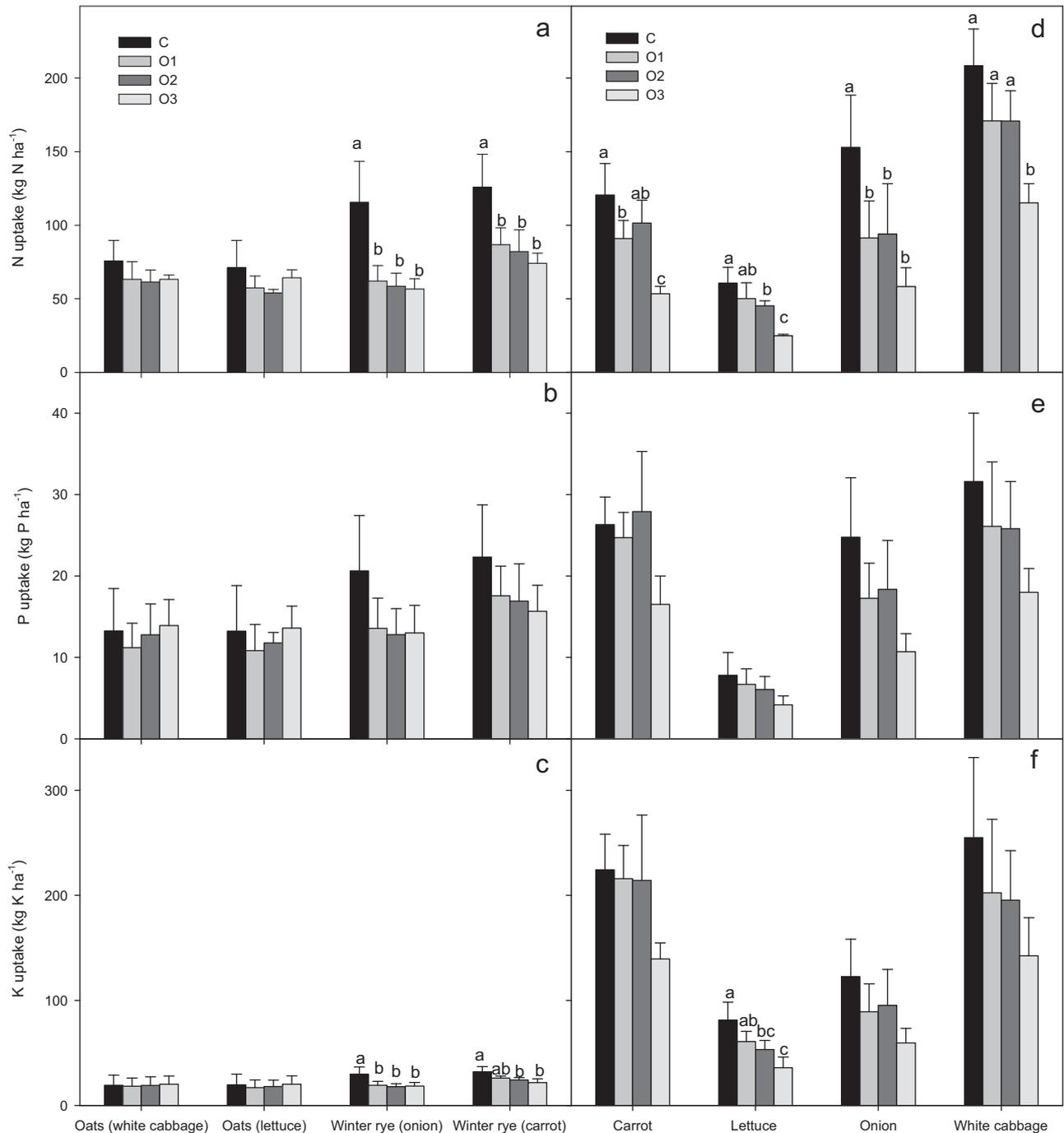


Fig. 3. Nutrient uptake (N, P and K) on harvestable parts of the crops. Results are means of 3 years and bars show standard deviation. Bars with different letters within each crop are significant different ($P < 0.05$).

Before the vegetable crops, i.e. where cereals had been grown the year before, subsoil N_{inorg} was generally rather low, in the range of 20–55 kg N ha⁻¹ between 1 and 2 m depth. In general subsoil N_{inorg} was lower in O2 than in C (Fig. 6), but the difference was not large.

In May in the cereal plots, subsoil N_{inorg} was much more variable from 20 to 130 kg N ha⁻¹. The values were clearly lower in O2 than in C, except for winter rye after onion. In general, low values of 30–50 kg N ha⁻¹ were found in the subsoil under winter rye, whereas large variation was found under the young oat crop. Under

Table 8

Average relative soil exploitation by crop root systems. Data were calculated based on the measured root depths (Fig. 6). A root depth value for each day was obtained by interpolation between the measurement dates. Then the average was calculated across all days in the period March to November, but excluding the winter months where root activity was assumed to be very low.

	0–2.4 m (% root occupancy)	0–1 m (% root occupancy)	1–2.4 m (% root occupancy)	Average rooting depth (m)
C	21	30	12	0.42
O2	38	49	27	0.76

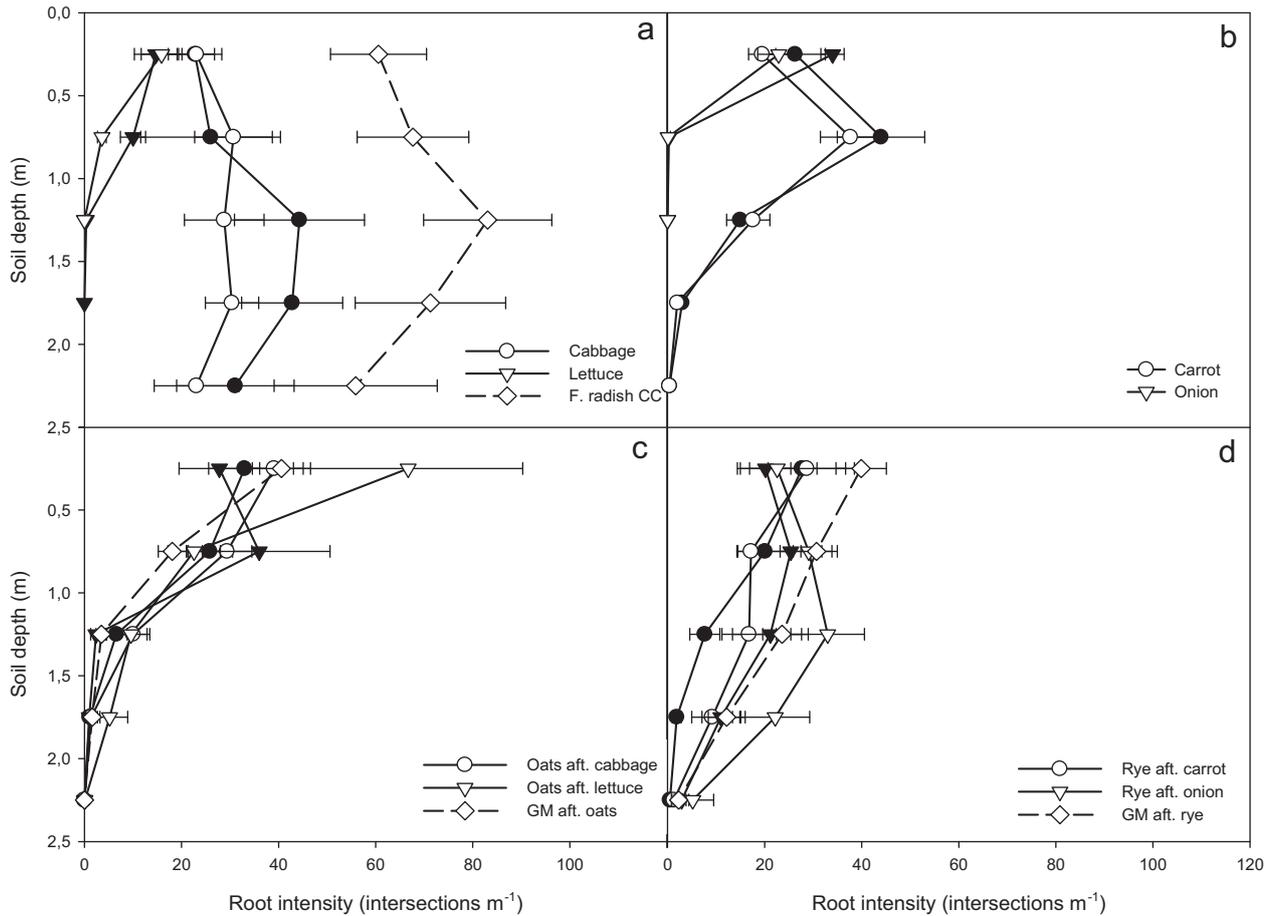


Fig. 4. Root intensity distribution at the end of the growing season of vegetables, cereals and fertility building crops in the rotation from the O2 system (open symbols) and the C system (closed symbols). Solid lines show main crops, dashed lines with diamond symbols show fertility building crops; fodder radish or green manure (GM). Each point show average of 2 years, with measurements from three plots in each year, error bars show SE.

oats in C very high subsoil N_{inorg} values of 90 and 130 kg N ha⁻¹ were found when oats were grown after white cabbage and lettuce respectively, but in O2 the values were low at 40 and 20 kg N ha⁻¹ respectively.

In the autumn there were large differences between the N_{inorg} in the soil after the vegetable crop species, and also clear differences

between the systems. After white cabbage N_{inorg} was low both in C and in O2, and after onion they were high and similar in the two systems. A large difference between the two systems was found after lettuce with very low N_{inorg} in O2 where lettuce was followed by a fodder radish catch crop and very high N_{inorg} in C. In all soil layers except the top 0 to 0.5 m layer, significantly less N_{inorg} was

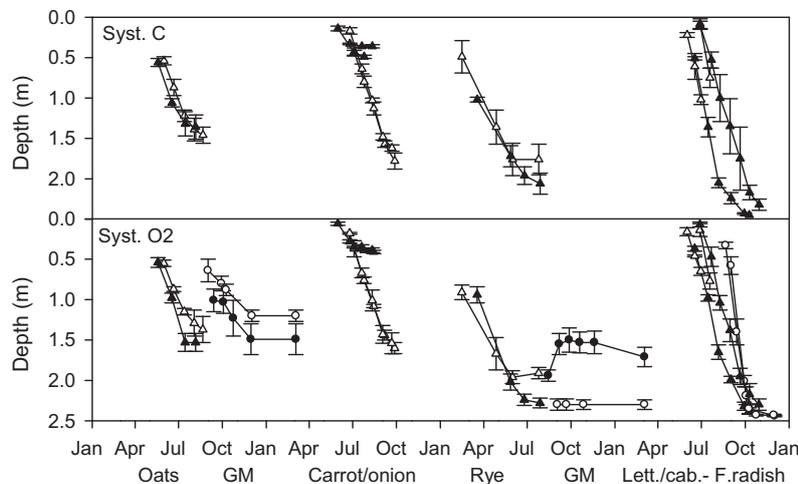


Fig. 5. Rooting depth of main crops and fertility building crops in the C and O2 systems. The rotation is shown with an overlay so that year 1 and 5 with oats are shown first, then year 2 and 6 with carrot and onion etc. Main crops are shown with triangles, fertility building crops with circles. Crops in year 1–4 are shown with open symbols while crops in year 5–8 are shown with solid symbols. For each crop results from 2 years are shown with error bars (SE, $n = 3$).

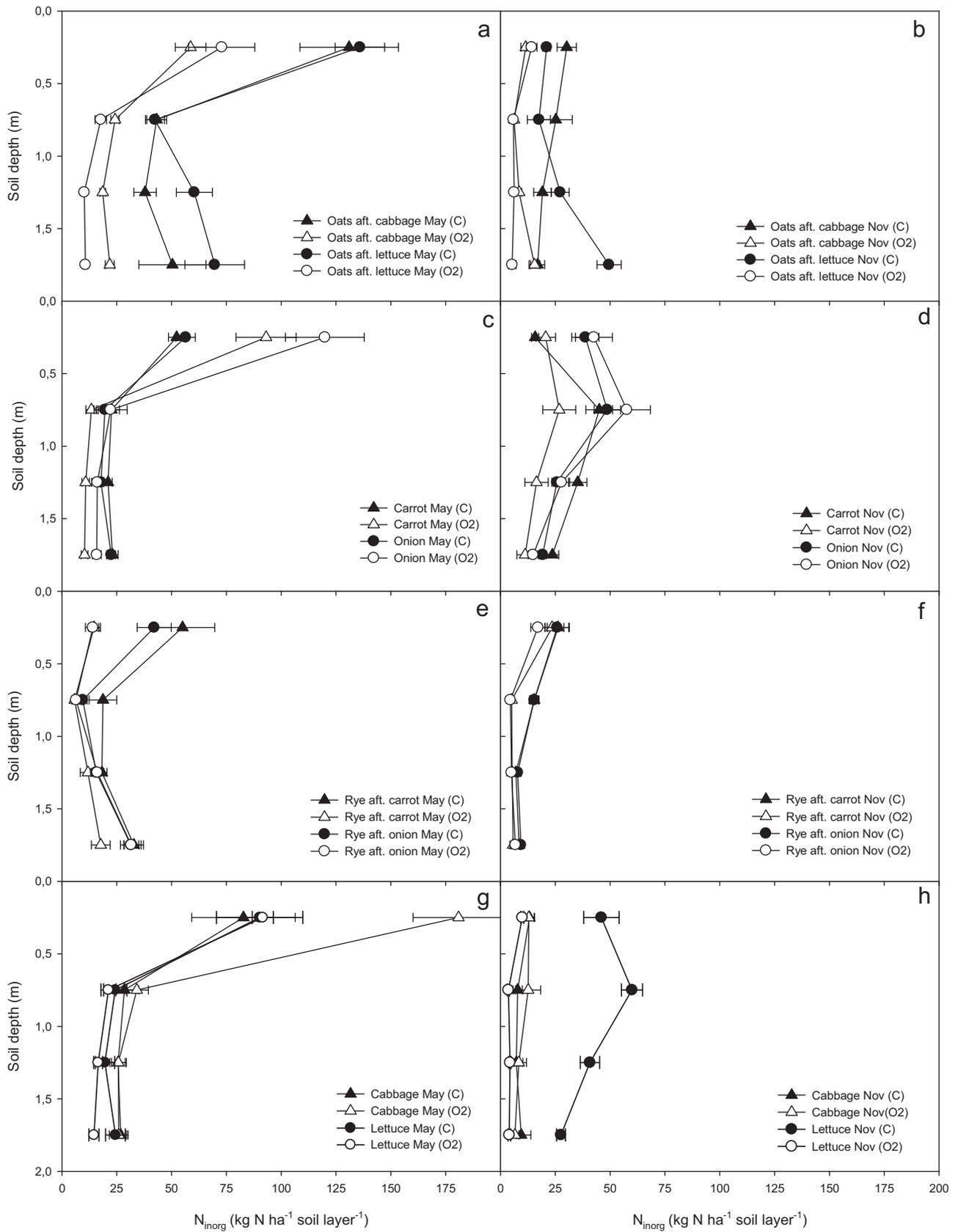


Fig. 6. Profiles of soil N_{inorg} in May (a, c, e and g) during early season and November after all crops were harvested (b, d, f and h) in the C (filled symbols) and O2 (open symbols) systems. Results are averages from the 2 years 2008 and 2009, error bars show SE.

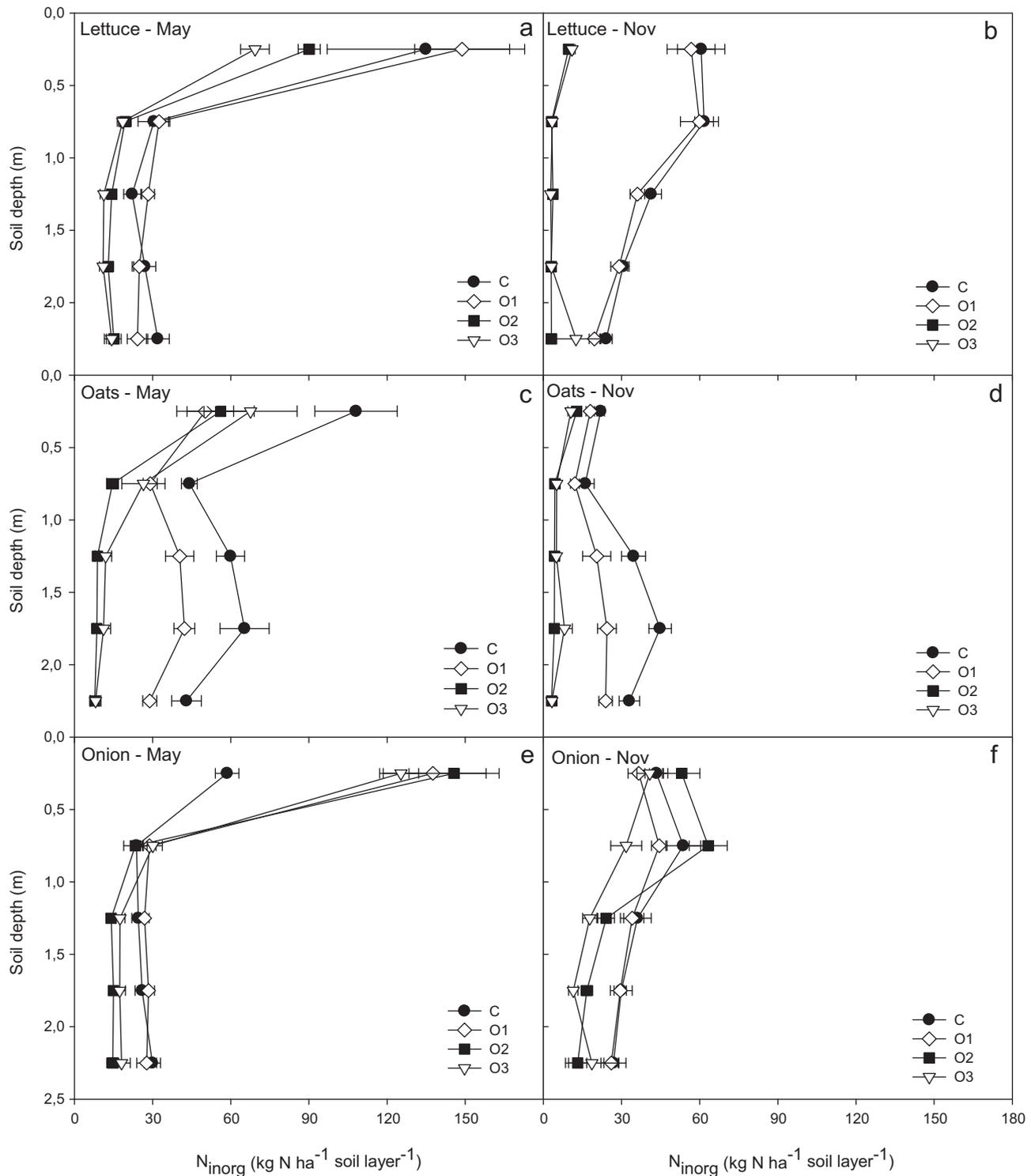


Fig. 7. Profiles of soil N_{inorg} in May (a, c and e) during early season and November after all crops were harvested (b, d and f) during the lettuce–oats–onion sequence of the four cropping systems. Results are from the 3 years 2008, 2009 and 2010, error bars show SE.

found in O2 than in C after carrots as well. After the cereals N_{inorg} was relatively low and except from the top 0.5 m soil layer after winter rye it was always significantly lower in O2 than in C. The only somewhat higher N_{inorg} value after cereals was observed after oats following lettuce in the C system.

Comparing soil N_{inorg} of all four systems during a shorter sequence of the rotation showed that the systems could be paired according to their main effects on soil N_{inorg} ; C and O1 showed one type of results, O2 and O3 another (Fig. 7). On average across

all measurements, N_{inorg} in the 0–2 m soil layer was 184 and 170 $kg\ N\ ha^{-1}$ in C and O1 which was not significantly different, but was significantly higher than the 104 and 95 $kg\ N\ ha^{-1}$ found in O2 and O3 (Fig. 8). In the subsoil layer (1–2 m depth) the similar average values were 74, 61, 22 and 21 $kg\ N\ ha^{-1}$ respectively, again C and O1 were significantly higher than O2 and O3. In both spring and autumn, subsoil N_{inorg} was significantly higher in C and O1 than in O2 and O3. Generally the O2 and O3 systems had almost identical soil N_{inorg} levels. Also C and O1 showed rather similar N_{inorg}

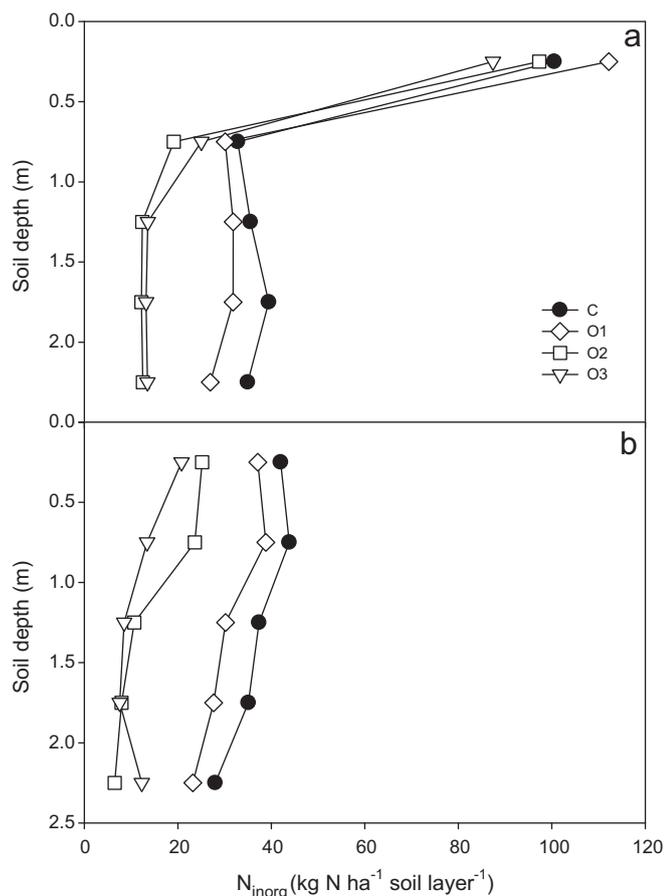


Fig. 8. Profiles of soil N_{inorg} in May (a) and November (b) on average of all data measured in the lettuce–oats–onion sequence of the rotations during 2008, 2009 and 2010.

distribution, though N_{inorg} was significantly higher in C than in O1 ($P < 0.05$). In the years of the lettuce and onion crops very little difference was found except in the topsoil in the spring before onions due to early slurry application in O1. Before and after the oat crop soil N_{inorg} was clearly higher in C than in O1, but they showed the same general depth distribution of N_{inorg} , and both showed much higher subsoil N_{inorg} than O2 and O3. Looking specifically at the subsoil, N_{inorg} was on average reduced by 18% in O1 compared to C, but by as much as 71% in both O2 and O3.

4. Discussion

4.1. Autumn crop cover and yields

The organic systems were found to give only moderate yield reductions compared to the conventional farming system. In O1 the average yield level of the vegetable crops was 83% of the conventional yield, and in the O2 system based on fertility building crops the yield level was almost the same with 81% of conventional yields. The exact yield comparison between cropping systems depend strongly on the choice of crop species for the rotation as shown by the similar yield levels of oats and carrots in the organic and the conventional systems, whereas onion and winter rye showed much larger yield reductions in the organic (28% and 40%). Such differences in crop response are generally seen depending on e.g. crop nutrient demand (Dresbøll et al., 2008; Thorup-Kristensen, 1999) and are not mainly an effect of the specific crop rotation here. The vegetable crops in this experiment were chosen to range from very sensitive crops (onion) to crops with low sensitivity to cropping

system (carrot), whereas the two cereal crops oats and winter rye were selected based on their performance and their strong competitive ability towards weeds in organic production. In conventional farming, spring barley and winter wheat would have been the typical choice of cereals. It is likely that especially spring barley would have shown larger yield reduction under organic conditions than oats, but as one crop out of six in the rotation, this would not have changed the overall productivity much. As the experiment was established on an area where an unfertilized organic rotation had been grown for the preceding 10 years, the good productivity of the organic crops was not a consequence of recent conventional cropping practices on the area.

The crop yields in the O2 and O3 systems where fertilizer input was reduced was very close to the yields of O1 when the comparison was based on the vegetable yields per m crop row. In general, there were no clear examples of crops responding differently towards the three organic systems. Similar good effects of catch crop use on yields has been found in organic cereal rotations, however, with continued reliance on high manure inputs, and some differences in response of different crops in rotation (Doltra et al., 2011).

If the comparison was based on vegetable yield per hectare, the yield reductions in O3 was clearly more substantial compared to O1 and O2, as growing intercrops left less area for the vegetable crops. Whether the comparison to yield per m crop row or yield per hectare land is the most relevant, depend on the situation at the farm. The cost of producing one unit of vegetables will not be much higher with intercrops than without intercrops. Therefore, if the vegetable production at the farm can be maintained by increasing the total vegetable area at the expense of e.g. cereal crops, introducing intercropping systems is economically feasible. However, if the available land area for vegetables is limited, introducing intercrops will reduce the overall vegetable production at the farm, and thereby strongly reduce its income. In this last situation, yield per hectare rather than yield per m crop row is the most relevant yield parameter.

The fact that vegetable yield per m crop row was maintained in the O3 system show that the intercropping strategy can be practiced with a moderate extra cost. This was obtained by improved intercropping strategies to control crop–intercrop competition based on species choice for intercrops, root pruning strategies (Báth et al., 2008) and altered spatial field design with intercrops growing between every second vegetable crop row. Most other studies have shown that well developed intercrops will reduce vegetable yield unacceptably (Báth et al., 2008). Intercrop planting had to be delayed until 8 weeks after leek planting (Müller-Schärer, 1996) or seeded 30 days after pumpkin seeding (Vanek et al., 2005) to avoid negative yield effects. A further advantage of the intercrop strategy in the present study was that the intercrops were established already 1 year earlier than the vegetable crops which enhanced their ecological functioning by keeping the soil continuously vegetated during the previous year of cereal production and during the growth season of the vegetables.

4.2. Product quality and biological pest regulation

The results confirm that the product quality in the organic systems did not differ significantly from the conventional system or in the comparison between the O1 system and the O2 and O3 systems with fertility building crops. The general product quality parameters (product size, dry matter percentage, N content and level of damages/discarding) were not generally affected; there were examples of differences between systems in specific years, but the effects were not consistent over the 3 years of the experiment, and some examples pointed to advantages of the organic systems others to advantages of the conventional system. Based on this, the results did not point towards improved biological pest regulation in the O2

and O3 systems, but also that the use of pesticides and fungicides in the conventional system did not reduce pest and disease damage to the products. The year to year variation in climate and management and the variation among quality parameters studied show that such studies must be rather comprehensive; studying only few quality parameters or for too short time may lead to results which are far from representing the performance of the systems and may even lead to wrong conclusions.

However, our results did show some examples of interesting effects of intercropping on vegetable quality (e.g. decrease of thrips attacks in white cabbage and fewer onions with signs of decay and watery scales) and affected factors such as natural regulation of insect pests through effects on insect pathogenic fungi (Meyling et al., 2011) and early season carabid beetle activity and species composition (S. Navntoft and N.V. Meyling, unpublished). Nevertheless, no clear benefits of the intercrops were observed, and they were thereby not able to compensate for even a moderate extra cost in this case. More advantage may be achieved by developing the design of the intercropping system or the species choice. In the present study none of the intercrop species were especially attractive to insects through their production of pollen or nectar in their flowers, but potentially introduction of such species could have a significant effect on insect population dynamics in the crops (Hogg et al., 2011).

4.3. Reduced nutrient losses to the environment

The N leaching was not measured directly, but measurements of soil N_{inorg} twice a year to 2 or 2.5 m depth gave detailed information of soil N dynamics and how much N leached to the deeper soil layers. As previously shown (Thorup-Kristensen, 2006a; Thorup-Kristensen et al., 2009) the introduction of fertility building crops may strongly reduce deep soil N content during the season while the fertility building crop is grown, but the effect may also remain for a longer period, and still be strong in the next autumn/winter season.

As fertility building crops were grown at least every second year and the average presence of active roots in the soil was almost doubled by the inclusion of fertility building crops as done in O2 and O3, it is not surprising that a consistently strong reduction of subsoil N_{inorg} was observed. On average the subsoil N_{inorg} in O2 and O3 was around 30% of the levels found in C and O1, indicating strongly reduced N leaching losses. In many studies of N leaching, N leached to below a depth of 1 m or even less is assumed to be lost by leaching (e.g. Hansen et al., 2010). Management of crop and soil during autumn has been identified as the main determinant of N leaching in an organic crop rotation with lowest nitrate leaching when a catch crop soil cover during autumn and winter was established (Askegaard et al., 2011). Also Torstensson et al. (2006) found that systems with intensive use of fertility building crops had significantly lower N leaching loss than other systems, though in their system the fertility building crops were added to a conventional system making this more N efficient than the organic and other conventional systems. Such results point to fertility building crop strategies being much more important than conventional vs. organic farming systems in optimizing N utilization and reducing N leaching losses.

When using average subsoil N_{inorg} as an indicator of N leaching losses from the systems, it is indicated that O1 reduced leaching by 18% during the most leaching intensive sequence with shallow rooted crops (lettuce, oats, onion), very close to its effects on crop yields. This means, that even though there was a small reduction in leaching per hectare, there was no improvement in leaching loss per unit of food produced. This is similar to results of e.g. Aronsson et al. (2007) who also found that lower N leaching losses per hectare in organic systems did not lead to significantly lower leaching losses

per unit crop product. On the other hand, O2 and O3 reduced subsoil N_{inorg} by 71% while reducing average yields only by 19% and 37% respectively, showing systems where nitrogen leaching per unit food produced is also clearly reduced.

It is noteworthy that the fertility building crop strategies were able to almost double the soil exploitation by crop roots, from 21% to 38% of the top 2.4 m of the soil and more than double the exploitation of the deeper part half of this soil profile from 12% to 27%. The increased root exploitation in the fertility building crop systems represent a strong change towards a more natural ecosystem system where also the subsoil form an active part of the resource base for plant growth. However, it also illustrates how different even this system is from a natural system where the soil exploitation would be expected to be close to 100% (Canadell et al., 1996; Sun et al., 1997). Still the results on soil N and especially soil N in deeper layers show that this increased root exploitation of the soil has strongly improved the ability of the system to retain N and avoid that this resource is being lost by leaching, i.e. that a normal function of natural ecosystems has to a significant extent been introduced into a farming system and that the biogeochemical cycles of carbon and N has been recoupled by the fertility building crop strategies (Tonitto et al., 2006; Gardner and Drinkwater, 2009). Further significant improvement in this aspect of arable cropping systems will require much more dramatic changes to the system, e.g. a shift towards perennial crops (Cox et al., 2010).

This improved soil exploitation was not an effect of improved root growth of the crops in organic compared to conventional systems, as only very few differences were observed in root growth of crops between the C and O2 system. Where comparisons were possible, the root growth of the crops was close to previous results (Kristensen and Thorup-Kristensen, 2007; Thorup-Kristensen, 2006b). Instead it was the addition of the extra element of fertility building crops and their root growth which so strongly improved the soil exploitation of the O2 system.

Another aspect allowing the development of N efficient rotations here was the mixed rotation of vegetables and cereal crops. In the spring, subsoil N_{inorg} values were relatively low before the vegetables, i.e. after cereal crops, and the highest values were found before oats following lettuce and cabbage. This illustrates that growing cereals as part of a vegetable rotation allow improved N husbandry. Cereals are typically more efficient in depleting soil N_{inorg} than vegetables (Wehrmann and Scharpf, 1979), and as cereals leave crop residues with less N and higher C/N ratios in the field than vegetable crops, they also reduce N mineralization after harvest. In the winter rye crop N_{inorg} was already low in May, even after onion leaving high N_{inorg} levels in the autumn, but this N_{inorg} had probably already been taken up by the winter rye in the early spring. In a previous study winter wheat was found to take up much soil N already before mid April under similar conditions (Thorup-Kristensen et al., 2009), again confirming the typically higher N efficiency of cereal crops. Finally, cereal crops offer better options for introducing fertility building crops into the system than most vegetables do, as cereals allow undersowing of fertility building crops and because small yield losses caused by their establishment can more easily be tolerated in cereal crops than in vegetables. This was a characteristic which was critical for the design of the present rotation study.

4.4. Less dependence on nutrient import

The results showed that strategic use of fertility building crops could strongly reduce the dependence on import of nutrients. While the import of N in slurry was reduced from 85 kg N ha⁻¹ year⁻¹ in O1 to only 25 kg N ha⁻¹ year⁻¹ in O2, only few effects were observed in terms of crop N uptake and content. While all crops were fertilized in O1, four out of the six crops were

left without any fertilizer application in O2, but still the yields were the same as O1. The average yearly N removal with harvested crops was 84 kg N ha⁻¹ in O1 and 83 kg N ha⁻¹ in O2. To further improve the yield performance of the organic systems, the results indicate that N management should be improved to the organic crops. Their yield reductions compared to the conventional system was found not to be caused by pests and damages, whereas the N content was lower of some of the organic crops.

The organic systems were tested during the period 2006–2009, which is not long enough to test long term sustainability. Based on nutrient balances it is clear that especially O2 and O3 will need to find sources of P and K to balance what is removed, as the fertility building crop strategy primarily improve N husbandry. However, a farmer practicing such systems will be free to find fertilizers as mineral sources or waste products with available P and K, which can be used even if they have no or little N effect. A farmer practicing a system like O1 on the other hand, will need to import fertilizers with a high N effect, which may be difficult or expensive to get in competition with other organic farmers.

Regarding nitrogen, the results indicate that the O1 system may actually not be sustainable, as the amount of fertilizer N added to the system is almost identical to the amount harvested. There will be further N input through atmospheric deposition (c. 20 kg N ha⁻¹), but also N losses in terms of leaching and denitrification, and an N balance including all factors is likely to show a net loss of N from the O1 system. The N balance of O2 and O3 is harder to analyze. Much more N is harvested than what is added with fertilizer, but at the same time N is also added through N fixation of the green manures growing after the cereals, and the N leaching loss is lower than in O1. In another experiment (Thorup-Kristensen, unpublished data) similarly undersown green manure of white clover, black medick and kidney vetch contained on average 190 kg N ha⁻¹ in November compared to 75 kg N ha⁻¹ on average across non-legume species, indicating an N fixation of more than c. 115 kg N ha⁻¹. If this was the case also in the present experiment, the N fixation of the green manures in O2 and O3 almost precisely match the reduced N input with fertilizer compared to O1. As N leaching loss was clearly lower in O2 and O3, this would lead to an improved overall N balance and higher degree of sustainability of these two systems compared to O1. The increased input of organic matter adding to the soil C and N pool may also point towards O2 and O3 as more nitrogen sustainable systems than O1, though to what extent cannot be evaluated here.

5. Conclusion

- Yield loss in organic compared to conventional systems could be maintained at a moderate level of on average less than 20%, but it varied strongly depending on crop species.
- Pest and disease damage to vegetable crops was not systematically different among the conventional and the three organic systems.
- Nutrient management could be improved strongly in organic systems by intensive use of fertility building crops, which also reduced nitrogen losses to the environment strongly.
- The use of fertility building crops in 5 of 8 years in the rotation almost doubled the root exploitation of the soil volume.
- When looking at the soil N and nutrient balance of the systems the main differences were not observed in the comparison of conventional and organic systems, but in the comparison of systems with and without intensive use of fertility building crops, whereas the organic system without fertility building crops resembled the conventional system.

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