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Contributions from carbon and nitrogen in roots to closing the yield gap between conventional and organic cropping systems

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Abstract

This study investigates the effect of different crop rotation systems on carbon (C) and nitrogen (N) in root biomass as well as on soil organic carbon (SOC). Soils under spring barley and spring barley/pea mixture were sampled both in organic and conventional crop rotations. The amounts of root biomass and SOC in fine (250-53 µm), medium (425-250 µm) and coarse (> 425 µm) soil particulate organic matter (POM) were determined. Grain dry matter (DM) and the amount of N in harvested grain were also quantified. Organic systems with varying use of manure and catch crops had lower spring barley grain DM yield compared to those in conventional systems, whereas barley/pea showed no differences. The largest benefits were observed for grain N yields and grain DM yields for spring barley, where grain N yield was positively correlated with root N. The inclusion of catch crops in organic rotations resulted in higher root N and SOC (g C/m^2) in fine POM in soils under barley/pea. Our results suggest that manure application and inclusion of catch crops improve crop N supply and reduce the yield gap between conventional and organic rotations. The observed positive correlation between root N and grain N imply that management practices aimed at increasing grain N could also increase root N and thus enhance N supply for subsequent crops.

Keywords Particulate organic matter, root carbon, root nitrogen, catch crops, manure, low input system

Introduction

The expansion of resource-intensive (conventional) agriculture has increased productivity of major crops and enhanced global food security (Leifeld, 2012). Although intensive farming systems achieve high crop productivity, meeting environmental goals remains a challenge for conventional crop production systems. Organic cropping systems, which aim to achieve food production without depleting natural resources may be a viable solution (IFAD, 2011). However, the productivity of organic cropping systems is reduced by nutrient limitations, and higher productivity can be obtained by implementing management approaches that enhance soil nutrient availability and increase nutrient use efficiency (Berry *et al*., 2002).

In organic cropping systems, nitrogen (N) may be obtained from animal manure or through strategic inclusion of non-leguminous or leguminous catch crops (Thorup-Kristensen *et al*., 2003). Non-leguminous catch crops may retain and recycle soil N as they recover surplus N from fertilizer applied to the previous crop or from mineralised soil organic N, preventing it from being lost through several N loss pathways. Leguminous catch crops fix atmospheric N and represent an important renewable source of N that enhances soil fertility for the benefit of subsequent crops, reducing dependence on external N sources (Jensen *et al*., 2012). Soil-incorporated leguminous and non-leguminous crop residues decompose and contribute nutrients for subsequent crops (Li *et al*., 2015a).

Carbon inputs directly influence soil organic matter (SOM), soil microbial processes and crop productivity (Janzen, 2006). Katterer *et al*. (2011) estimated that C derived from crop roots contributes more to soil C and its stability than that from aboveground residues. Previous studies suggest that different crop management measures (i.e., inorganic fertilizer, organic manure, pesticides, tillage intensity) can affect root biomass (Van Noordwijk *et al*., 1994; Swinnen *et al*., 1995). Yet, there is growing evidence showing inconsistent management effects on root C inputs (Chirinda *et al*., 2012; Lazicki *et al*., 2016; Hu *et al*., 2018). The addition of above- and belowground crop residues to soils increase their particulate organic matter (POM) content (Fronning *et al*., 2008). Previously, POM (50-2000 μm), which refers mostly to organic matter that has not yet been subject to microbial degradation, has been used as an index of labile SOM, which is also more sensitive to management than total SOM (Carter, 2002). Soil POM content may be considered a predictor of N mineralization potential and thus correlate with the amounts of soil-derived N taken up by crops (Willson *et al*., 2001).

The objective of this study was to determine cropping system effects on C and N in roots and shoots as well as the amount of N returned in above- and belowground residues from cereals and grain legume/cereal intercrops in systems differing in approaches to soil fertility management. Additionally, the study explored whether system differences in soil fertility were related to C in soil POM.

Materials and methods

Field site and soil description

Field measurements were made in a long-term organic and conventional cropping experiment (established in 1997) at Research Centre Foulum in western Denmark (Olesen *et al*., 2000). The mean annual temperature at the study site is 7.3 °C and average rainfall is 704 mm. The soil type at the site is a sandy loam classified as a Mollic Luvisol according to The World Reference Base for Soils (WRB) with the following chemical and physical characteristics at 0-0.25 m depth at the commencement of the crop rotation experiment: pH 6.5 ($CaCl_2$), 0.05 g P/kg soil, 0.13 g K/kg soil, 78 % sand, 13 % silt, 9 % clay, 23 g SOC/kg soil, 1.8 g total N/kg soil and soil bulk density was 1.35 g/cm^3 (Djurhuus & Olesen, 2000).

Experimental layout

The experiment had a factorial design with three factors and two replicate blocks. The experimental factors were 1) different cropping systems, i.e. organic with whole-year green manure (O2) or organic (O4) or conventional (C4) without whole-year green manure, 2) with (+CC) and without (-CC) a catch crop, and 3) with animal manure (+M) or inorganic fertilizer (+IF) and a treatment where fertilizers were excluded (-M). Four-year crop rotations were used between 1997 to 2009. All systems were managed as organic until 2004. From 2005 the treatment combination of no manure and no catch crop (-CC/-M) in O2 or O4 was converted to a conventional system (C4) that include application of inorganic fertilizers (+IF) and use of agrochemicals. From 2005, the crops in O4 and C4 were the same, although the species used for catch crops differed, with legume-based mixtures in O4 and non-legumes in C4. During 2005-2009, the C4 and O4 rotations included spring barley (*Hordeum vulgare* L.), faba bean (*Vicia faba* L.), potato (*Solanum tuberosum* L.) and winter wheat (*Triticum aestivum* L.) while the O2 cropping sequence was spring barley with undersown ley, grass-clover, potato and winter wheat. In 2009, the faba bean crop in C4 and O4 was replaced with a mixture of spring barley and pea (*Pisum sativum* L.) to avoid soil borne diseases. From 2010, O4 and C4 rotations were changed to spring barley, hemp (*Cannabis sativa* L.), spring barley/pea, spring wheat and potato, and rotation O2 had lucerne (*Medicago sativa* L.) instead of hemp and spring barley/pea. For the current study, three crop sequences were used (Table 1) with either spring barley or spring barley/pea mixture in 2012. The following treatments were included in the organic rotations (O2 and O4): -CC/+M, +CC/-M and +CC/+M. The conventional rotation (C4) included treatments with and without catch crops: -

CC/IF and +CC/IF. The size of individual plots was 216 m^2 and each plot was sub-divided (4 sub-plots of 54 m^2) (Olesen *et al*., 2000; Shah *et al*., 2017).

Crop management

Spring barley was sown at row distances of 12.5 cm, except for barley/pea in organic systems (24 cm) (Table 2). Sowing was at a target density of 250 plants/m^2 in O2, 400 plants/m^2 in O4 and 350 plants/m^2 in C4 for spring barley and 150/35 plants/m^2 in O4 and 200/45 plants/m^2 in C4 for barley and pea, respectively, in barley/pea plots. Harvesting was done on 20 August 2012.

Catch crops in organic rotations were a mixture of perennial ryegrass (*Lolium perenne* L.), chicory (*Cichorium intybus* L.), red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.) (10 kg/ha) undersown after weed harrowing. The conventional system (C4/+IF/+CC), had a mixture of winter rye (*Secale cereale* L.) and winter rape (*Brassica napus* L.) (52 kg/ha) as catch crops sown after harvest. All catch crops were sown at a row distance of 12.5 cm and were incorporated by ploughing in spring prior to sowing of spring crops (Table 2). Lucerne was undersown (30 kg/ha) in the spring barley after the end of weed harrowing in spring in the O2 rotation and left in the field to complete its growth cycle as a main crop in the following year.

The spring barley plots receiving manure were supplied with anaerobically digested slurry (mixture of cattle and pig) in O2 and pig slurry in O4 (Table 2). About 60 kg total N/ha of manure was applied in organically grown spring barley. The barley/pea crop grown in O4 and C4 (*a* and *b*) did not receive any amendments. Spring barley in C4 plots received inorganic fertilizer (122 kg N/ha). Soil incorporation of crop residues was done after harvest.

Plant measurements

In July and August of 2012, shoot and root samples were collected at maturity from plots with spring barley and from plots with barley/pea mixture (Table 1). Shoots were sampled from two 0.5 m^2 areas and pooled to obtain a representative plot value. We took approximately one kilogram from these samples and separated this sample into barley, pea, catch crop and weeds. The dry matter (DM) content of all plant samples was determined after oven drying at 80 ºC for at least 24 h.

Root biomass was measured through soil samples collected from within and between crop rows in each treatment plot. The samples were collected after crop harvest in the same area as shoot samples, at 0-0.30 m depth using a hand auger. Composite samples consisting of 3 cores of 5 cm diameter were collected from within and midway between crop rows and pooled according to sampling positions (Bolinder *et al*., 1997). Soon after sampling, soils were frozen at -18 ºC to avoid root decomposition. The roots were processed as described by Chirinda *et al*. (2012). Nitrogen content in finely milled shoot and root samples was assessed using the Dumas method (Hansen, 1989). The root C content was estimated by assuming C concentrations are 45 % of DM biomass. To extrapolate shoot and root biomass and estimated C concentrations from point to field scale, we used a similar approach to Bolinder *et al*. (1997).

Crops from each treatment were harvested from two sub-plots (~27 m^2) using a combine harvester for grain DM determination. In the barley/pea mixture a sub-sample was used to determine the yield of the respective components. Total N in the pea grain was determined on finely milled samples by the Dumas method, whereas N in barley grains was determined using a near infrared spectroscopy analyzer (Infratec TM 1242 Grain Analyzer, Foss A/S).

POM fractionation and laboratory analysis

The soil sampling strategy was similar to that used for estimating root biomass: samples were collected from between and within rows. Samples stored at -18°C were thawed and fractionated based on size and POM was fractioned as SOM > 53 μm (Marriott & Wander, 2006). The procedure described by Willson *et al*. (2001) was used to process the soil samples. We defined the different fractions of POM-C as coarse (>425 μm), medium (425-250 μm) and fine (250-53 μm). The amount of C to 30 cm depth was calculated by multiplying by the bulk density. All three fractions were analyzed for total C by combustion-based elemental analysis (ELTRAs CS-580A "Helios").

Statistical analyses

Data were first checked for normality, and since all data could be considered normally distributed, no data transformations were applied. The experimental setup applied a division of treatments into sub-blocks, where the three-way interaction between treatments was confounded by the sub-blocks. However, since our selection of treatments did not include three-way interactions, these sub-blocks were not included in the statistical models. All data on barley grain DM, grain N, shoot N, root C and N amounts and the C content in different fractions of POM were analysed using a mixed effect model with treatments as fixed effects and blocks as random effects. Analyses were performed using PROC MIXED of SAS (SAS Institute 1996). Since the experimental layout did not include a balanced design between treatment combinations, we applied four statistical models with different subsets of the data. The first analysis included all data for each crop type and allowed results to be compared between treatment combinations based on Least Significant Difference at P<0.05 (Table 3). In addition, we selected three combinations of subsets to test the overall treatment effects (crop rotation, catch crop, manure, Table 4) as follows: 1) Only organic systems with catch crops to test the effects of rotation and manure for spring barley, 2) Both conventional and organic systems with manure and fertilizer to test the effects of rotation and catch crops for spring barley, and 3) Both crop types for conventional and organic systems with manure/fertilizer to test the effects of crop type and catch crop.

In addition, correlation analyses were performed between grain DM and grain N yield and root and soil POM variables to determine relationships for treatment means using PROC CORR in SAS.

Results

Grain DM and grain N yields

When all treatment combinations for spring barley were compared, the conventional rotations had higher grain DM yields irrespective of catch crop inclusion than the organic rotations, except for O2, which included both catch crops and manure. The latter also had higher grain DM yields than the two O4 rotations, which included either catch crops or manure (Table 3). When only organic rotations were compared, the presence of manure significantly increased spring barley grain DM yields (Table 4). Moreover, the presence of catch crops significantly increased spring barley grain N yields and shoot N, and it tended to increase spring barley grain DM and shoot C (Table 4). The corresponding grain DM yield benefits from catch crops were 30 and 23 g DM/m^2 in the O2 and O4 rotations, respectively.

The average grain DM benefit from presence of catch crops was 102 and 36 g DM/m^2 in the O4 and C4 rotations, respectively. The largest benefits from manure and catch crops were obtained for spring barley, whereas there was little effect for the barley/pea mixture (Table 4).

Root N and its relation to grain N

The amount of N in root was significantly affected by crop and rotation system (Table 4). On average, the amounts of N in roots from the O4 and C4 cropping systems were 3.3 and 2.6 g N/m^2, respectively, for barley/pea, and 2.1 and 3.0 g N/m^2, respectively, for spring barley (Table 3).

Mean root N was 3.0 and 2.3 g N/m^2 in barley/pea and spring barley, respectively. Root N in barley/pea in O4 increased by 0.45 g N/m^2 with the presence of catch crops. For spring barley, all rotations tended to have higher root N when the crop was grown in systems with catch crops (Table 3). For spring barley, the root N benefits from catch crops were 0.65, 0.95 and 0.60 g N/m^2 in rotations O2, O4 and C4, respectively. A positive correlation was observed between N harvested in grain and N in spring barley roots (Fig. 1). This correlation was not found for the barley/pea crop.

Particulate organic matter in soil

Total POM-C contents in the O2 and O4 organic rotations were similar for soils under spring barley (Table 3). For barley/pea plots, total POM-C contents were similar across crop rotations. Similarly, POM-C contents in the coarse, medium, and fine fractions were similar across systems for both crops, except barley/pea, which had higher fine POM-C in the conventional rotations with catch crops than without catch crops.

Root C and total N recycling

Root C tended to be higher under organic (O4) than conventional (C4) crop rotation for barley/pea (Table 4) and was 84 and 64 g C/m^2, respectively (Table 3). By contrast, it was similar among treatments for spring barley and averaged 72 g C/m^2. For barley/pea, there was a higher root C in the organic (O4) compared to the conventional (C4) rotation (Table 3). Overall, root C contents were similar across both crops (Table 4). Our results allow the estimation of N recycled in the above- and below-ground residues of barley and barley/pea crops. For barley/pea an average amount of 119 kg N/ha was returned in crop residues, composed of 89 and 30 kg N/ha in above- and belowground residues, respectively. There were no pronounced differences between cropping systems in these amounts. This should be compared with an average value of 65 kg N/ha in residues from spring barley, where 41 and 24 kg N/ha originated from above- and belowground residues, respectively.

Discussion

Productivity of cropping systems

Several studies have shown beneficial effects of intercropping grain legumes with cereals, because this can increase and stabilize yields compared to sole grain legume crops, and it also reduces the need for inputs (e.g., fertilizer and agrochemicals for pest and weed control) compared to sole cereal crops (Hauggaard-Nielsen & Jensen, 2001; Sahota & Malhi, 2012). Our results showed that grain N yields and shoot N of the barley/pea intercrop were generally considerably larger than when spring barley was a sole crop. Similar results have previously been reported for intercropping of barley and pea (Sahota & Malhi, 2012; Hunady & Hochman, 2014). We observed that grain DM for spring barley responded to the different crop systems (organic/conventional, manure and catch crop), whereas this was not the case for barley/pea. This corroborates with previous studies reporting that a grain legume-cereal mixture provided more stable yields

(Hunady & Hochman, 2014). Therefore, intercropping and catch crop inclusion may both contribute towards stabilizing yields in organic systems and closing the yield gap between organic and conventional systems.

While a lack of effective weed and pest control measures has been given as the reason for lower grain DM yields in organic systems (Clark *et al*., 1998; Melander *et al*., 2016), others report that deficient nutrient supply (especially N and phosphorus) often constitutes the major limitation (Shah *et al*., 2017). A key difference in N management is related to the fact that unlike the more targeted fertilizer use in conventional systems, organic cropping systems are often characterized by poor synchrony between nutrient supply and plant demand (Berry *et al*., 2002). In the current study, the effect of catch crops and the application of manure were evaluated for both organic and conventional rotations. The legume-based catch crops in the organic cropping systems contributed N to the cropping systems through both biological N fixation (Li *et al*. 2015b) and through retaining N by recycling this in above- and belowground plant residues.

The highest spring barley yields (DM and N) in the organic systems were obtained when both manure and catch crops were used (Table 3). Both factors contribute to crop N supply, albeit in different ways. The application of manure adds a substantial amount of mineral N as ammonium, whereas the N from the catch crops is supplied over a longer time through mineralization of organic matter (Olesen *et al*., 2007; Doltra & Olesen, 2013). For spring barley, enhanced soil N availability following incorporation of catch crops prior to sowing and application of manure probably explains the yield similarities between the low-input organic and the high-input inorganic fertilizer based systems. These findings are consistent with those from previous studies in which the use of catch crops and application of animal manure showed positive effects on grain DM yields (Olesen *et al*., 2007; Chirinda *et al*., 2010). Moreover, the larger grain yields from O2 compared with the O4 rotation suggest a positive response to the inclusion of grass-clover green manure in the rotation (Olesen *et al*., 2007). Nonetheless, it is important to note that prior to 2005, the current conventional plots had not received fertilizer or manure and did not include a catch crop. It is reasonable to assume that this system was, to some extent, depleted in readily degradable organic N when converted to conventional management.

N inputs by roots

No significant differences in root N content were observed between crop rotation systems, but there was a tendency for higher values for the barley/pea intercrop compared to spring barley. In addition, the inclusion of catch crops in organic systems led to higher shoot and root N input. This is simply a consequence of the presence of more plant biomass in systems where pea and catch crops were included, and this indicates a larger N accumulation capacity in organic systems with inclusion cereal-legume crops and catch crops.

Grain DM yields have been reported to closely relate to the growth and development of root systems in high yielding cropping systems (Wang *et al*., 2014). However, Hu *et al*. (2018) found no relationship between shoot and root biomass of cereals when comparing organic and conventional systems. This lack of difference in root biomass and root C between cropping systems of different intensities was also found in our study (Table 3). We found a linear relationship (Fig. 1) between root N and grain DM for spring barley, but not for the barley/pea intercrop. This relationship was caused by differences in N concentration in roots of different systems (15.0 g N/g DM in spring barley versus 17.9 g N/g DM in barley/pea), rather than differences in biomass (data not shown). The lower N availability in the organic systems was thus found to result in lower N concentration in root biomass, which would delay net N mineralization of these residues (Thomsen *et al*., 2016).

Residual N effects of spring barley and barley/pea

The productivity of organic cropping systems depend on the recycling of nutrients through crop residues. We observed considerably higher amounts of N in residues following barley/pea compared with spring barley. This may be expected to enhance the risk of N leaching losses during autumn, but such differences in N leaching between spring barley and barley/pea were not found by Askegaard *et al*. (2011). Other previous studies (e.g., Bergström & Kirchmann, 2004) show that when legumes instead of ryegrass are included in cropping systems, leaching of N increase considerably over the short-term. In the case of our study, it is likely that barley/pea contributes to the long-term fertility of the cropping system rather than short-term losses. These temporal aspects of N release are affected by the N concentration and C:N ratio of the crop residues (Jensen *et al.*, 2005), and the root N concentrations of both barley/pea and barley roots were so low that they would likely cause net N immobilization.

Crop management implications on POM

The amounts of POM-C strongly depend on organic matter inputs, which are influenced by cropping systems and management practices. In this study, if we consider all crop residues, there were no pronounced differences in average organic matter inputs between different management systems (data not shown). Fine POM-C (250-53 µm) was only significantly higher in soils under barley/pea in the organic rotation that included catch crops and manure, and in conventional systems that included catch crops, than in the conventional system that excluded catch crops. As fine POM is a biologically and chemically active part of the easily decomposable organic matter, the high amount of fine POM-C in rotations including catch crops may be the reason for the higher soil respiration from rotations, including catch crops, as reported in a previous study conducted on the same experiment (Chirinda *et al*., 2010). However, this higher soil respiration may be associated with higher N mineralization that increases the risk of N loss through leaching, which thus emphasizes the need for maintaining the use of catch crops to retain N in the system.

As observed by Marriott & Wander (2006) for a study conducted on nine farming system trials, similar POM-C (>53 µm) was observed in organic and conventionally managed systems. We also found little difference between cropping systems in POM-C. The POM-C may therefore not in itself be a good indicator of soil fertility, but may have to be supplemented with indicators that better reflect nutrient contents and nutrient availability, in particular N mineralization potential.

Conclusions

Our results suggest that manure application and inclusion of catch crops improves crop N supply and reduces differences between yields in conventional and organic rotations, resolving some of limiting factors of organic systems such as low N supply. Although application of manure in organic systems reduces differences in yields between conventional and organic systems, limitations in availability of manure from livestock farms may challenge this option for enhancing N inputs in organic systems. The observed positive correlation between root N and grain N for spring barley suggests that high yielding cereal crops may be contributing more N to soil fertility. These findings suggest that grain N can be used as a proxy for N in root N residues and thus the amount of residual N available for subsequent crops. Overall, targeted management of manure application and catch crop inclusion combined with knowledge on root derived residual N should be able to improve crop yields and sustainability of organic cropping systems.

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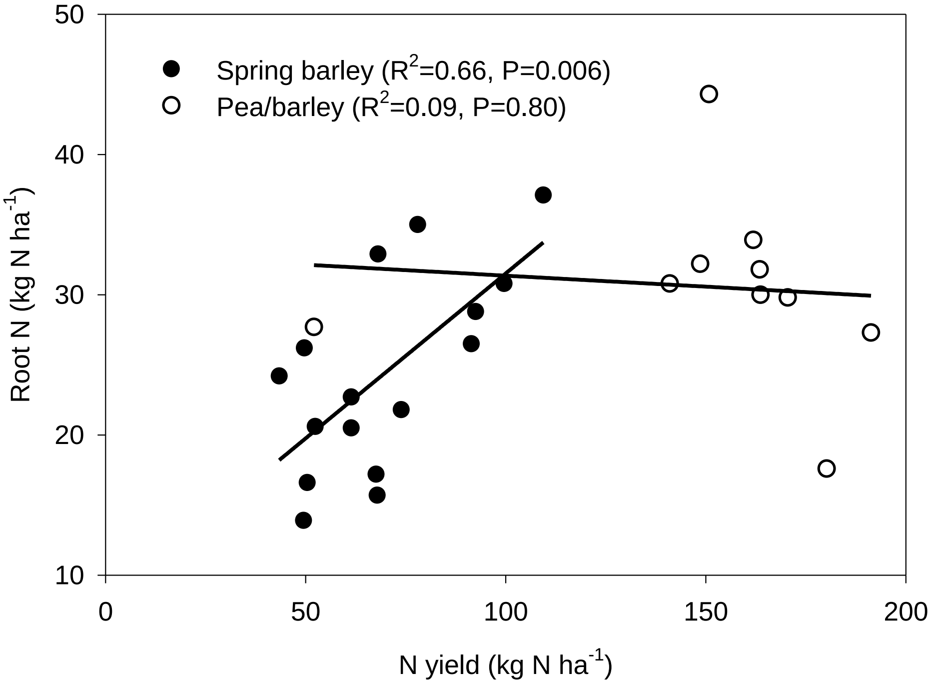

Fig. 1: Relationships between root and grain nitrogen for pea/barley and barley only cropping systems for samples collected in 2012. The statistics are shown for linear regressions of root N on N yield.