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Cereal yield and quality as affected by nitrogen availability in organic and conventional arable crop rotations: A combined modeling and experimental approach

Jordi Doltra*, Mette Lægdsmand, Jørgen E. Olesen

Aarhus University, Department of Agroecology and Environment, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark

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ABSTRACT

The effects of nitrogen (N) availability related to fertilizer type, catch crop management, and rotation composition on cereal yield and grain N were investigated in four organic and one conventional cropping systems in Denmark using the FASSET model. The four-year rotation studied was: spring barley–(faba bean or grass-clover)–potato–winter wheat. Experiments were done at three locations representative of the different soil types and climatic conditions in Denmark. The three organic systems that included faba bean as the N fixing crop comprised a system with manure (stored pig slurry) and undersowing catch crops (OF + C + M), a system with manure but without undersowing catch crops (OF − C + M), and a system without manure and with catch crops (OF + C − M). A grass-clover green manure was used as N fixing crop in the other organic system with catch crops (OG + C + M). Cuttings of grass-clover were removed from the plots and an equivalent amount of total-N in pig slurry was applied to the cropping system. The conventional rotation included mineral fertilizer and catch crops (CF + C + F), although only non-legume catch crops were used. Measurements of cereal dry matter (DM) at harvest and of grain N contents were done in all plots. On average the FASSET model was able to predict the yield and grain N of cereals with a reasonable accuracy for the range of cropping systems and soil types studied, having a particularly good performance on winter wheat. Cereal yields were better on the more loamy soil. DM yield and grain N content were mainly influenced by the type and amount of fertilizer-N at all three locations. Although a catch crop benefit in terms of yield and grain N was observed in most of the cases, a limited N availability affected the cereal production in the four organic systems. Scenario analyses conducted with the FASSET model indicated the possibility of increasing N fertilization without significantly affecting N leaching if there is an adequate catch crop management. This would also improve yields of cereal production of organic farming in Denmark.

1. Introduction

The proportion of organic farms in Denmark has been stable during this century after a rapid increase during the previous two decades (Plantedirektoratet, 2009). Nevertheless, there is an increasing demand for organic products by consumers, who are increasingly concerned about food quality and safety. Furthermore, from an environmental perspective, organic farming may lower the environmental impacts of the cropping system and improve biodiversity compared with conventional agriculture (Lampkin, 1998; Hole et al., 2005).

One of the important obstacles to the conversion from conventional to organic farming in cereal production is the possible reduction in yields (Berry et al., 2002). The yields in organic farming are restricted by a higher proliferation of weeds and diseases, and are dependent on the availability of N mineralized from organic manure and plant debris. The adoption of adequate rotations and management practices, such as weed control, crop residue treatment, use of catch crops, or an appropriate timing and amount of manure application determine the degree to which yields and nutrient losses are affected (Thorup-Kristensen et al., 2003; Rasmussen et al., 2006; Olesen et al., 2009).

Spring barley and winter wheat constitutes about 24% and 6%, respectively, of the area under organic farming in Denmark (Plantedirektoratet, 2009). In a long-term field experiment initiated in 1997 (Olesen et al., 2000a) these two crops are part of a rotation in combination with grass-clover, pulse and row crops in a variety of cropping systems and tested at three different sites with varying soil types. Long-term field studies enables direct and residual treatment effects on soil fertility to be compared taking yearly crop yield variability due to different weather conditions into account, and their importance has been addressed in previous

* Corresponding author. Tel.: +45 8999 1828; fax: +45 8999 1200.
E-mail address: Jordi.Doltra@agrsci.dk (J. Doltra).

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Table 1
Cropping systems investigated in this study. Cuttings of grass-clover in the OG + C + M system were removed and an equivalent amount of total N was applied as manure in the rotation.

Rotation acronym	Type	Catch crops	Nutrient source	N-fixing crop
OF + C + M	Organic	Present	Pig slurry stored	Faba bean
OF − C + M	Organic	Absent	Pig slurry stored	Faba bean
OF + C − M	Organic	Present	None	Faba bean
OG + C + M	Organic	Present	Pig slurry stored	Grass-clover
CF + C + F	Conventional	Present	Mineral fertilizer	Faba bean

works (Peterson et al., 1993; Wei et al., 2001).

The investment of time and resources required by long-term experiments limits the range of agronomic practices studied in this type of research. Agronomic models are complementary tools that, when properly used, enable similar information to be derived. An additional and unique feature of modeling is the possibility to assess the effects and interactions under alternative environmental and management scenarios, as for example those related to the effect of policy implementations (Nendel, 2009) or climate change (Olesen, 2005). The crop submodel of the FASSET dynamic whole-farm model (Berntsen et al., 2003) has been calibrated and validated for winter wheat (Olesen et al., 2002a,b) and assessed for intercrops of pea and barley (Berntsen et al., 2004) under Danish conditions. FASSET can simulate the effects of soil management and those of nitrogen (N) and water availability on growth and yield of a range of crops, including cereals and catch crops, under a variety of soil types and cropping systems. The objective of this work was to investigate the effects of N availability on winter wheat and spring barley yield and quality in conventional and organic cropping systems that differed in the type and amount of fertilizer received and in the composition of the rotation including the presence or absence of catch crops. The FASSET model is used to discuss the results from the field experiment and to suggest possible management strategies that may improve organic cereal production in Denmark.

2. Materials and methods

2.1. Site and experimental details

Winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) were grown in crop rotations between 2005 and 2008 at three sites in Denmark: a coarse sandy soil at Jyndevad (54°54′N, 9°08′E), a loamy sand soil at Foulum (56°30′N, 9°34′E) and a sandy loam soil at Flakkebjerg (55°19′N, 11°23′E). Soil organic matter (SOM) and clay content in the top 25 cm of soil were 2.01 and 4.5%, respectively, at Jyndevad, 3.94 and 8.8% at Foulum, and 1.74 and 15.5% at Flakkebjerg. The soils can be considered as free draining and are described in more detail by Olesen et al. (2000a) and Berntsen et al. (2004). Average annual temperature and rainfall are 7.9 °C and 964 mm, 7.3 °C and 704 mm and 7.8 °C and 626 mm for Jyndevad, Foulum and Flakkebjerg, respectively. Five treatments were considered in this paper (Table 1) and all were variations on a rotation of spring barley–grass clover or faba bean (*Vicia faba* L.)–potato (*Solanum tuberosum* L.)–winter wheat. The first treatment was an organic rotation with faba bean as a N_2-fixing crop, a catch crop mixture undersown with the cereals and legume crops and nutrient added as manure (OF + C + M). Three other organic treatments were considered and these were similar to the one above but differed by the exclusion of the undersown catch crops from the rotation (OF − C + M), the exclusion of manure applications (OF + C − M) and the use of a grass-clover green manure undersown with spring barley as a N-fixing crop instead of faba bean (OG + C + M). The fifth treatment considered was a conventional treatment with mineral fertilizer applied instead of manure (CF + C + F) and with the use of pesticides for crop protection. Each treatment was replicated twice for each crop and location, and all crops were represented every year.

2.2. Crop management

The varieties used were Tommi for winter wheat, and a mixture of Power, Simba and Smilla or a mixture of Cicero, Simba and Smilla for spring barley. Crops were sown at a depth of 2–4 cm and at a row distance of 12–12.5 cm. The sowing was done from end of March to end of April for a target density of 300 plants m^{-2} for spring barley, and from late September to beginning of October for a target density of 400 plants m^{-2} for winter wheat. Both cereals were harvested in August. For the non-cereal crops in rotation the varieties used were Columbo (faba bean), sown from late March to late April at a density of 45 plants m^{-2} and harvested in August, and Sava (potato) that was sown from mid-April to early May at a density of 4.5 plants m^{-2} and harvested in September. The grass-clover green manure was composed of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.). It was undersown with spring barley and ploughed before the potato crop in spring (Foulum and Jyndevad) or autumn (Flakkebjerg). The grass-clover cuts (2–5 per season) were removed from the field. Average annual rates of 125 mm (Jyndevad) and 55 mm (Foulum) of irrigation were applied during the growing periods to avoid critical water deficits. All crop residues were incorporated into the soil after harvest. In the organic treatments with manure, winter wheat received approximately 110 kg N ha^{-1} from anaerobically stored pig slurry and 100 kg K ha^{-1} from dry vinasse. The same products were used to supply 60 kg N ha^{-1} and 55 kg K ha^{-1} to the spring barley crop. The manure was applied using trail hoses in winter wheat and injected into the soil before sowing of spring barley. The N–P–K (kg ha^{-1}) applied in the mineral fertilization of the conventional rotations was on average 164–24–87 and 124–25–84 for winter wheat and spring barley, respectively. At Flakkebjerg the amount of P was increased to 40 kg ha^{-1} for winter wheat and 47 kg ha^{-1} for spring barley. Fertilization was performed in spring for all crops (end of March to mid-June). A more detailed composition of the manure and fertilizers applied as well as the amount applied to the other crops is shown in Table 2.

The catch crop combination varied between rotations and locations. In the organic rotations, a mixture of perennial ryegrass, chicory (*Chicorum intybus* L.), white clover and red clover and a mixture of winter vetch (*Vicia villosa* Roth.), winter rye (*Secale cereale* L.) and winter rape (*Brassica napus* L.), with or without ryegrass, were sown in Foulum and Jyndevad. In the conventional systems different mixtures of ryegrass, winter rape and winter rye were used in these two locations. In the organic rotations at Flakkebjerg the catch crop mixture was composed of winter rye, winter vetch and oil radish (*Raphanus sativus* L), with and without ryegrass, while in the conventional one it consisted of different combinations of winter rye, ryegrass, oil radish and winter rape. Catch crops were grown after the harvest of spring barley, faba bean and winter wheat, and incorporated to the soil in spring (Foulum and Jyndevad) or autumn (Flakkebjerg).

Weeds were controlled in all rotations according to the characteristics of the systems, i.e., mechanical weed harrowing for the organic rotations (tine harrowing in cereals and pulses and ridging in potatoes) and chemical spraying in the conventional ones.

At harvest grain yields were determined in all the rotations in two subplots of 22.5, 24 and 16 m^2 at Jyndevad, Foulum and Flakkebjerg, respectively. Grain dry matter and N content (crude protein) were analyzed on a bulked sample for each plot by near infrared transmittance (NIT).

Suction cups were installed in all plots at a depth of 1 m at Foulum and Flakkebjerg and 0.8 m at Jyndevad, and the soil solution extracted every one to four weeks for nitrate analyses. N leaching

Table 2
Average amounts (kg ha^{-1}) and composition of the manure and fertilizers applied to the different cropping systems.

	Spring barley	Faba bean/grass-clover	Potato	Winter wheat
OF + C + M				
N-total	62	1	114	109
NH_4	47	0	71	82
P	14	0	22	19
K	59	53	142	105
OF − C + M				
N-total	62	1	114	110
NH_4	46	0	71	82
P	14	0	22	19
K	55	57	140	107
OF + C − M				
N-total	1	1	1	1
NH_4	0	0	0	0
P	4	0	4	0
K	37	57	80	64
OG + C + M				
N-total	59	2	114	109
NH_4	45	1	71	82
P	13	4	22	18
K	55	134	141	101
CF + C + F				
N-total	124	0	146	164
NH_4	55	0	45	74
P	25	35	40	24
K	84	125	201	87

was obtained from the measurements and a water balance estimated with the EVACROP model (Olesen and Heidmann, 1990) as explained in detail in Askegaard et al. (2005). The EVACROP model applies a simple cascading model of soil water, and the modeled drainage at the soil suction depth was multiplied with measured soil N concentrations to obtained estimates of N leaching.

2.3. The FASSET model

Simulations with the cropping system component of the FASSET whole-farm model (Berntsen et al., 2003) were run to evaluate the performance of the model in predicting cereal DM production and N content. FASSET is a deterministic dynamic model that simulates crop growth in terms of DM accumulation using a daily time-step. DM accumulation is affected by temperature, solar radiation, water and N availability. A detailed description of the crop model can be found in Olesen et al. (2002b). Here we briefly present the general formulation for crop growth during different development phases.

At sowing time, the DM in the crop (W, g m^{-2}) is set to equal DM in the seed. Half the DM from the seed is assigned to top DM (W_t) and the other half to root DM (W_r). The amount of DM in the crop on the ith day (W_i) is calculated as:

$$W_i = W_{i-1} + \varepsilon \cdot f_{PAR} f_E g(\mathrm{N}) f_T(T_i) R_{pi}$$

where W_{i-1} is total crop DM on the previous day, ε is the radiation use efficiency (g MJ^{-1}), f_{PAR} is the fraction of intercepted radiation, f_E is the ratio of the actual to the potential transpiration, $g(\mathrm{N})$ accounts for the effect of N status, $f_T(T_i)$ is a temperature function taken from Hansen et al. (1990), and R_{pi} is the daily incident photosynthetic active radiation (MJ m^{-2}) set to 48% of global radiation. The partitioning of W_i in above-ground and below-ground DM declines linearly with time following the approach of the DAISY model (Hansen et al., 1990). The part of above-ground matter transferred to the storage organs is calculated according to Olesen et al. (2002b).

The development of the root system is calculated from the accumulated temperature from crop planting, after a lag period (Hansen et al., 1990). Root length is obtained from root biomass using a constant specific root length value (Gerwitz and Page, 1974; Olesen et al., 2002b), and the distribution of roots follows the functions of DAISY. At harvest, root DM is transferred to the soil profile, while the above-ground crop residues can be removed or incorporated in the soil organic material.

Crop N uptake is a function of potential demand and soil N availability. The demand of N is defined by the maximum N concentration, which follows the N dilution curve approach (Justes et al., 1994). Both NO_3-N and NH_4-N can be taken up by roots. The maximum rates of uptake are adapted from the DAISY model (Olesen et al., 2002b). Water uptake is a function of potential evapotranspiration and soil water availability. For each soil layer the amount of N and water taken by roots depends on its root density, thickness of the layer, and the water and N contents.

In the case of N_2 fixing crops, the potential N fixation is assumed to be proportional to the dry matter increase and is limited by a maximum daily N fixation rate. Fixation has an associated energetic cost, reducing the daily dry matter accumulation (Berntsen et al., 2004).

The soil module has a one-dimensional vertical structure and consists of series of layers of user-defined thickness. Each of the layers is characterized by its physical and chemical properties as water retention parameters, saturated hydraulic conductivity, texture, carbon (C) and N contents in the added and soil organic matter pools. The movement of water and N in the soil follows the approach of the solute leaching intermediate model (SLIM) described in Addiscott and Whitmore (1991). The FASSET model implements the CN-SIM sub-model to account for the turnover of soil organic matter, which is fully described in Petersen et al. (2005a,b). Three types of soil organic matter pools are used: added organic matter, microbial biomass and soil organic matter. The added organic matter is divided into the slowly (AOM1) and easily (AOM2) decomposable fractions. The decay of AOM1 and AOM2 pools is routed to the microbial biomass prior to the native organic matter (NOM). Partly decomposed materials as animal manure have a fraction that goes directly to NOM. The model also includes an inert soil organic matter (IOM) pool. The turnover of all pools follows first-order kinetics. Mineralization and immobilization of N as well as nitrification are simulated. Preferential immobilization of ammonium over nitrate follows a Langmuir-type equation (Petersen et al., 2005b). In the approach C and N fluxes are calculated from all pools, where N follows C stoichometrically. AOM1 and AOM2 pools are created every time an organic material is added and have a constant C/N ratio. Incoming matter to the NOM pool has a fixed C/N value set to 10, although the initial C/N value is a specific soil property as it is for IOM. If the C/N ratio of the incoming material is lower or equal to the receiver pool the result is a net N mineralization, while if it is higher it causes immobilization. Volatilization of ammonia (NH_3) from added manure was simulated using a constant emission factor (Hansen et al., 2008).

The FASSET model requires daily values of maximum and minimum temperatures, precipitation, potential evapotranspiration and global radiation that were obtained from weather stations located at each of the three experimental sites. The initial soil conditions of simulations were obtained by starting the model runs two or three years before the considered period of simulation using management data from the previous course of the rotations. Specific soil parameters required in the mineralization module (initial SOM from the different soil organic pools, %C and % clay) were obtained from measurements or taken from similar soils. In the simulations manure was applied by trail hose. Table 3 shows the main crop input parameters used in the simulations. The values for winter wheat were derived from actual experimental results (Olesen et al., 2000b,2002a,b). Parameterization of spring barley was obtained from literature (Muurinen and Peltonen-Sainio,

Table 3
Values for selected crop parameters used in FASSET for the main crops in the rotations: *Ts* and *Tb* are the sum of temperatures and the base temperature in each crop phase, respectively, where the subscript indicate 0 the phase from sowing to emergence; 1 from emergence to anthesis or start of tuber growth; 2 from anthesis to the end of grain filling (or end of tuber growth in potato); and 3 from the end of grain filling to ripeness; ε is maximum radiation use efficiency; *k* is extinction coefficient; *LAI_DM* is maximum ratio between LAI and dry matter of the vegetative above-ground biomass; *LAI_N* is maximum ratio between LAI and nitrogen of the vegetative above-ground biomass; *Nstorage* is minimum and maximum nitrogen concentration of the storage organs; *Fill factor* is net production fraction after anthesis that goes into grain, and *FixN_DM* is maximum nitrogen fixation per produced dry matter.

Parameter	Units	Winter wheat	Spring barley	Faba bean	Ryegrass	Clover	Potato
Ts_0	°C	125	130	100	125	125	150
Ts_1	°C	250	250	450	300	300	235
Ts_2	°C	600	500	300	420	420	1300
Ts_3	°C	155	175	360	155	155	0
Tb_0	°C	0	0	0	0	0	0
Tb_1	°C	4	4	4	4	4	0
Tb_2	°C	6	6	6	6	6	0
Tb_3	°C	0	0	0	4	4	0
ε	$\mathrm{g\,MJ^{-2}}$	3.4	3.7	3.0	4.5	3.2	4.0
k	–	0.44	0.65	0.85	0.5	1.0	0.62
LAI_DM	$\mathrm{m^2\,g^{-1}}$	0.011	0.015	0.015	0.01	0.008	0.015
LAI_N	$\mathrm{m^2\,g^{-1}}$	0.4	0.4	0.25	–	–	0.75
Nstorage (min/max)	%	1.8/2.2	1.5/2.5	4/6	1.6/2,6	1.6/2.6	1.1/1.8
Fill factor	–	0.57	0.60	0.5	0.2	0.3	–
FixN_DM	$\mathrm{g\,g^{-1}}$	–	–	0.026	–	0.022	–

2006) and intercropping studies (Berntsen et al., 2004). The rest of the parameters were default model values except the maximum and minimum N concentrations in the faba bean storage organs (*Nstorage*), which were adjusted to observations, the faba bean maximum N fixation rate was obtained from Hauggaard-Nielsen et al. (2009), and the clover light extinction coefficient (*k*) taken from the literature (Joggi et al., 1983; Lantinga et al., 1999). Parameter values for species included in the catch crop mixtures were all default model values.

Magid et al. (2001) have shown that under cold temperatures in Denmark there can be a rapid release of N from N-rich residues of green manure and catch crops. They suggested that simulation models must be adjusted to capture this disproportionately high N mineralization. A preliminary test of FASSET showed that the model was not able to capture this rapid release of N at its current state of development. This was evident when N-rich catch crops were incorporated in the early spring. Furthermore, the model predicted the opposite effect to that observed on the succeeding spring cereal yield due to an unrealistic lack of soil mineral N following catch crop incorporation. For modeling purposes, in order to simulate the observed response of cereal yield to spring ploughing, the N from clover residues incorporated in the soil was in this work considered to be in mineral form and its carbon content reduced to maintain the C/N ratio of the added soil organic matter.

2.4. Scenario analyses

The effects on cereal grain yield and N leaching produced by increases in the application of manure in organic farming were assessed with FASSET. Five manure management scenarios were tested giving 1.5–6 times the amount of N applied in the OF + C + M rotation, using the same manure products (i.e. pig slurry). Levels were 165 and 90 kg N ha^{-1} (SC1), 220 and 120 kg N ha^{-1} (SC2) 330 and 180 kg N ha^{-1} (SC3), 440 and 240 kg N ha^{-1} (SC4) and 660 and 360 kg N ha^{-1} (SC5) of N in manure for winter wheat and spring barley, respectively. Simulations were performed with 20 years of weather data (1989–2008).

An additional management scenario was conducted in the manured organic rotations with undersowing catch crops in order to investigate the yield benefits of including N-fixing species in the catch crop mixture. Simulations omitting legumes from the autumn catch crops in the OF + C + M and OG + C + M cropping systems were run and the results compared with the original simulations that included N-fixing catch crops.

2.5. Statistical analyses

The ability of FASSET to predict grain DM yield and quality in terms of grain N yield was assessed using four different statistical indexes. The coefficient of determination r^2 is an indicator of the closeness of the relationship between model predictions and observations:

$$r^2 = \frac{\left(\sum(M_i - \bar{M})(O_i - \bar{O})\right)^2}{\sum(M_i - \bar{M})^2 \sum(O_i - \bar{O})^2}$$

where O_i and M_i are the observed and simulated values; $\bar{O}_i$ and $\bar{M}_i$ are the means of the observed and simulated values; and n is the number of pair values. A value of 1 indicates that the model is highly precise, while the lowest precision level is represented by 0. The root mean square error (*RMSE*) reflects the differences between observations and predictions and the mean bias error (*MBE*) shows the systematic deviations. A negative *MBE* is an indication of model underestimation and, if it is positive, overestimation. The equations proposed by Willmott (1982) were used to calculate these two statistics:

$$RMSE = \frac{\sum_i^n (O_i - M_i)^2}{n}$$

$$MBE = \frac{\sum_i^n (M_i - O_i)}{n}$$

Finally, the accuracy of predictions was calculated with the model efficiency (*EF*) following Nash and Sutcliffe (1970):

$$EF = 1 - \left(\frac{\sum(M_i - O_i)^2}{\sum(O_i - \overline{O})^2}\right)$$

This parameter ranges from −1 to 1, with values lower than zero indicating that the mean of the measured values is a better estimator than model-predictions. The quality of predictions increases when approaching 1.

The same statistical indexes were used to assess model performance of N concentration in soil water.

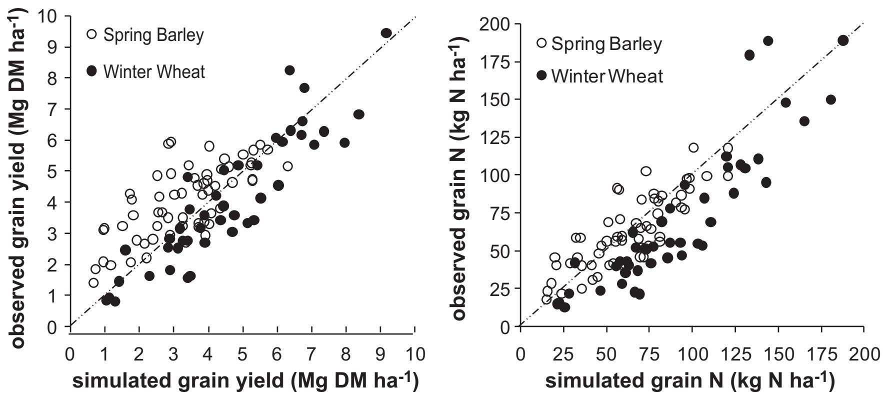

Fig. 1. Observed and simulated winter wheat and spring barley grain dry matter (DM) and grain N content pooling the three experimental sites and the five cropping systems. Values are for 44 winter wheat and 60 spring barley plots in the period 2005–2008. Dashed lines indicate 1:1 relation.

3. Results

3.1. Model performance

The ability of the FASSET model to predict grain yield dry matter and N content evaluated by pooling data of winter wheat and spring barley is shown in Fig. 1 and in the statistical indexes presented in Table 4. The standard deviation of observations was 1.61 Mg ha^{-1} for grain DM and 35.9 kg ha^{-1} for N, which is higher than the respective *RMSE* values when considering data for both cereals. The simulations for winter wheat were considerably better than for spring barley. The quality of predictions was good for winter wheat DM (*EF* = 0.76). Wheat grain N was also well predicted by FASSET as reflected by an *EF* value of 0.61. For spring barley, yield simulations had a negative *EF* due to differences in performance for sites and treatments, whereas this was not the case for grain N simulations. Fig. 1 also shows a general underestimation of spring barley yield and overestimation of winter wheat grain N yield, as reflected in the *MBE* values. Nonetheless, observed and predicted values were well correlated (r^2 was 0.62 and 0.71 for DM and grain N, respectively, with n = 104) and in most cases close to the unity line. The overall performance for simulations of soil water N concentration showed less favorable statistical indexes with a *EF* close to zero and a general tendency to underestimate the concentrations as indicated by a negative *MBE* (Table 4).

3.2. Effects of site and cropping system on cereal yield and crop N at harvest

Figs. 2 and 3 show the observed and simulated average grain yield and N content of winter wheat and spring barley for all rotations at the three locations. The highest winter wheat yields were found at Foulum and the lowest at Jyndevad (Fig. 2a). The same pattern was found for grain N and this trend was also simulated by FASSET (Fig. 2b). For spring barley, the highest yields were again found at Foulum, while the differences between Flakkebjerg and Jyndevad were small (Fig. 3). The spring barley yields simulated with the model were in agreement with the observations at Flakkebjerg, but were underestimated at Foulum and, especially, at Jyndevad (Fig. 3a). However, at all three sites there was good agreement between observed and simulated grain N yields (Fig. 3b).

The results show that lower DM and N grain yields were obtained with the organic systems at all locations and in both cereal species, and that the yield differences between organic and conventional systems are reduced, firstly by using manure, and secondly, but not always, by introducing catch crops in the autumn. These effects are well reproduced by FASSET, as observed in Figs. 2 and 3, despite some under- or overestimation, in particular for winter wheat N (Fig. 2b) and for spring barley DM yields (Fig. 3a).

The observed and simulated effects of the rotation treatment on grain yield and N are quantified in Table 5 for winter wheat and in Table 6 for spring barley. The results given in the tables were obtained using the OF + C + M rotation as the reference cropping system. The system that resulted in the highest observed relative cereal production was the conventional one, with the largest differences with OF + C + M being of 3.73 Mg ha^{-1} and 1.46 Mg ha^{-1}, for winter wheat and spring barley, found at Flakkebjerg. In contrast, the maximum reduction in cereal yield was observed for the unmanured treatment, with the largest differences at Foulum (2.91 Mg ha^{-1}) for winter wheat and at Jyndevad (1.88 Mg ha^{-1}) for spring barley. There was a positive effect of catch crops on yields and grain N in both cereals, except at Jyndevad for winter wheat. This benefit was higher for spring barley (0.54–1.09 Mg ha^{-1}) than for winter wheat (0.50–0.67 Mg ha^{-1}).

Substituting faba bean in the rotation for the grass-clover green manure crop produced the highest increase in DM yield at Jyndevad for both crops, although it was only significant for winter wheat with a 1.01 Mg ha^{-1} difference (P < 0.05). For spring barley the increase in DM yield was 0.39 Mg ha^{-1}, which was lower than the standard error of the difference between means. A non-significant positive effect was also observed at Flakkebjerg and

Table 4
Statistical performance of grain dry matter yield (DMg), N content (Ng) and soil NO_3-N concentration of soil water at 1 m depth (Foulum and Flakkebjerg) or 0.8 m depth (Jyndevad). Data are for 44 winter wheat (years 2006–2008) and 60 spring barley plots (years 2005–2008), and 244 observations of soil N concentration, from the three experimental sites. Values for the coefficient of determination (r^2), root mean square error (*RMSE*), mean bias error (*MBE*), and model efficiency (*EF*) are shown. Units are for *RMSE* and *MBE*.

	Total cereal		Winter wheat		Spring barley		Soil NO_3-N
	DMg (Mg ha^{-1})	Ng (kg ha^{-1})	DMg (Mg ha^{-1})	Ng (kg ha^{-1})	DMg (Mg ha^{-1})	Ng (kg ha^{-1})	(mg L^{-1})
r^2	0.62	0.71	0.82	0.80	0.50	0.67	0.24
RMSE	1.13	22.2	1.02	29.2	0.94	12.3	13.67
MBE	−0.19	9.1	0.50	20.6	−0.70	0.72	−2.79
EF	0.50	0.61	0.76	0.61	−0.09	0.60	−0.06

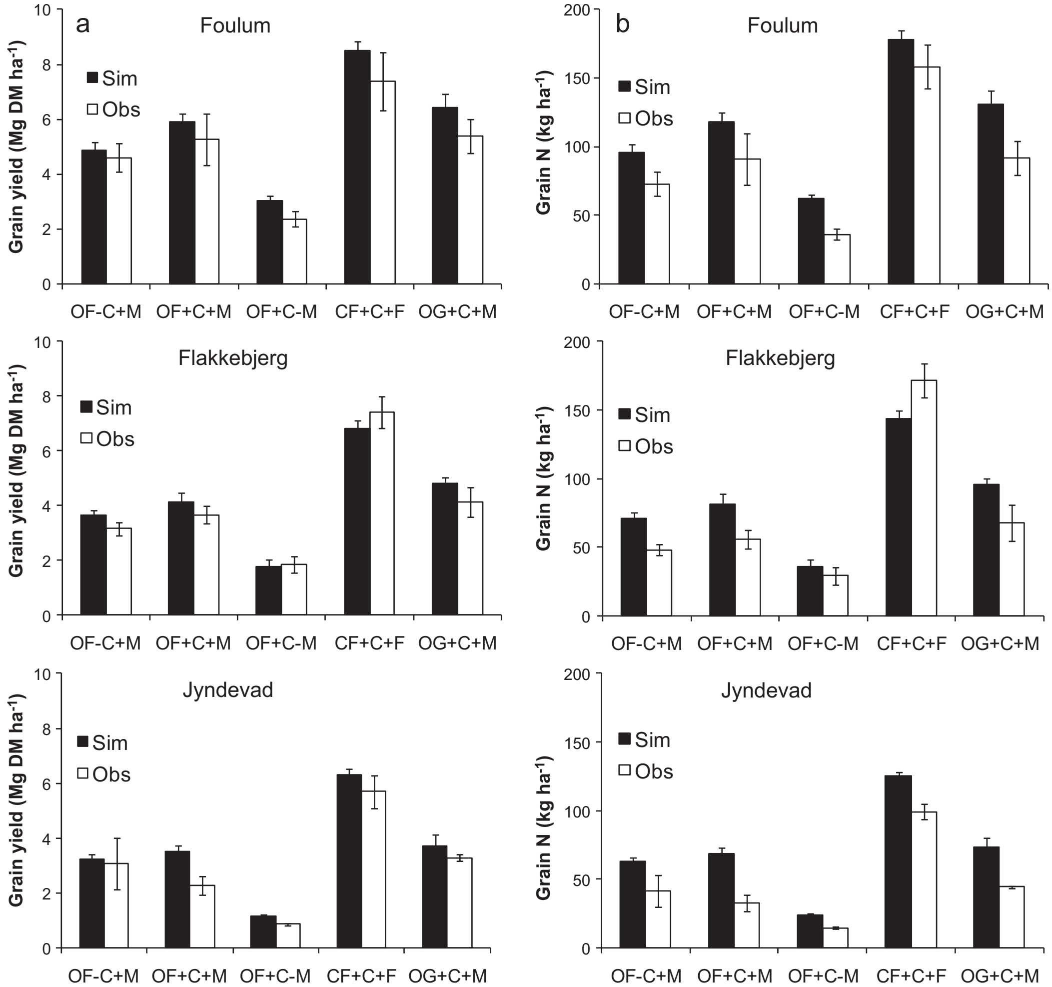

Fig. 2. Simulated (sim) and measured (obs) winter wheat grain yield (a) and N in grain (b) at harvest for the three experimental sites. Columns represent averages of three years and bars indicate the mean standard error.

Foulum for winter wheat, but it did not result in any noticeable improvement in DM yield for spring barley.

Table 5 shows that the model-predicted treatment effects relative to the OF + C + M system on winter wheat DM and N yields were in agreement with observations in all the cases, except when using catch crops at Jyndevad, where the measured DM and N yields were higher without catch crops. The spring barley simulations (Table 6) also follow the same pattern as observations in all the treatments, the only exceptions being the green manure effect at Foulum and Flakkebjerg. According to FASSET there should be an improvement in spring barley yield when faba bean was grown instead of the green manure crop in the rotations at Foulum and Flakkebjerg, but

Table 5
Effects of rotation (OF/OG/CF), catch crop (−C/+C) and nitrogen fertilizer (−M/+M/+F) on dry matter (DMg, Mg ha^{-1}) and N content (Ng, kg N ha^{-1}) of winter wheat grain yield. Results are presented in terms of the average difference (diff) of three years (2006, 2007 and 2008) against rotation OF + C + M as the reference cropping system. The standard error of the difference is also reported (SE).

Rotation	Foulum				Flakkebjerg				Jyndevad				Average			
	DMg		Ng		DMg		Ng		DMg		Ng		DMg		Ng	
	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE
OF − C + M																
Obs	−0.67	1.06	−18.1	20.7	−0.50	0.41	−7.9	7.8	0.79	1.01	8.7	12.9	−0.13	0.83	−5.8	13.8
Sim	−1.02	0.42	−22.4	8.8	−0.49	0.41	−9.9	9.0	−0.27	0.29	−6.4	5.5	−0.59	0.37	−12.9	7.8
OF + C − M																
Obs	−2.91	0.97	−54.7	19.2	−1.83	0.46	−26.9	9.4	−1.43	0.34	−18.4	6.1	−2.05	0.59	−33.3	11.6
Sim	−2.85	0.36	−56.3	7.3	−2.36	0.45	−45.6	9.6	−2.35	0.24	−45.6	4.5	−2.52	0.35	−49.2	7.1
OG + C + M																
Obs	0.11	1.12	0.7	22.4	0.46	0.65	11.8	14.6	1.01	0.36	11.3	6.1	0.53	0.71	7.9	14.3
Sim	0.55	0.56	12.5	12.0	0.69	0.41	14.3	9.1	0.22	0.48	4.6	9.4	0.48	0.46	10.5	9.7
CF + C + F																
Obs	2.13	1.41	67.4	24.6	3.73	0.67	115.9	14.1	3.42	0.69	66.5	8.2	3.09	0.93	83.3	15.6
Sim	2.61	0.47	59.8	9.3	2.70	0.46	62.8	10.0	2.82	0.31	56.6	5.2	2.67	0.42	58.6	8.2

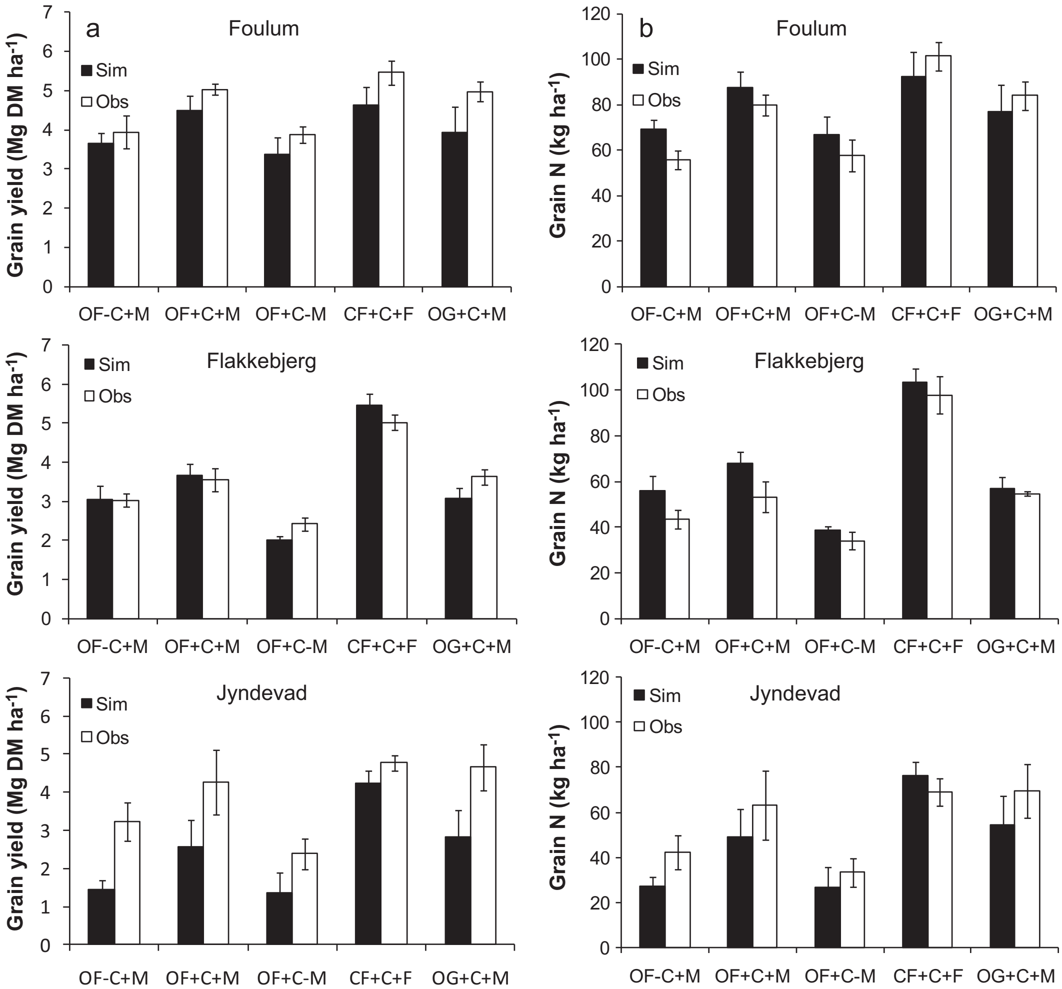

Fig. 3. Simulated (sim) and measured (obs) spring barley grain yield (a) and N in grain (b) at harvest for the three experimental sites. Columns represent averages of four years and bars indicate the mean standard error.

this did not match observations. This was the only case where the cropping system effect in cereal yield and grain N was not closely captured by the model when averaging across all three sites.

Model predictions of crop N at harvest (excluding roots) for the non-cereal crops in the rotation are presented in Table 7. A fertilization and catch crop effect was predicted for potato with the highest N content in the organic systems with catch crops and manure as well as in the conventional system. No treatment effect was predicted for the legume crop. Differences between sites were also found. According to the model the amount of N at harvest would increase at Foulum for all the non-cereal crops in the rotation. The N content would be lowest for faba bean at Flakkebjerg and for potato

Table 6
Effects of rotation (OF/OG/CF), catch crop (−C/+C) and nitrogen fertilizer (-M/+M/+F) on dry matter (DMg, Mg ha^{-1}) and N content (Ng, kg N ha^{-1}) of spring barley grain yield. Results are presented in terms of the average difference (diff) of four years (2005, 2006, 2007 and 2008) against rotation OF + C + M as the reference cropping system. The standard error of the difference is also reported (SE).

Rotation	Foulum				Flakkebjerg				Jyndevad				Average			
	DMg		Ng		DMg		Ng		DMg		Ng		DMg		Ng	
	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE	Diff	SE
OF − C + M																
Obs	−1.09	0.44	−24.1	6.2	−0.54	0.34	−9.9	8.0	−1.03	0.99	−21.0	17.1	−0.89	0.59	−18.3	10.4
Sim	−0.83	0.46	−18.4	8.2	−0.64	0.45	−11.9	8.4	−1.12	0.75	−21.7	13.1	−0.86	0.55	−17.3	9.9
OF + C − M																
Obs	−1.16	0.25	−22.4	8.5	−1.14	0.34	−19.2	7.8	−1.88	0.94	−30.0	16.7	−1.39	0.51	−23.8	11.0
Sim	−1.12	0.59	−20.5	10.5	−1.67	0.29	−29.0	5.6	−1.19	0.87	−22.3	15.4	−1.33	0.58	−23.9	10.5
OG + C + M																
Obs	−0.06	0.28	4.2	7.9	0.06	0.35	1.5	6.9	0.39	1.05	6.2	19.5	0.13	0.56	3.9	11.4
Sim	−0.55	0.77	−10.6	13.8	−0.59	0.43	−11.1	7.5	0.27	1.00	5.4	17.8	−0.29	0.73	−5.4	13.0
CF + C + F																
Obs	0.43	0.34	21.6	7.9	1.46	0.36	44.7	10.8	0.50	0.88	5.7	16.7	0.80	0.52	24.0	11.8
Sim	0.14	0.59	4.9	12.9	1.79	0.39	35.7	8.0	1.69	0.78	27.3	13.7	1.20	0.59	22.3	11.5

Table 7
Modeled crop N at harvest in the storage organs and in the above-ground residues (kg N ha^{-1}) for the non-cereal crops in rotation. Values represent averages of three (faba bean) or four (other crops) years. For grass-clover total crop N represents the cumulative N in the above ground biomass including that removed from cuttings (2–5 during the season). Values in brackets indicate mean standard error.

	Faba bean		Grass-clover	Potato	
	Storage	Residues	Total crop N	Storage	Residues
Foulum					
OF + C + M	131 (4.2)	40 (1.0)		111 (9.2)	64 (2.9)
OF – C + M	130 (3.8)	47 (0.9)		95 (8.4)	56 (2.7)
OF + C – M	131 (4.4)	40 (1.0)		81 (8.8)	51 (3.4)
CF + C + F	128 (3.4)	42 (1.1)		109 (9.1)	63 (4.0)
OG + C + M			306 (27.3)	129 (11.2)	71 (4.0)
Flakkebjerg					
OF + C + M	95 (12.7)	58 (7.2)		98 (7.7)	57 (2.8)
OF – C + M	95 (12.7)	58 (7.1)		81 (7.1)	49 (2.6)
OF + C – M	95 (12.7)	58 (7.2)		61 (4.2)	43 (2.6)
CF + C + F	87 (11.3)	43 (9.6)		104 (12.9)	59 (4.8)
OG + C + M			259 (23.6)	115 (12.8)	64 (4.3)
Jyndevad					
OF + C + M	116 (11.0)	47 (1.2)		58 (6.9)	40 (2.9)
OF – C + M	124 (9.7)	46 (1.5)		44 (5.5)	34 (2.8)
OF + C – M	121 (10.5)	45 (2.2)		32 (4.5)	27 (2.3)
CF + C + F	118 (10.9)	45 (2.3)		64 (6.5)	42 (2.8)
OG + C + M			226 (18.9)	61 (6.7)	41 (2.9)

at Jyndevad.

3.3. Soil N dynamics

The simulated NO_3-N leaching amounts below 1 m depth during the years of spring barley and winter wheat cultivation are presented in Table 8, together with those obtained from suction cup measurements. On the whole, both approaches gave similar estimates of N leaching, except for the OF – C + M system during the winter wheat year, and for the same system in Jyndevad for spring barley. According to both simulated and estimated values, N leaching was higher when no catch crops were undersown in all cases, except for the winter wheat estimates at Foulum. The highest leaching rates were found for the sandy soil at the Jyndevad, especially for spring barley. No important differences were found between the rest of the organic systems and the conventional one, showing low N leaching rates on the two more loamy sites. Estimations also indicated a slightly higher leaching level at Foulum than at Flakkebjerg, but the FASSET model was not able to reproduce this.

Table 8
Yearly amounts of NO_3-N leached (kg N ha^{-1}) below 1 m depth when spring barley was grown in 2005 (1 April 2005–31 March 2006) and winter wheat in 2008 (1 April 2008–31 March 2009), as predicted by FASSET and obtained from suction cup measurements and the EVACROP model (Olesen and Heidmann, 1990) (estimated). Estimated values were at 0.8 m depth at Jyndevad.

Location	Rotation	Spring barley		Winter wheat	
		FASSET	Estimated	FASSET	Estimated
Foulum	OF + C + M	6	9	3	11
	OF – C + M	25	32	40	11
	OF + C – M	6	16	2	10
	CF + C + F	2	14	5	12
	OG + C + M	1	7	5	13
Flakkebjerg	OF + C + M	11	5	12	1
	OF – C + M	29	19	45	15
	OF + C – M	10	4	14	2
	CF + C + F	5	8	4	5
	OG + C + M	1	5	20	3
Jyndevad	OF + C + M	57	40	14	17
	OF – C + M	60	108	27	45
	OF + C – M	41	37	15	21
	CF + C + F	57	49	13	19
	OG + C + M	42	51	17	27

Measured and simulated daily N concentrations in soil water at 1 m depth during the whole rotation period are represented in Fig. 4 for the OF + C + M and OG + C + M cropping systems at the three locations. The overall simulation performance gave a model efficiency of −0.06 (n = 244) (Table 4). The periods with a high N leaching risk were generally well simulated by FASSET in the Foulum and Jyndevad soils. This occurred at Foulum from potato harvest (beginning of September 2007) to the onset of spring growth in winter wheat in the next year, and at Jyndevad during spring barley growth (2005) and in the autumn periods. In this last case, however, the peaks in soil water N concentration were not always well predicted. There was also an underestimation of soil water N concentration before and during potato growth at Foulum. The general pattern of soil water N concentrations was not equally well reproduced at Flakkebjerg, where concentrations during the leaching periods were overestimated, particularly in the autumn of 2006.

The simulated cumulative net mineralization resulting from the mineralization–immobilization processes in the added and native soil organic matter fractions was higher at Foulum, the soil with high SOM content (Fig. 5). The lower simulated mineralization at Jyndevad agrees with a higher soil C/N ratio for this particular site that restricted the release of soil mineral N according to the model. Within each site the highest rates were found in the OG + C + M system and the lowest in CF + C + F and OF – C + M. Fig. 5 shows as an example the cumulative N mineralized at the different sites and cropping systems when the cereals were grown in 2005 (spring barley) and 2008 (winter wheat). In this case, cumulative N mineralized in the OG + C + M system was 787, 715 and 544 kg N ha^{-1} at Foulum, Flakkebjerg and Jyndevad, respectively, during the entire rotation period that represented average yearly values of 230, 209 and 159 kg N ha^{-1}, respectively. The large N mineralization in the system with green manure, which differed from the other organic and conventional systems, mainly took place during the growing of grass-clover in 2006. Differences in mineralization rates between the other systems developed more gradually over time. The average yearly N mineralization was 191, 155 and 104 kg N ha^{-1} in the OF + C + M system and 139, 131 and 63 kg N ha^{-1} in CF + C + F at Foulum, Flakkebjerg and Jyndevad, respectively.

3.4. Yield responses to increased manure rate

The resulting effects on cereal grain yield, total crop N (including roots) at harvest and N leaching produced by increases in the application of manure are shown in Fig. 6. Yields increased with manure application rates up to a level of about 350–400 kg total-N ha^{-1} in both cereals and in all three soils (Fig. 6a). The predicted response to higher rates was marginal, with the only exception of spring barley in Jyndevad, where the trend indicates a possible yield increase with higher manure applications. The relative benefit of increasing manure N was more pronounced at Jyndevad where yields could be doubled. Crop N uptake increased with manure rate up to the highest application rate at all three locations, with the lowest uptake at Jyndevad (Fig. 6b). At the highest rate, crop N uptake was similar at the other two sites, although somewhat higher for winter wheat in Foulum and for spring barley in Flakkebjerg. The impact on N leaching by increasing N in manure to cereals was small up to the SC3 scenario (Fig. 6c). The SC3 scenario would represent an average increase of 6% at Flakkebjerg and 22% at Jnydevad of the annual N leached in the OF + C + M system. This scenario did not increase N leaching at Foulum. The predicted losses of N through leaching increased considerably with increasing N inputs in scenarios SC4 and SC5. The same pattern was found for the three locations, despite the pronounced differences between soils in the absolute amount of N leaching. These amounts were largest for the Jyndevad sandy

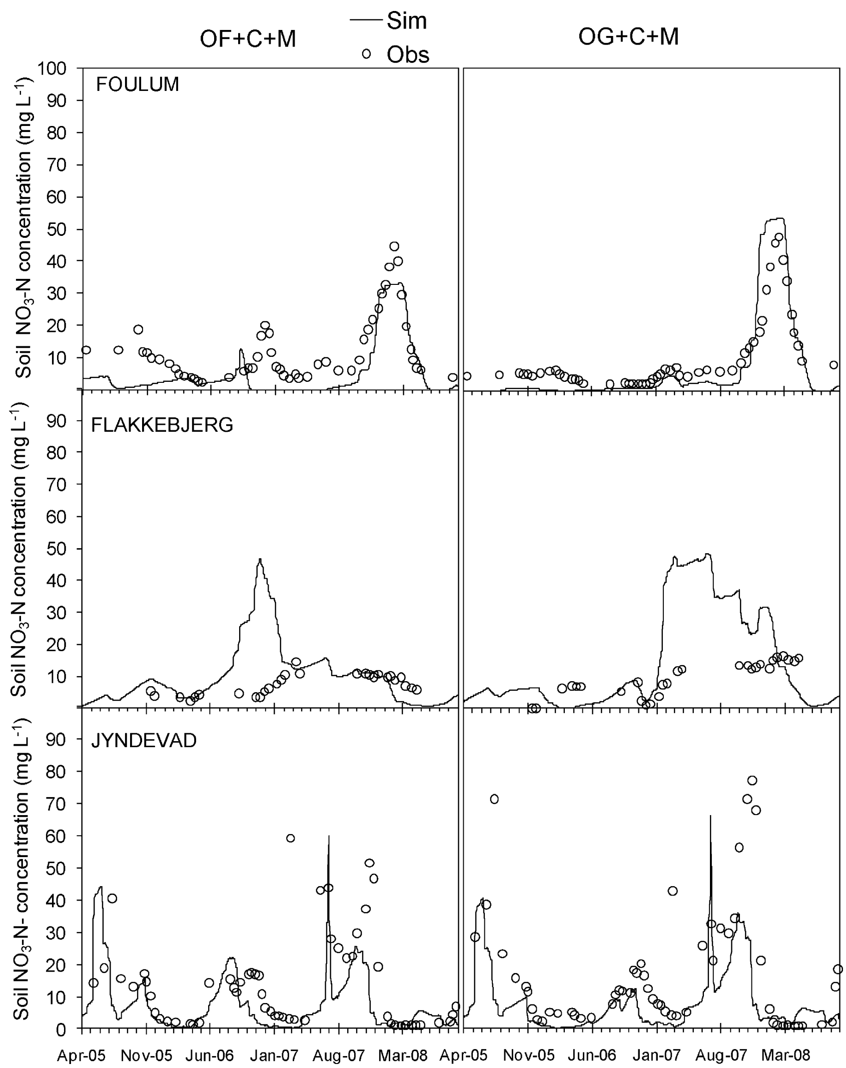

Fig. 4. Measured and simulated nitrogen concentration of soil water during the course of the four-year rotation in two organic cropping systems that included catch crops: spring barley in 2005, faba bean (OF + C + M) or grass-clover (OG + C + M) in 2006, potato in 2007, and winter wheat in 2008. Measurements and simulated values were at 0.8 m depth at Jyndevad and 1 m depth at Foulum and Flakkebjerg.

soil and lowest for the Foulum loamy sand. According to FASSET, there is a linear increase in the N lost as NH_3 by spreading manure from current applications to the SC5 scenario. Volatilization of NH_3 accounted for about 15% of the amount of manure N, which supposed average losses from 6 to 99 kg N ha^{-1} depending on crop and manure rate. An increase of N in the added and soil organic matter pools (10–30% of the amount of N applied as manure, depending on soil type and manure composition) was also predicted with the model (data not shown).

3.5. Yield responses to N-fixing catch crops

The results indicated that the inclusion of legumes in the catch crop mixture had a positive effect on cereal yield in all the cases and sites, although its magnitude was variable and dependent on when the catch crop residues were incorporated in the soil (Fig. 7). In the case of winter wheat, when no catch crops were grown before sowing, the residual effect of previous N-fixing catch crops that were grown before potato, ranged between 0.8 and 7.5% in the OF + C + M system and between 0.4 and 2.2% in the OG + C + M. Spring barley yields were much more affected by catch crop type in the case of spring ploughing, when N-fixing species increased it by 30–45%, depending on location and cropping system. The effect was much lower with autumn ploughing (4–6%), which was used at Flakkebjerg.

4. Discussion

4.1. Cereal yield and N availability

The agronomic practices related to N use, such as type of fertilization, the introduction of N-fixing crops in the rotation and the use of autumn catch crops were the main factors, together with soil characteristics, that affected N availability in the organic and conventional systems studied here. The amount of N from manure and from the mineralization of crop residues varied among the different cropping systems and it clearly affected cereal DM and N yield. Of these factors, fertilizer type was the most important in both winter wheat and spring barley, irrespective of soil type (Figs. 2 and 3). The application of mineral N fertilizers according to the Danish standards (Plantedirektoratet, 2009) along with pesticide application resulted in the highest yields. The increase of weed proliferation in the systems without manure may have had an adverse effect on yield performance (Olesen et al., 2007, 2009). A higher net N mineralization in the OG + C + M system, which mainly improved during the seasonal growth of the grass-clover green manure as identified

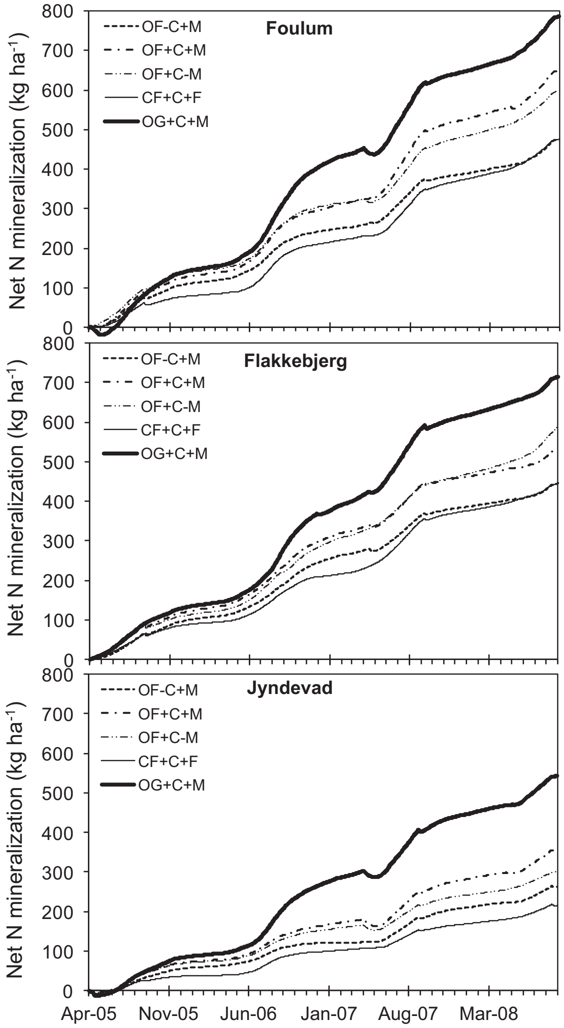

Fig. 5. Simulated cumulative soil net N mineralization during the course of the four-year rotation in the five cropping systems ("see Section 2") in the loamy sand (Foulum), sandy loam (Flakkebjerg) and sandy (Jyndevad) soils. Data represented are for the particular case where cereals were grown in 2005 (spring barley) and 2008 (winter wheat).

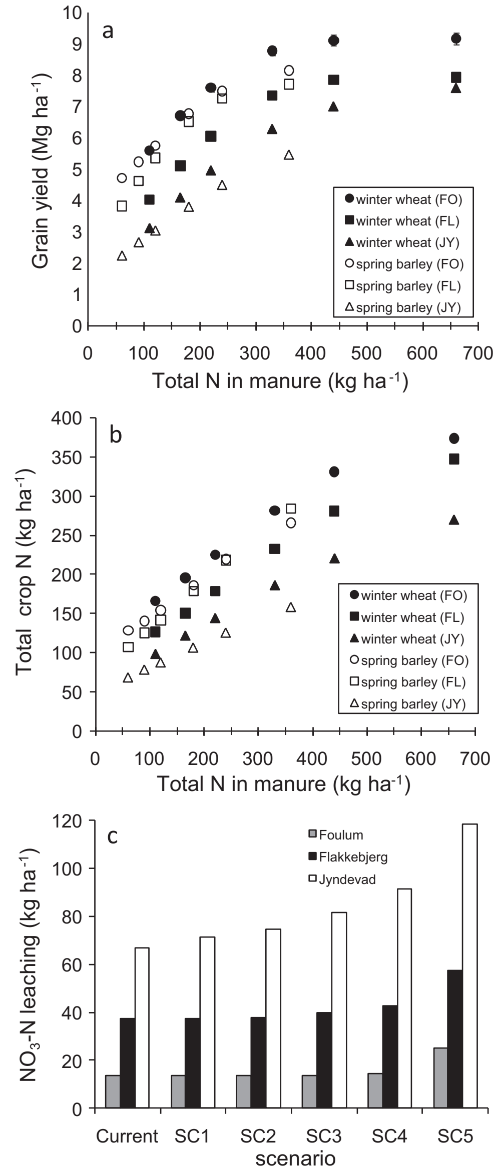

Fig. 6. Simulated response in terms of cereal DM yield (a), total N in crop at harvest (b), and average annual leaching during the four-year rotation (c) to increased levels of N applied to cereals in manure: 60 and 110 kg N ha^{-1} (current), 90 and 165 kg N ha^{-1} (SC1), 120 and 220 kg N ha^{-1} (SC2), 180 and 330 kg N ha^{-1} (SC3), 240 and 440 kg N ha^{-1} (SC4) and 360 and 660 kg N ha^{-1} (SC5) in the OF + C + M rotation in the loamy sand (Foulum), sandy loam (Flakkebjerg) and sandy (Jyndevad) soils. Values area averages of simulations performed with 20 years of weather data (1989–2008).

by the modeling results, might explain the overall improvement in cereal yield in this system compared with OF + C + M. A benefit to mid-season soil N mineralization of a green manure crop has also been suggested by Olesen et al. (2009). This would be supported by the fact that the largest effects were observed on the Jyndevad sandy soil, which had the lowest estimated mineralization (Fig. 5) and was probably the site that was most limited in terms of N availability in the organic systems.

The simulated soil fertility level in terms of annual N released through soil net mineralization from soil organic matter and added crop residues increased with soil organic matter content in correspondence with winter wheat yields. In general, higher winter wheat yields were found in the organic systems with manure for the loamy soils, as also reported by Olesen et al. (2009). A generally higher yield of spring barley for the coarse sandy than for the sandy loam soil was observed for the organic systems with manure and catch crops. This may be attributed to the ploughing in of the catch crop in spring instead of autumn when the benefits of using N-fixing catch crops are expected to be much lower (Fig. 7). There is also an element of uncertainty linked to the high variability among years.

Organic systems are limited by N availability as demonstrated in the scenario analysis conducted with the FASSET model. This topic was extensively discussed in Berry et al. (2002). The amount of N in the organic manure was lower than that applied with the mineral fertilizer and the ammonia volatilization was larger, and this had an impact on grain yields. According to our model simulations, it would be possible to improve cereal yield performance in organic arable farming in Denmark by introducing more N into the system. This could be achieved by increasing the amount of manure N applied by up to three to four times that applied in the organic systems in this study (Fig. 6a). However, this will contravene current regulations that limit the amount of manure N that can be imported from conventional farming in organic farming in Denmark, and the aim is to totally phase out this import option.

Other sources of N such as catch crops and green manure crops can be used to improve the N available for cash crops in organic farming (Thorup-Kristensen et al., 2003). We have found that grow-

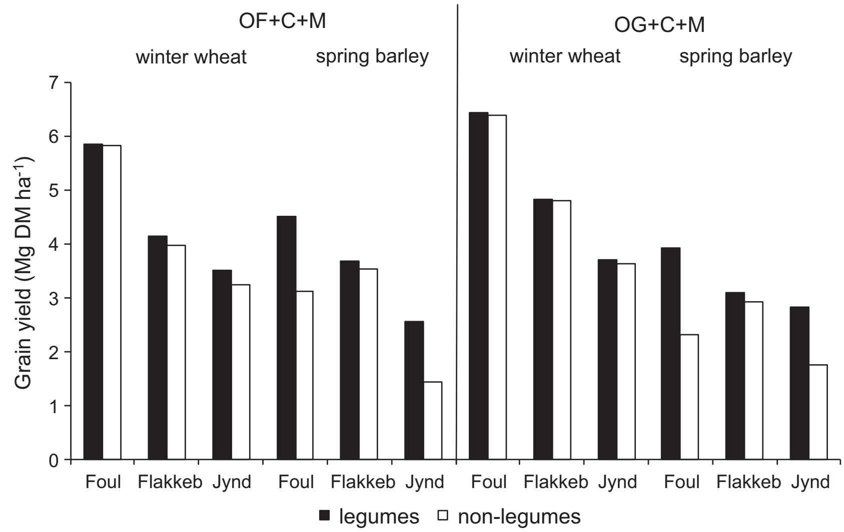

Fig. 7. Predicted response in terms of cereal DM yield of having (legumes) or not having (non-legumes) N fixing catch crops in the OF + C + M and OG + C + M cropping systems.

ing catch crops in the crop rotation had a positive effect on yield in most of the cases. This has not been so for winter wheat in the early part of this long-term experiment, partly due to weed pressure (Olesen et al., 2009), whereas yield benefits were previously observed for spring barley (Olesen et al., 2007). Our results showed cereal yield increases ranging from about 0.5 to 1.1 Mg ha^{-1} in the systems where N-fixing species (clover or winter vetch) were used as catch crops. This benefit was higher for spring barley, although only significant at the Foulum ($P < 0.05$) and Flakkebjerg ($P < 0.10$) sites. The increases in observed grain N yield were highest at Foulum at 18 and 24 kg N ha^{-1} for winter wheat and spring barley, respectively. The simulation scenarios conducted in the manured systems with catch crops where legumes were excluded, showed that the role of N-fixing species as catch crops was most important when incorporated in spring before sowing a spring cereal. A catch crop effect would also explain why spring barley yields were higher than those of winter wheat in the unfertilized rotations at all three sites, since a catch crop was not grown directly before winter wheat.

Despite the positive effect of catch crops on grain yield and protein content in the organic systems, there is still a considerable yield difference between those from organic and conventional systems. There is therefore still the need to further investigate additional sources of N that could boost the productivity in organic farming such as those leading to a better recovery of N from soil (i.e. deep rooted catch crops) or to a higher availability to cereal of N from N-fixation during the crop rotation. Moreover, the possibility of modifying some of the current restrictions (policies, transport, storing facilities and technology, etc.) to allow for a more flexible fertilization in organic farming should be considered. It is emphasized that increases in manure application must be done with high efficiency and be synchronized for N release to match crop requirements.

4.2. N losses in the organic and conventional systems

Besides increasing N input in a system with limited availability, N use must be optimized and leaching and atmospheric losses minimized. Emissions of NH_3 from spreading manure might contribute to an important fraction of the N losses in the organic systems as indicated by our model simulations and the scenario analysis. The linearity of the response obeys to the constant emission approach implemented in the model for ammonia volatilization. Strategies to reduce NH_3 volatilization have been reviewed by Sommer and Hutchings (2001). An adequate timing and procedure (i.e. injection depth) have been proposed among the management strategies to successfully reduce NH_3-N emissions from manure applications (Sommer and Hutchings, 2001; Smith et al., 2009). Chirinda et al. (2010) used the same long-term experiment to study nitrous oxide (N_2O) emissions in the 2008 winter wheat crop in the three organic systems with the application of manure and one conventional system that did not include a catch crop. They observed no differences between the cropping systems with annual emissions close to 1 kg N ha^{-1}. Although these authors did not include N_2 emissions in their study, there is a considerable difference in magnitude when comparing this figure with the amounts of N leached in this study.

Controlling N leaching is thus the other critical process by which N losses from the cropping system can be minimized in arable farming in Denmark. Except in the OF – C + M system, the annual N lost by leaching starting the first of April of the year when cereal was grown was only high in the coarse sandy soil of Jyndevad (Table 8). These results show the effectiveness of using autumn catch crops in cereal rotations to decrease N leaching irrespective of soil type, with the amount or type of fertilizer applied having no significant effect. This suggests that it is feasible to increase the N inputs for cereal production in a system with catch crops without significantly affecting N leaching. The scenario analysis for the OF + C + M rotation confirms that applications of N up to 180 kg N ha^{-1} and 330 kg N ha^{-1} for the spring barley and winter wheat crops, respectively, would not significantly affect leaching but would improve cereal yields (Fig. 6a) up to levels similar to those obtained in the conventional system. Although increases in spring barley yield were found up to SC5 (360 kg N ha^{-1}) in the coarse sandy soil, it should be noted that model predictions underestimated grain yield in Jyndevad, and therefore the response to N applications at this particular site might be overestimated. Moreover, it must be taken into account that an excessive application of N (>350 kg N ha^{-1}) would result in N luxury consumption and in a considerably increase of N leaching at all three sites (Fig. 6b and c).

Askegaard et al. (2005) found in the first course of the current long-term experiment (1997–2000) that N leaching was primarily related to soil type with the highest leaching in Jyndevad, as corroborated by our simulations. These authors also observed a very small (non-significant) effect of manure application in the organic crop rotations on N leaching, while catch crops reduced it significantly. This strengthens the hypothesis that it is possible to increase productivity of cereals in organic farming by increasing the amount of N from manure in the system. An adequate management of catch crops would avoid an impact on leaching as a result of increasing manure application rates.

4.3. FASSET modeling implications

The modeling results obtained in this work show the feasibility of using FASSET as a research tool in studies dealing with winter wheat growth and yield in a variety of cropping systems, as reflected in the statistics of Table 4. Nevertheless, there is still the need to adjust the relation between dry matter and grain N for a more precise prediction of protein concentration and flour baking quality. Further research is required to improve the performance of the simulation of spring barley yield. This may be because, unlike winter wheat where parameter values were derived from specific experiments, the parameterization of spring barley was mainly adapted from the literature and intercropping studies. Moreover, differences in the actual manure application system for spring barley and the one considered in FASSET probably resulted in an overestimation of NH_3 volatilization that most likely lead to underestimation of spring barley yield. However the general performance of cereal yield and grain N was good enough to allow for scenario studies.

As stated in Section 2, it was necessary to adjust the parameters of the clover residues by setting the N content as mineral and reducing C to capture the effects on yield of the fast decomposition of N-rich residues (Magid et al., 2001). The improvement of the simulation of the catch crops that are more frequently used in organic farming and of their competition for resources is one of the major challenges for future versions of the FASSET model. This should lead to a more accurate simulation of the turnover of N from crop residues and of its effects on the succeeding cash crop.

The usefulness of models that accurately simulate productivity of crop rotations and at the same time estimate processes that are hard to measure but can greatly affect crop N availability must be emphasized. Examples of this can be found in the literature for a variety of cropping systems and simulation models (e.g. Hansen et al., 1991; Littleboy et al., 1992; Acutis et al., 2000; Confalonieri et al., 2006; Doltra and Muñoz, 2010; Bedoussac and Justes, 2010). In this work the FASSET model has enabled the quantification of the N released from soil net mineralization and that lost due to leaching during a four-year rotation in a variety of cropping systems, and to evaluate its effects in cereal productivity. Moreover, the modeling show the usefulness of increasing manure N rates to cereals in organic farming and that this can be done without jeopardizing N leaching by using catch crops. This should help improve the competitiveness of organic cereal production in Denmark.

5. Conclusions

The effects of N availability on cereal production in four organic and one conventional cropping systems that differed in fertilizer type, catch crop and rotation composition were studied on three soil types experimentally and with the help of the FASSET model. Yield responded to soil fertility and it was better in the more loamy soils. Dry matter yield and grain N content were mainly affected by the type and amount of N in manure at all three locations, with the largest values in a conventional cropping system. N was found to limit the productivity in the organic cropping systems, with the smallest yields obtained in the systems without manure application. A catch crop benefit on DM and N grain yield was also observed in all rotations and sites, except for winter wheat on the sandy soil. This effect was more pronounced in spring barley and it was probably caused by the N-fixing catch crop species. Winter wheat yields were less affected by catch crops because they were not cultivated before this cereal. The FASSET model was able to predict on average the yield and grain N of cereals with a reasonable accuracy for the range of cropping systems and soil types studied. The quality of predictions was especially good for winter wheat, while for spring barley further work will be needed to improve crop parameterization. A better simulation of the dynamics of N turnover from catch crops residues will also be desirable to better capture its effects on cereal growth and N use. The results from this work indicate that the best management practices in relation to catch crop and manure might vary for spring and autumn sown cereals and between sites. However, a good management of catch crops was shown to effectively reduce N losses due to leaching on all soil types and cropping systems. The modeling results indicate that when using a catch crop, it would be possible to increase manure application rate without increasing N leaching.

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