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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

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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

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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