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Short communication

Catch crops affect nitrogen dynamics in organic farming systems without livestock husbandry—Simulations with the DAISY model

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Abstract

This paper presents simulations of the soil–plant–atmosphere model DAISY based on an organic crop rotation with incorporation of different catch crops following pea as a leguminous cash crop. Special emphasis was placed on the simulation of nitrogen (N)-mineralisation/immobilisation and of soil microbial biomass N. The DAISY model was able to simulate soil mineral N and soil microbial biomass N after soil incorporation of catch crop plant residues to some extent only. Several processes need further attention and should be integrated into the DAISY model: (1) soil tillage induced mobilisation of organic material including considerable amounts of organic N; (2) winter killing of sensitive plant species and varieties; (3) decomposition of plant residues at the soil surface; (4) decomposition of easily decomposable plant residues at low temperatures, both with respect to the temperature modifier function and to the linkage of C and N turnover; (5) furthermore, reliable criteria for the subdivision of green plant residues into an easily decomposable pool and a more recalcitrant pool have to be developed.

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1. Introduction

One of the major challenges in sustaining agricultural plant production is optimising the nutrient cycling of the agro-ecosystem, especially in organic and integrated farming systems. This includes recycling and

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utilisation of natural nitrogen (N) sources, such as N in residues of N-fixing crops, green manures or catch crops. On stockless organic farms, full year green fallow, i.e. legume–grass mixtures, is commonly used at least once in every rotation, preceding the most N demanding crops. In addition, annual green manures and catch crops are used more and more intensively, to increase N recycling by reducing leaching and supplying more N through fixation, thus reducing the requirement for green fallow, which is an economically unfavourable component of the crop rotation. Thus, prediction of N supply and recycling in such cropping systems is essential in order to design appropriate crop rotations for stockless organic farms (Thorup-Kristensen and Nielsen, 1998).

Existing knowledge of N processes in the soil and N utilisation by crops has been used to formulate mechanistic models with increasing levels of complexity and detail of both pools and processes (Jensen et al., 2001). Many of these models have been developed and calibrated with data from conventional, high N input farming systems, and were furthermore developed with the aim of simulating N losses during the 1980s, when environmental problems with N leaching became an issue of public concern (De Willigen, 1991). But, can these models simulate crop growth and N cycling adequately in organic farming systems? One evident problem is the fact that the N inputs are usually in organic form and lower in total amount compared to the mineral fertiliser N inputs in conventional systems, which means that some modifications or recalibration may have to be carried out. However, if existing, valid models can be applied, their use holds great promise, because they can be a very powerful tool for evaluating the productivity, sustainability and environmental impact of different organic crop rotation strategies.

The point of departure for our investigation was the following hypothesis: the soil–plant–atmosphere model DAISY is able to simulate organic crop rotations including an extended use of catch crops and green manure.

An important factor is the expected N-mineralisation and immobilisation after soil incorporation of the plant materials. Therefore, the main emphasis of this paper was placed on the simulation of N-mineralisation/immobilisation and of soil microbial biomass N.

2. Materials and methods

2.1. Field experiment

The field experiment was conducted at the Agricultural Research Centre Aarslev (10°27'E, 55°18'N), located on the island of Funen (Denmark) in a wet temperate climate (Thorup-Kristensen, 2001). Mean annual temperature and precipitation were 8.1 °C and 719 mm, respectively, during the period 1986–1998. All field treatments were carried out in triplicate in a completely randomised design.

Data from the first year of the experiment reported by Thorup-Kristensen (2001) were chosen for this investigation. The soil was a Typic Luvisol. The topsoil was a sandy loam with 14.7% clay, $\text{pH}_{\text{CaCl}_2}$ 7.0, 1.8% C and 0.16% N.

Pea was sown on 22 April 1996. On 25 July 1996, harvest was mimicked by ploughing down the above ground plant material (regular green pea harvest removes a very small fraction of plant dry matter only) completely into the soil (ca. 23 cm). On 2 August 1996, different catch crops were sown. For the model simulations, we chose four catch crops differing in chemical properties (Table 1) and growth patterns. Oil radish (*Raphanus sativus* cv. *oleiformis*) and winter rape (*Brassica napus* cv. *napus*) are non-persistent catch crops that usually die off completely during winter. Italian ryegrass (*Lolium multiflorum*) and rye (*Secale cereale*) are more winter-persistent catch crops and are only partly killed during wintertime, with some re-growth in late winter–early spring. On 2 April 1997, the remaining catch crop plant materials were incorporated into the soil by shallow rotavation (ca. 5 cm). Thereafter, the soil remained as bare fallow.

After rotavation, soil was sampled five times until 1 July 1997 to a depth of 25 cm. Soil microbial biomass nitrogen (N_{mic}) was estimated by chloroform fumigation extraction, using ethanol free chloroform for 24 h fumigation at 25 °C and 0.5 M K_2SO_4 for extraction of fumigated and non-fumigated soil samples (Brookes et al., 1985). Total N in the extracts was measured after persulphate-oxidation at 120 °C for 30 min, according to Cabrera and Beare (1993). N_{mic} was calculated as the difference between fumigated and non-fumigated samples multiplied by an f_{EN} -factor of 1.85 (Brookes et al., 1985; Joergensen and Mueller, 1996). Soil mineral N (NH_4^+ and NO_3^-) was measured in the 0.5 M

Table 1
Properties of the above ground catch crop plant materials before soil incorporation on 2 April 1997

Plant	Total plant material						Water insoluble material			Water soluble material		
	C _t [% afdm]	N _t [% afdm]	C/N	Cellulose [% afdm]	Lignin [% afdm]	Lignin/N	C [% C _t]	N [% N _t]	C/N	C [% C _t]	N [% N _t]	C/N
Rye	49.0	4.3	11.3	19.8	2.9	0.7	60.9	49.3	14.9	39.1	50.7	9.0
Italian ryegrass	48.9	4.2	11.7	22.8	3.9	0.9	74.3	61.0	14.3	25.7	39.0	7.7
Winter rape	47.9	3.9	12.5	30.7	7.0	1.8	72.6	56.3	16.1	27.4	43.7	9.9
Oil radish	48.5	3.4	14.3	33.5	8.1	2.39	77.7	67.7	16.4	22.3	32.3	7.7

afdm: ash free dry matter.

K₂SO₄ extracts from non-fumigated soils by colorimetric methods using flow-injection analysis (Keeney and Nelson, 1982).

2.2. The DAISY model

DAISY is a deterministic model, which simulates water, energy, C and N-fluxes in a one-dimensional soil–plant–atmosphere system (Hansen et al., 1990, 1991). In this study, an open source DAISY version (Abrahamsen and Hansen, 2000) was used.

Three discrete soil organic pools (added organic matter (AOM), soil microbial biomass (SMB) and native non-living soil organic matter (SOM)), soil mineral N (N_{min}) and soil respiration (CO₂) are simulated by the soil–organic-matter submodel. Remaining plant residues are simulated as AOM. The organic pools (AOM, SMB and SOM) are each considered, being a continuum having a certain range of turnover rates. In the original development of the model, it was found that these continuums could be simulated satisfactorily if each pool was subdivided into two conceptual sub-pools, one with a slower turnover (i.e. AOM1) and one with a faster turnover (i.e. AOM2). The turnover of all organic pools follows first-order kinetics.

During simulation, turnover rates of the different pools are adjusted to actual environmental conditions using rate modifiers for soil temperature, soil water potential and soil clay content. Carbon fluxes into microbial biomass are calculated using source-specific substrate utilisation efficiencies.

After each time step, the N pools are calculated from the actual amount of the C-pools by multiplication by the reciprocal value of a fixed C/N-ratio for each pool. Net N-mineralisation or N-immobilisation is then derived from the N-balance. If immobilisation

occurs during growth of the SMB-pools, this growth may be limited by the lack of mineral N in the soil.

A detailed description of the soil–organic-matter submodel was given by Mueller et al. (1997). A detailed description of the whole DAISY model was given by Hansen et al. (1990, 1991) and Abrahamsen and Hansen (2000).

Soil physical and chemical properties were parameterised using measured data. The soil organic matter module was parameterised using a setup calibrated on a field experiment with incorporation of rape straw (Mueller et al., 1997). In this setup, plant residues (AOM) were subdivided by simply allocating the water-insoluble C and N to AOM1 (slow turnover) and the water-soluble C and N to AOM2 (fast turnover).

For the simulation of pea, a default pea module including symbiotic N₂-fixation was used. For the simulation of Italian ryegrass and rye, default plant modules for grass and winter rye were used. Oil radish was simulated using a plant module calibrated in an earlier investigation (Thorup-Kristensen et al., 1997). Winter rape was simulated using a modification of the same plant module.

2.3. The modelling scenarios

In the first step, above ground dry matter production of the modelled pea was successfully fitted to the amounts of above ground plant dry matter and plant N measured in the field before soil incorporation by rotavation (model predicted/measured was between 99 and 101%). This was an important prerequisite for the model simulation of the following period in the different scenarios. Simultaneously, the initial amount of N_{mic} was adjusted with respect to the level of N_{mic} during spring 1997 in the fallow treatment. The initial

amount of N_{mic} derived from the fallow treatment was then applied to all other treatments.

In the second step, the plant modules for grass, rye, oil radish and winter rape were fitted to the amounts of plant dry matter and plant N before and after winter. The plant model does not currently include algorithms for simulating winter killing and increased litter loss during frost periods (grass). Hence, this had to be simulated by manually increasing leaf and root death rates during periods of very low temperature (grass). Oil radish and winter rape died completely during winter. This was simulated by shallow soil incorporation of the whole plants at the end of December 1996.

No further adjustments were made to the parameterisation of the soil organic matter turnover.

3. Results and discussion

3.1. Fallow treatment

In the fallow treatment, simulated soil microbial biomass N was adjusted to the correct level during spring 1997 (Fig. 1). However, the model did not simulate the short-term increase of N_{mic} and N_{min} within the first three sampling dates after rotavation (Fig. 1). Easily available soil organic matter mobilised by rotavation and a subsequently accelerated microbial turnover may have been the reason for this increase measured in the field (Joergensen and Raubuch, 2003; Roberts and Chan, 1990). Together with other models of soil organic matter turnover, DAISY does not yet include

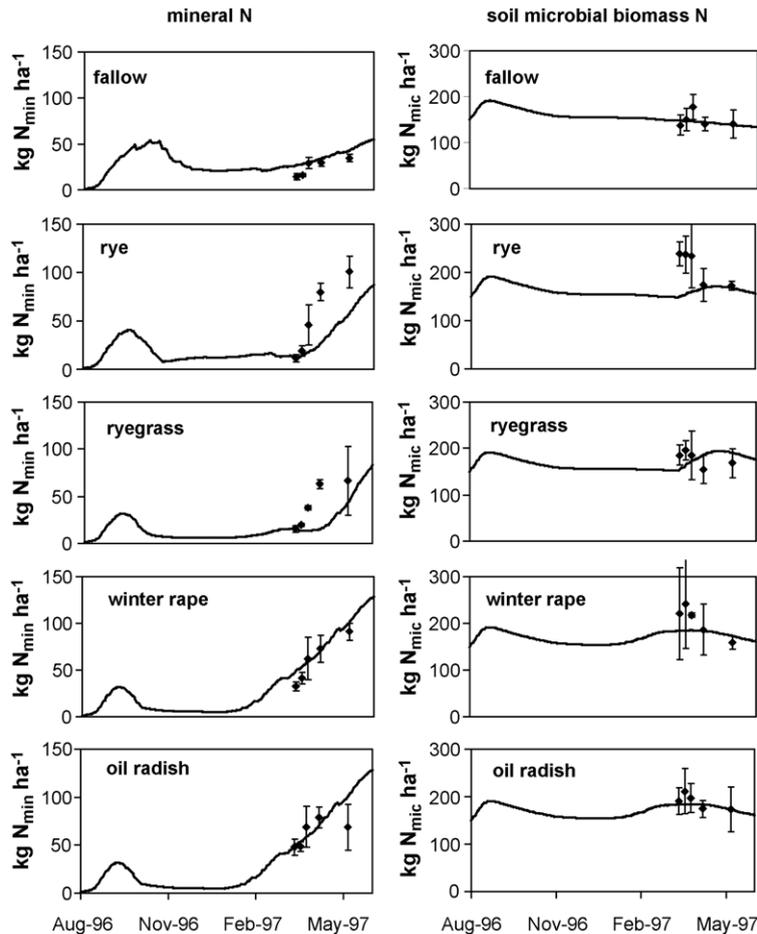


Fig. 1. Mineral N (N_{min}) and soil microbial biomass N (N_{mic}) at 0–25 cm soil depth. Measured (diamonds) and model simulated values (lines). Bars show the 95% confidence interval of the measured data ($n = 3$).

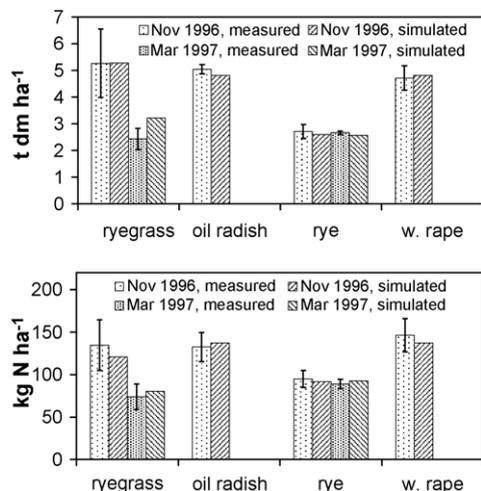


Fig. 2. Amount of dry matter and N in the different catch crops in November 1996 (shoot and root) and in March 1997 (shoot only). Measured and model simulated values. Bars show the 95% confidence interval of the measured data ($n = 3$).

algorithms for the simulation of organic matter mobilisation by soil tillage.

3.2. Catch crop treatments

As shown in Fig. 2, simulated dry matter and N in the catch crops were in the correct order of magnitude both before and after winter. It was decided to accept slight over or underestimations without further modifications of the plant modules.

The DAISY model underestimated N_{\min} in April and May 1997 in the rye and ryegrass treatments (Fig. 1). In addition, the model was not able to simulate the early increase of N_{mic} correctly. Simulated N_{mic} -peaks appeared too late (rye and ryegrass) and tended to be too low (all treatments except ryegrass). The observations indicate that the turnover of winter-killed plant material began earlier and happened faster in the field than predicted by the model.

In the simulations, winter-killed plant material remained at the soil surface until 2 April. In the field, it could be seen that decomposition of these plant residues began during late winter and early spring. Microorganisms originating from the phyllosphere are known to be very effective decomposers of dead plant material remaining at the soil surface (Flessa, 2002). The DAISY model, however, initiates plant material

decomposition only after incorporation into the soil, which in this case means after rotavation on 2 April 1997. As a result, the turnover of rye and ryegrass residues was initiated too late. Bio-incorporation of plant residues by macro- and mesofauna as simulated by the DAISY model could not compensate for this shortcoming.

In the winter rape and oil radish treatments, the early increase of N_{\min} was simulated satisfactorily (Fig. 1). Here, the complete eradication of the plants during winter was simulated by shallow soil incorporation at the end of December 1996. This enabled the DAISY model to initiate the turnover of the plant residues earlier.

Surface decomposition of organic matter is an integrated part of models originally developed for forest and grassland systems (e.g. Parton, 1996). However, our results indicate that this process should be considered for arable systems too, at least if including winter-killed plants or considerable senescence.

Another aspect may explain late simulated decomposition: the current DAISY temperature modifier reduces the turnover rates of all organic matter pools at 5 °C to only 25% of the rates at 20 °C (Hansen et al., 1990). Below 0 °C, turnover rates turn to zero. This is in contrast to other models, which allow turnover of organic matter even below 0 °C (Wu and McGeachan, 1998). Magid et al. (2001) showed that disproportionately high net N-mineralisation rates from green manures occur at low temperatures. Furthermore, Magid et al. (2004) proposed that the decomposition of intracellular low molecular substances and proteins can be viewed as a process separate from the decomposition of macro-polymers in cell walls. At higher temperatures these processes coincide and thus the distinctiveness is blurred, whereas at low temperatures they may occur more separated in time as well as space. This is in contrast to the DAISY approach defining fixed C/N-ratios in all simulated pools including AOM, as also used in comparable models (e.g. Smith et al., 1996). Other models define fixed C/N-ratios for some pools, whereas other pools are allowed to vary (Li, 1996) or allow fluctuations of soil organic matter C/N-ratios within a certain range as a function of soil mineral N (Parton, 1996). Dutt et al. (1972) proposed a model including only one organic matter pool keeping track of its C/N-ratio throughout the mineralisation process by assuming that a certain amount of C-atoms are released for every N-atom. Bosatta and Ågren (1991) modelled

C/N-ratios as a function of quality coefficients changing during decomposition of added organic matter.

A third explanation for the late simulated decomposition may be the simple subdivision of the plant residues (AOM) into water-insoluble (AOM1) and water-soluble C and N (AOM2). Mueller et al. (1998) suggested that a considerable part of the water-insoluble C and N deriving from green plant materials may be easily decomposable and should be allocated to AOM2. This is also supported by Henriksen and Breland (1999) who found that the neutral detergent soluble fraction (and not the water soluble fraction) gave a good a priori distribution of easily degradable and more stable fractions.

Between the two last sampling dates in the oil radish treatment, the slight decay of simulated N_{mic} led to an ongoing simulated N-mineralisation in the model simulations (Fig. 1). During this period, measured N_{min} and N_{mic} remained fairly constant. Simulated N_{min} clearly exceeds measured N_{min} . To some extent, this trend is also visible in the other treatments. Obviously, soil microbial biomass returns to a steady state earlier in the field than simulated by the model.

The differences between the four catch crop treatments cannot be explained by the properties of the plant materials measured before soil incorporation on 2 April 1997 (Table 1). As mentioned above, considerable parts of the plant residues decomposed before sampling in April. Hence, the data shown in Table 1 may not reflect the properties of the original plant residues. Nevertheless, subdivision of AOM into AOM1 (water insoluble) and AOM2 (water soluble) was done according to Table 1, which may have been inadequate to a certain extent.

Our findings have their biggest impact when simulating short-term turnover of C and N. Wrong predictions of subsequent crop N-uptake and N-leaching may be the consequences. In the long term, however, the exact turnover time and rate of a specific soil organic matter pool is of minor importance.

4. Conclusion

The DAISY model was able to simulate mineral N after incorporation of catch crop plant residues to some extent only. The following processes need further attention and may be integrated into models of soil C and

N turnover and in particular into the DAISY model: (1) soil tillage induced mobilisation of organic matter which can mobilise considerable amounts of organic N; (2) winter killing and increased litter loss of sensitive plant species and varieties during frost periods; (3) decomposition of plant residues at the soil surface as occurring after winter killing; (4) decomposition of easily decomposable plant residues at low temperatures, both with respect to the temperature modifier function and to the linkage of C and N turnover; (5) furthermore, reliable criteria for the subdivision of green plant residues (AOM) into AOM1 and AOM2 have yet to be developed.

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