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Calibration of the EU-Rotate_N model with measured C and N mineralization from potential fertilizers and evaluation of its prediction of crop and soil data from a vegetable field trial

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ABSTRACT

Mechanistic models are useful tools for understanding and taking account of the complex, dynamic processes such as carbon (C) and nitrogen (N) turnover in soil and crop growth. In this study, the EU-Rotate_N model was first calibrated with measured C and N mineralization from nine potential fertilizer resources decomposing at controlled soil temperature and moisture. The materials included seaweeds, wastes from the food industry, food waste anaerobically digested for biogas production, and animal manure. Then the model's ability to predict soil and crop data in a field trial with broccoli and potato was evaluated. Except for seaweed, up to 68% of added C and 54–86% of added N was mineralized within 60 days under controlled conditions. The organic resources fell into three groups: seaweed, high-N industrial wastes, and materials with high initial content of mineral N. EU-Rotate_N was successfully calibrated for the materials of industrial origin, whereas seaweeds, anaerobically digested food waste and sheep manure were challenging. The model satisfactorily predicted dry matter (DM) and N contents (root mean square; RMSE: 0.11–0.32) of the above-ground part of broccoli fertilized with anaerobically digested food waste, shrimp shell pellets, sheep manure and mineral fertilizers but not algal meal. After adjusting critical %N for optimum growth, potato DM and N contents were also predicted quite well (RMSE: 0.08–0.44). In conclusion, the model can be used as a learning and decision support tool when using organic materials as N fertilizer, preferably in combination with other models and information from the literature.

1. Introduction

Recycling of organic materials is central to the circular bioeconomy, which is high on the political agenda in Norway and the EU (Meld.St. nr. 45 (2016-2017); COM, 2015). In 2017, 99 300 Mg nitrogen (N) of mineral fertilizer was sold in Norway, and the corresponding amount for the EU was 11 600 000 Mg N (Eurostat, 2017). Organic resources contain N and other nutrients of potential fertilizer value which could replace some of the mineral fertilizer used in agricultural and horticultural production. Using N from organic resources would be positive for both environment and production in several ways: firstly, by reducing the enrichment of the biosphere with reactive N through the highly energy-demanding Haber-Bosch process (Galloway et al., 2003); secondly, by turning a waste problem into a positive resource; thirdly, by contributing to carbon (C) storage in the soil and an increase in soil quality (Loveland and Webb, 2003). Furthermore, local N sources are desirable for N-demanding vegetables, e.g., in organic cropping systems, as their use reduces the dependency on transportation of input factors.

The N fertilizer value of and N recovery from organic resources depend on how well the amount and dynamics of N mineralization from these materials match a crop's N demand. N mineralization depends on the quality of the added organic materials (AOM) and edaphic factors such as soil temperature and moisture, soil structure and texture, and soil pH. Properly calibrated and validated simulation models can help scientists and advisers to gain a better understanding of the complexity of processes involved during decomposition of organic materials and to

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Table 1

Dry matter (DM), total organic carbon (TOC), total Kjeldahl-N (TKN), ammonium-N (NH_4^+-N), nitrate-N (NO_3^--N) and C:N ratio of the organic resources.

	pH (H_2O)	DM (%)	TOC (g kg^{-1} DM)	TKN (g kg^{-1} DM)	NH_4^+-N (g kg^{-1} DM)	NO_3^--N (g kg^{-1} DM)	C:N ratio
Shrimp shell pellets (SSP)	9.2	91.8	288	71.0	0.3	<0.1	4
Shrimp shell powder (SSM)	9.4	93.2	297	73.4	6.5	<0.1	4
Commercial algal meal (AM)	6.0	89.5	336	12.0	0.1	<0.1	28
Algal meal *Laminaria digitata* (LD)	6.4	90.3	338	18.3	0.1	0.3	19
Algal meal *Saccharina latissima* (SL)	6.4	90.5	342	22.2	0.3	0.8	15
Fish sludge waste (FW)	5.7	86.0	450	69.0	2.6	<0.1	7
Meat bone meal (MBM)	6.5	94.2	432	91.6	0.4	<0.1	5
Anaerobically digested food waste (AD)	8.6	0.85	286	676.0	619	<0.1	0.5
Sheep manure (SM)	8.8	15.0	336	33.7	8	<0.1	10

predict effects of various factors on N mineralization, crop biomass and marketable yield when using organic materials as fertilizers.

Models for simulating C and N dynamics in soil differ in complexity regarding biogeochemical processes and spatial and temporal resolution. An important class of such models describe litter and soil organic matter as conceptual, homogeneous compartments decomposing at specific rates according to first-order kinetics. N mineralization is stoichiometrically linked to C mineralization from those compartments. Some of these models are included as modules of soil–plant ecosystem or soil–plant–atmosphere models designed to simulate plant growth and environmental impacts at field level (Manzoni and Porporato, 2009).

The EU-Rotate_N model is a dynamic, deterministic soil–-plant–atmosphere model developed primarily for vegetable crop rotations. The model takes account of C and N mineralization and soil organic matter dynamics, soil inorganic N, losses of N to the environment, water balance, root growth, crop growth, N uptake, marketable yield and economic return as influenced by environmental factors such as water, temperature, snow and frost and by agronomic practices, including fertilization (Rahn et al., 2010). The model is largely process-based but departs from its mechanistic orientation by introducing an empirical element when it comes to crop growth: "[….] a maximum achievable yield needs to be provided on the basis of the user's experience. This approach is considered the most feasible, considering the vast range of different crop types and morphologies among field vegetables and the resulting difficulties in applying generic photosynthesis-driven algorithms" (Nendel et al., 2013). The model has been calibrated for more than 70 vegetable and cereal species and has been tested in field studies in many parts of Europe (Rahn et al., 2010; Doltra and Muñoz, 2010; Nendel et al., 2013; Suárez-Rey et al., 2016) as well as in greenhouse studies (Guo et al., 2010; Sun et al., 2012; Soto et al., 2014). The calculation of N mineralization from organic matter in EU-Rotate_N is based on the routines used in the DAISY model (Hansen et al., 1991), which among available alternatives appears to be intermediately complex in terms of variables used to take account of microbial biomass, soil organic matter, mineralization products and the physical environment (Manzoni and Porporato, 2009). The mineralization module of EU-Rotate_N has been developed to simulate N release from soil organic matter and traditional organic fertilizers such as animal and green manures, but not from organic N resources such as industrial wastes and seaweed. Thus, the model has a potential to be further developed for locally available organic resources relevant for both organic and conventional vegetable production.

For a wide range of plant residues, there is data available on the dynamics of C and N mineralization (e.g., Jensen et al., 2005), examples of model calibration with (Henriksen and Breland, 1999b) and testing against such data (Henriksen et al., 2007) and of testing under field conditions (Henriksen and Breland, 1999a). To our knowledge, there are few studies—particularly with more comprehensive soil–crop–atmosphere models—on organic materials from the sea and recyclable wastes from the food industry, households and animal husbandry. Such studies are needed to understand how to include and make better use of these materials as fertilizers under various scenarios.

The aim of the present study was to calibrate the EU-Rotate_N model with C and N mineralization data from incubation of selected organic resources in soil at controlled temperature and moisture, and to evaluate the model performance by comparing subsequent predictions with results from a field experiment with broccoli (*Brassica oleracea*) and potato (*Solanum tuberosum*) conducted at Bodø in northern Norway. Our assumption was that waste-derived organic materials and algal meals may have decomposition patterns that differ from those of the crop residues, manure and slurries already included in the model and, therefore, require separate model calibration.

2. Materials and methods

2.1. Organic resources

In our experiment, we tested the following organic resources: 1) macro-algae (seaweeds) suitable for capturing nutrients in integrated multi-trophic aquaculture (IMTA; Wang et al., 2012; Marinho et al., 2015), *viz.*, a commercial algal meal (AM), and washed, dried and ground algal meal of *Laminaria digitata* (LD) and *Saccharina latissima* (SL), 2) industrial waste with high N concentrations, *viz.*, meat bone meal (MBM), shrimp shell powder (SSM), shrimp shell pellets (SSP) and dried fish sludge waste (FW), which was a combination of fish excrement and feed residues, 3) anaerobically digested food waste (AD) and 4) sheep manure (SM) including straw. The chemical composition of the nine waste-derived organic materials and macro-algae were analyzed by ALS Laboratory Group Norway AS, Oslo, Norway. Total Kjeldahl N (TKN) was determined according to ISO 937 and 1871 (TKN for SM was measured according to ISO 7150 -1,2/CSN 83 0530) and mineral N (NO_3^- and NH_4^+) by flow injection analysis according to local methods (SOP 8.18 A and SOP 8.64 A). The major chemical characteristics are shown in Table 1. MBM was produced by Norsk Protein AS, Mosvik, Norway. Similar MBM products have been described and tested by Jeng et al. (2004, 2006)) and Brod et al. (2012, 2014). SSP and SSM were produced by Nofima, Bergen, Norway, and Bioprawns AS, Nord-Leangen, Norway, respectively. The production process of SSP is described in Johansen et al. (2019) and the material has been tested in pot and field experiments (Øvsthus et al. 2015, 2017; Johansen et al., 2019). FW is fish sludge waste which was collected from an on-land salmon hatchery, Åsen settefisk AS (Levanger, Norway). Similar products have been described by Brod et al. (2012, 2014, 2017). MBM, FW and SS are mainly composed of protein, fat and ash (Hendriks et al., 2002, Brod et al., 2018; Ibrahim et al., 1999). AD was digested household waste from the HRA biogas plant, using technology produced by BioTek AS. The product has been described and tested in several studies (Brod et al., 2017; Möller and Stinner, 2009; Haraldsen et al., 2011). SM was from NIBIO Tjøtta, Norway. AM is a commercial product from Nordtang AS (Vestbygd, Norway), consisting mainly of the algae species *Ascophyllum nodosum*. SL and LD were collected from the shelf of the North Sea close to Bodø, washed, dried and ground. These macro-algae products are brown algae or seaweed, which vary in contents of protein

Table 2

Parameter values for the organic resources included in the EU-Rotate_N model calibration. Pool fractions are based on data from literature, and decay constants and C:N ratios are calibrated based on measured C and N mineralization from the organic resources (for explanation of their abbreviations, see Table 1).

Parameters	Units	SSP	SSM	MBM	FW	AM	SL	LD	AD	SM
Part_S (AOMs)	% of added materials	28	28	38	28	65	65	65	72	65
Part_F (AOMf)	% of added materials	72	72	62	72	35	35	35	18	25
K_Slow (AOMs)	day^{-1}	0.0002	0.0001	0.0001	0.0005	0.0001	0.0001	0.005	0.0001	0.004
K_Fast (AOMf)	day^{-1}	0.120	0.200	0.100	0.130	0.005	0.070	0.100	0.150	0.080
C:N ratio of AOMs		2.0	2.5	6.0	4.0	21.0	12.0	13.5	2.0	20.0
C:N ratio of AOMf		6.8	6.1	4.4	9.3	78.4	36.7	62.9	0.6	6.4

and amino acids, carbohydrates and polysaccharides (alginate, sulphated fucose-containing polymer, fucoidan, cellulose, alginic acid, and lamarin), minerals, lipids and fiber (Øverland et al. 2018). Literature data on the compositions of the nine organic materials were used to estimate the initial values for pool fractions included in the model (see the paragraph about model calibration).

2.2. Incubation of organic materials in soil at controlled temperature and moisture

A dark brown sandy soil (orthic humo-ferric podzol, 1% coarse sand, 38% medium sand (0.6 – 0.2 mm), 52% fine sand (0.2 – 0.06 mm), 7% silt and 2% clay, pH in water 6.1, with 2.1% total carbon (TC) and 0.17 % total N (TN)) was sampled to 0.2 m depth at random positions from the field located at the former research farm Vågønes, Norwegian Institute for Agricultural and Environmental Research, Division Bodø, Norway, where the experiment was conducted. The field had been used as cattle pasture for more than 25 years. The soil was stored at ca. 4 °C for 3 months in two black 50 L plastic pots covered with black plastic (not airtight). At the end of the storage period, the soil was air-dried at about 15℃, sifted (2 mm) and thoroughly mixed. A sample of 100 g soil was dried at 105 °C to determine its moisture content (dry weight; DW). Soil moisture of the samples to be incubated was then adjusted by addition of tap water to field capacity, which was determined previously by Haraldsen and Grønlund (1989) to be 30 % (i.e., drainable pore volume of 18% subtracted from total pore volume of 48%). Organic materials equivalent to 380 kg N ha^{-1} (when considering a 0.2 m plough layer; 0.007 g N 50 g DW $soil^{-1}$) were thoroughly mixed with 50 g DW soil and packed into 210 ml plastic cups (NorEngros AS, Norway). Unamended soil served as control. Each treatment, with or without incorporated organic materials, consisted of 15 samples, giving a total of 150 samples. The samples were placed in an incubator at day zero (Termaks B 8420S, Norway, Bergen) at 15 °C for 60 days. A water tension, corresponding to 50% of field capacity at 5 kPa, was maintained by replenishing lost water to target weight twice a week. Triplicate cups were destructively sampled at days 1, 10, 18, 39 and 60 and frozen at –18℃ for analysis of inorganic N (NH_4^+ and NO_3^-) at the Norwegian Institute of Bioeconomy Research (NIBIO, Apelsvoll Research Station, Kapp, Norway) where 40 g soil was extracted in 200 ml 1 M KCl and analyzed using a Flow Injection Analyser (FIAstar 5000, Foss Analytical AB, Sweden).

To determine C mineralization in the treatments, triplicate samples from each treatment were placed in sealed 2 L glass jars equipped with alkali traps for capturing evolved CO_2. The alkali traps consisted of 5 ml 1 M NaOH in 20 ml liquid scintillation vials. Amount and molarity of NaOH were calculated to ensure sufficient capacity for trapping evolving CO_2 throughout the closing intervals. The alkali traps were removed, sealed and replaced by fresh ones at day numbers 3, 7, 12, 19, 27, 38, 43 and 60. The C contents of the alkali solutions were analyzed at NMBU in an extraction line mixing Na_2CO_3 with 3 M H_2SO_4 in a closed mixing cell filled with glass beads, and extracting the evolving CO_2 in a stream of argon (Ar), which was flushed to an infrared gas analyzer (IRGA). Standard solutions of Na_2CO_3 dissolved in 1 M NaOH were used for internal calibration.

Carbon and nitrogen mineralization from the organic resources were estimated by subtracting CO_2-C evolved and mineral N accumulated in soils in unamended control soil from CO_2-C evolved and mineral N accumulated in soils amendment with fertilizer materials. The average of the three replicate control samples was subtracted from each of the three replicates with organic materials. Mineralization was expressed as percentages of added C or N, amounts of mineralized C or N (kg ha^{-1}) or as average C or N mineralization rates (kg ha^{-1} d^{-1}) within each time interval. As the C input data for the organic resources are not entered directly in the models' input file, but are included indirectly by multiplying added DM by a constant factor of 0.45 (personal communication with Claas Nendel 4th of April 2019), and N input is calculated from C in each pool according to equation 2, the calibration was done in terms of C and N mineralization per hectare (Fig. 4) instead of % of added C and N.

2.3. The mineralization module of EU-Rotate_N and its calibration

The mineralization module of EU-Rotate_N takes account of organic matter in three main pools: added organic matter (AOM), soil microbial biomass (SMB) and soil organic matter (SOM). Each pool is divided into two sub-pools with slow (AOMs, SMBs and SOMs) and fast (AOMf, SMBf and SOMf) decomposition rates, respectively. The decomposition follows first-order kinetics:

$$dC_x/dt = k_x C_x \tag{1}$$

where dC_x/dt is the turnover rate (kg C day^{-1}) of pool x (AOM, SMB or SOM pools), C_x is the content of carbon in pool x at time t and k is the first-order decomposition rate coefficient (decay rate constant, day^{-1}), which is fixed for each pool (Hansen et al., 1991). The decomposition rate constants are multiplied by rate-modifying coefficients, which are functions of soil temperature and moisture as estimated on a daily basis from weather data (driving variables). In the original version of EU-Rotate_N, C:N ratio and partitioning coefficient for the crop residue pools were derived from stepwise chemical digestion (Goering and Van Soest, 1970) conducted by Jensen et al. (2005), whilst for manure and slurries the parameters were taken from the DAISY model. In organic materials where decomposition already has taken place, 10% of the C is not allocated to AOMs or AOMf. The amounts of N in AOMs and AOMf are calculated from the amounts of C in the pools, in the official model version assuming a fixed C:N ratio for AOMs and that the remaining organic N resides in AOMf:

$$N_t = C_t * N/C \tag{2}$$

where N_t is the amount of N in the actual pool at time t, C_t is the amount of C in the same pool at that time, and N/C is the reciprocal of C:N ratio in the respective pool. The daily loss of N from each pool is then proportional to the turnover of its organic C and the reciprocal of its C:N ratio.

In the present study, the initial C pools of the organic resources were first set by dividing total C into AOMs (slow pool) and AOMf (fast pool) according to model default values (Rahn et al., 2010). The proportions of these pools were, respectively, 38 and 62% in non-processed materials and 72 and 18% in processed materials. For some of the added materials, this resulted in poor fit with measured C mineralization. Therefore, estimation of the initial pool sizes for all the organic materials

Table 3
Input variables used in EU-Rotate_N for model calibration and performance evaluation.

Input variable	Unit	Value
Site properties		
Latitude		67.28
Altitude		35
Soil properties		
Sand (1st layer)	%	91
Sand (2nd layer)	%	95
Sand (3rd layer)	%	95
Clay (1st layer)	%	2
Clay (2nd layer)	%	1
Clay (3rd layer)	%	1
pH (all layers)		6.1
Bulk density (all layers)	$g\ m^{-3}$	1370
Total Carbon	$g\ kg^{-1}$ DM	21
Total Nitrogen	$g\ kg^{-1}$ DM	1.7
C:N ratio		12.4
Initial Mineral N	$mg\ kg^{-1}$	10.9
Organic Matter in soil (all layers)	DM	3.8
Soil moisture content (1st layer)	$cm^3\ cm^{-3}$	0.29
Soil moisture content (2nd layer)	$cm^3\ cm^{-3}$	0.23
Soil moisture content (3rd layer)	$cm^3\ cm^{-3}$	0.19
Mineral N (1st layer, measured in field)	$kg\ ha^{-1}$	23
Mineral N (2nd layer, measured in field)	$kg\ ha^{-1}$	9
Mineral N (3rd layer, same information as 2nd layer)	$kg\ ha^{-1}$	9
Physical soil properties		
Readily evaporable water (calculated after Allen et al 1998)		9
Evaporation		0.05
Drainage coefficient (unknown)		0
Vol.% water at Field Capacity (1st layer)		30
Vol.% water at Field Capacity (2nd layer)		17
Vol.% water at Field Capacity (3rd layer)		12
Vol.% water at Permanent wilting point (1st layer)		9
Vol.% water at Permanent wilting point (2nd layer)		6
Vol.% water at Permanent wilting point (3rd layer)		5
Vol.% water at Saturation (1st layer)		48
Vol.% water at Saturation (2nd layer)		50
Vol.% water at Saturation (3rd layer)		49

included in the model calibration was instead done *a priori* based on literature values on the biochemical quality of the AOM pools, which is hemicellulose- and cellulose-like (AOMs pool) and soluble components (AOMf pool). It was difficult to find literature values for AM and SSP. Therefore, pool sizes for AM were set equal to those of LD and SL. Thus, for all brown algae, AOMs and AOMf were set at 65 and 35%, respectively. SSP pool sizes were set equal to those for SSM, due to its similar chemical composition, even though other fractionation alternatives resulted in a better shape of the curve and statistical indices for SSP. The partitioning of initial C is shown in Table 2.

The model calibration was then done by adjusting the values of the decomposition rate coefficients (k in equation 1 for fast and slow pools, respectively) and the C:N ratio of each pool (CN_slow and CN_fast) to obtain the best possible fit between simulated and measured values of C and N mineralization from the added resources. First, decomposition rate coefficients (k) for AOMs and AOMf of the materials were adjusted by trial and error until simulated C mineralization in the incubation experiment upon visual examination was considered to give the best possible representation of the measured values (both absolute level and shape of the time series). Four statistical indices were then used to possibly improve the match further (see Section 2.6 below for details). Next, the C:N ratios of AOMs and AOMf for each organic material were adjusted to achieve the best possible fit, as judged both visually and statistically, between simulated and measured N mineralization. No fixed constraint was set on the range of the estimated parameter values, but values were kept within limits considered realistic based on data from relevant literature. The calibrated decay rate constants and C:N ratios for the AOMs and AOMf pools of each organic material are shown in Table 2.

By first setting initial AOMs and AOMf pool sizes according to literature values, then forcing the model to simulate measured C mineralization and finally N mineralization, equifinality due to simultaneous adjustment of sizes, decay rate constants and C:N ratio of each pool was ruled out. As decay rate constants of the two pools were adjusted simultaneously, there was some room for equifinality in simulation of C mineralization. It was limited, however, by the shapes of the mineralization curves. For most materials, the same is true for C:N ratios as estimated by fitting simulated values of N mineralization to those measured.

2.4. Model inputs for calibration and model performance evaluation

The model simulation period for the field experiment, which was conducted in 2008, 2009 and 2010, was from 1st January 2007 to 31st October 2010. The meteorological data were from a weather station located at Vågønes, Bodø, Norway, which is located nearby the field experiment. Air temperature (°C 2 m above ground), precipitation (mm), relative humidity (%), wind speed ($m\ s^{-1}$ 2 m above ground), and global radiation ($MJ\ m^{-2}\ d^{-1}$) were included in the weather file. The model inputs include soil texture, bulk density, pH, organic matter, C:N ratio, water saturation, permanent wilting point and field capacity, initial soil moisture content and soil mineral N for three soil layers (0–0.3 m, 0.3–0.6 m and 0.6–0.9 m), and readily evaporable water values were measured in this experiment or taken from Haraldsen and Grønlund (1989). The model's runoff and snow–frost simulations were switched off. The set-up values are shown in Table 3. Further information entered in the input files on management, crop species, time of planting, date of harvesting and target DM yield, are listed in Table 4.

For the calibration of the N mineralization module, the weather input file was altered by setting fixed values of temperature to 15 °C, rain to 0.1 mm (to avoid drying out of the soil), RH 80%, wind speed to 1 $m\ s^{-1}$, 2 $h\ d^{-1}$ sunshine and global radiation 5 $MJ\ m^{-2}\ d^{-1}$ (to ensure that model can be run).

Before running the model prediction of results from the field experiment, a target DM yield was set, which means that the highest achievable yield was estimated before running the model. According to Nendel et al. (2013), this approach is the best solution considering the vast variations of crop genetics, morphology and photosynthesis, which would otherwise require the use of very complex model algorithms. Target total DM yields were set at the highest total DM obtained with mineral fertilization at 80 and 170 kg N ha^{-1} for potato and broccoli, respectively (Table 4). The model then calculated daily crop growth as a function of day degrees, soil N status, temperature and soil moisture

Table 4
Day of the year (DOY) for field management operations (tillage, fertilization, planting, harvesting and sampling) at Vågønes. Data were used in the input files for the evaluation experiment.

	Year	ploughing	Rototill & harrowing	Soil sampling spring	Soil sampling autumn	Fertilization	Transplanting	Harvesting	Target total plant DM* yield
Potato	2009	158	159	145	275	160	160	274	11.6
Broccoli	2009	158	158	145	235	159	160	226	5.7
Potato	2010	158	158	132	275	160	160	274	9.0
Broccoli	2010	140	140	132	275	160	161	219	3.9

[*] Dry matter.

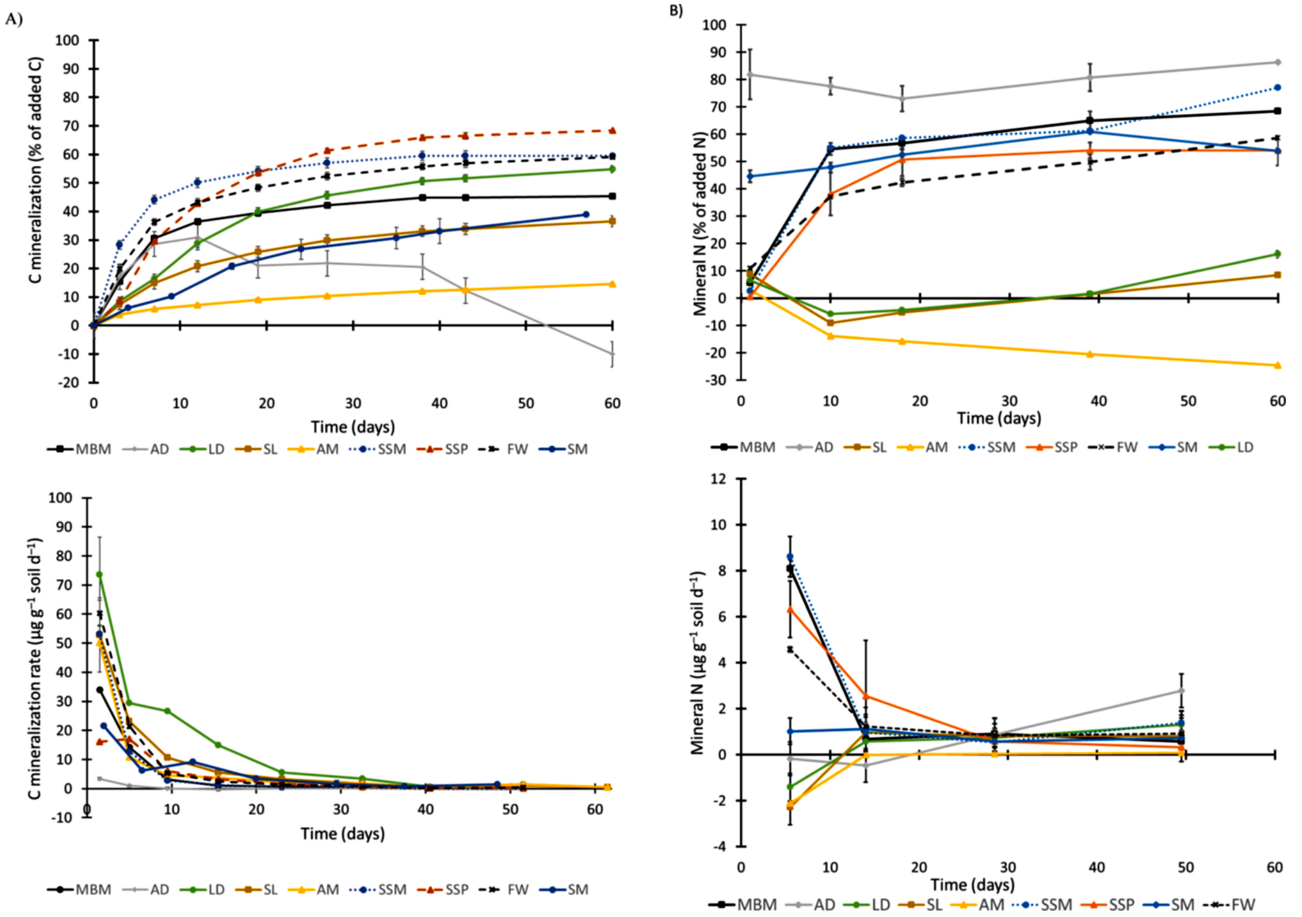

Fig. 1. Carbon mineralization (% of added C) and C mineralization rate (μg g^{-1} soil d^{-1}) (A) and N mineralization (% of added N) and N mineralization rate (μg g^{-1} soil d^{-1}) (B) from the organic resources during 60 days of incubation at 15℃ and constant soil moisture. Values are average of three replicates ($n = 3$) and bars indicate standard deviation. Abbreviations: SSP, shrimp shell pellets; SSM, shrimp shell powder; AM, commercial algal meal; LD, algal meal *Laminaria digitata;* SL, algal meal *Saccharina latissimi;* FW, fish sludge waste; MBM, meat bone meal; AD, anaerobically digested food waste; SM, sheep manure.

content.

The simulated crop growth is dependent on the crop-specific critical %N parameter, which is the lowest crop N concentration required for maximum growth during the growth period. This is expressed in relation to the total DM yield present at any time and is calculated as:

$$\text{Critical }\%\text{N} = \text{a}(1+\text{b}*\text{e}-0.26\ \text{W}) \tag{3}$$

where W is total crop DM weight (Mg ha^{-1}) and a and b are crop-specific constants (Greenwood et al., 1986). Originally, a and b for broccoli were 3.45 and 0.6, respectively, and 1.35 and 3 for potato. During the model evaluation, consistent underestimation was observed for potato yield and DM for all treatments including mineral fertilizer. Therefore, for potato the parameters of the equation 3 for critical %N was adjusted to fit the yield and DM for the mineral fertilizer treatment, resulting in a = 0.70 and b = 2.0.

The model has two strategies to calculate fresh yield: a direct conversion or a single-plant approach. The single-plant approach is for plants with a single product per plant. The fresh-weight and DM yields are calculated by using the harvest index. Direct conversion is used for crops with multiple harvests or products per plant. Marketable fresh yield is then calculated by multiplying the total DM yield by a factor that is a crop-specific, empirical function of plant-available N (Rahn et al., 2010). The predicted values presented here are those from the direct-conversion approach (lower yield was found when using the single-plant approach).

2.5. Field experiment

The field experiment has been described in detail by Øvsthus et al. (2015, 2017). In short, a three-year factorial crop rotation experiment including broccoli (*Brassica Oleracea* L. *var. Italica* cv. Marathon; first-year crop), potato (*Solanum tuberosum* L. *cv. 'Troll'*; second-year crop) and lettuce (*Lactuca sativa* L. *cv. 'Ametist'* and *Lactuca sativa* L. *cv. 'Argentinas'*; third-year crop) was set up with three replicate blocks. Four organic fertilizer materials (anaerobically digested food wastes (AD), shrimp shell pellets (SSP), sheep manure (SM) and algal meal (AM)) were applied at rates equivalent to 80 and 170 kg N ha^{-1} for broccoli, 80 kg N ha^{-1} for potato and 60 kg N ha^{-1} for lettuce, and mixed into the soil. Plots with mineral fertilizer and no fertilizer served as control plots. More information about fertilization, management and harvest dates is given by Øvsthus et al. (2015, 2017) and Table 4.

In the first year of the field experiment, broccoli was planted on biodegradable film based on corn starch (BioAgri, BioBag Norge AS, Askim, Norway) with the aim of reducing leaching and weed growth. Due to problems with dissolution and mineralization of fertilizers in the upper soil layers close to the biofilm, this practice was abandoned in the following years. Thus, the results for broccoli in 2008 were omitted as they were considered atypical as compared to those obtained in 2009 and 2010. The results for lettuce in 2010 were also omitted, as planting of two different cultivars in alternate rows led to different development of the cultivars and atypical yields.

Marketable yield, DM of yield (DM$_{\text{yield}}$), and total above-ground plant material (including tubers for potato) (DM$_{\text{total}}$), total N uptake of

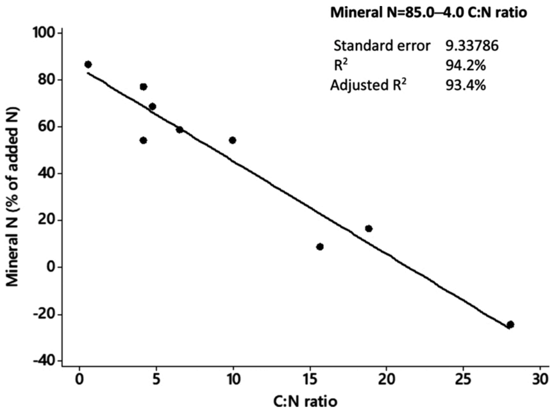

Fig. 2. Correlation between C:N ratio in the organic materials and the N mineralization after 60 days of incubation at 15°C and constant soil moisture.

Table 5
Summary of statistical parameters (see Section 2.6 for explanation) for goodness of fit between simulated and measured values of C and N mineralization (kg ha^{-1}) from nine organic resources and control soil (NF) incubated at 15℃ and constant soil moisture, as obtained by calibrating EU-Rotate_N. Values in boldface indicate that the simulation was deemed unsatisfactory according to the criteria listed in Section 2.6. For explanation of the abbreviations of the organic resources, see Table 1.

Resources	Variables (unit)	MAE	RMSE	ME	CRM
Scrimp shell pellets (SSP)	CO_2-C (kg ha^{-1})	**0.50**	**0.54**	**0.04**	**0.50**
	Mineral N (kg ha^{-1})	0.12	0.14	0.93	0.10
Scrimp shell powder (SSM)	CO_2-C (kg ha^{-1})	0.12	0.16	0.86	0.10
	Mineral N (kg ha^{-1})	0.14	0.20	0.85	0.10
Meat bone meal (MBM)	CO_2-C (kg ha^{-1})	0.09	0.12	0.93	–0.03
	Mineral N (kg ha^{-1})	0.08	0.09	0.96	–0.05
Fish sludge waste (FW)	CO_2-C (kg ha^{-1})	0.13	0.14	0.91	–0.13
	Mineral N (kg ha^{-1})	0.17	0.19	0.79	–0.17
Commercial algal meal (AM)	CO_2-C (kg ha^{-1})	0.13	0.14	0.90	–0.13
	Mineral N (kg ha^{-1})	**–0.75**	**–0.82**	**–0.56**	**–0.66**
Algal meal *Saccharina latissima* (SL)	CO_2-C (kg ha^{-1})	0.07	0.08	0.98	0.03
	Mineral N (kg ha^{-1})	**4.04**	**5.37**	0.53	–0.21
Algal meal *Laminaria digitata* (LD)	CO_2-C (kg ha^{-1})	0.04	0.05	0.99	0.00
	Mineral N (kg ha^{-1})	**1.22**	**1.54**	0.69	0.07
Anaerobically digested food wastes (AD)	CO_2-C (kg ha^{-1})	**0.66**	**0.93**	**–0.37**	0.06
	Mineral N (kg ha^{-1})	0.13	0.23	**–0.53**	–0.12
Sheep manure (SM)	CO_2-C (kg ha^{-1})	0.10	0.12	0.97	0.10
	Mineral N (kg ha^{-1})	0.23	0.27	**–5.51**	–0.23
No fertilizer (NF)	CO_2-C (kg ha^{-1})	0.19	0.26	0.90	–0.20
	Mineral N (kg ha^{-1})	**0.41**	**0.41**	**–1.09**	**–0.40**

above-ground plant material (including potato tubers) (N_{total}) were recorded for broccoli and potato. Soil mineral N contents (N_{soil}) in the 0–0.3 and 0.3–0.6 m soil layers were measured before planting and after harvest. Harvesting criteria and determination of yield, DM and N contents are described by Øvsthus et al. (2015, 2017).

2.6. Statistical evaluations

The goodness of fit between simulated and measured C and N mineralization values in the calibration experiment and prediction of observed crop data in the field trial were evaluated statistically. In the field trial, each crop was considered individually (not as a whole rotation). The evaluation included yield, DM, and N contents for each replicate in each of two years. To evaluate both the model calibration and the prediction of data from the field trial, mean absolute error (MAE) (Willmott, 1982), root mean square error (RMSE) (Willmott, 1982), model efficiency (ME) (Nash and Sutcliffe, 1970), and coefficient of residual mass (CRM) (Loague and Green, 1991) were chosen as indices:

$$\mathrm{MAE} = \frac{\frac{1}{n}\sum_{i=1}^{n}|P_i - O_i|}{\overline{O}_n} \tag{4}$$

$$\mathrm{RMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}}{\overline{O}_n} \tag{5}$$

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}_n\right)^2} \tag{6}$$

$$\mathrm{CRM} = \frac{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)}{\overline{O}_n} \tag{7}$$

where P_i is the simulated or predicted value and O_i is the measured or observed value at the i^{th} sampling instance ($i = 1, 2, \ldots, n$), and $\overline{O}_n$ is the average of observed values. In the calibration experiment, O_i is the average of three replicates whereas in the model evaluation experiment, O_i represents each of three replicates. Additionally, for the field experiment, the percent bias was calculated:

$$\%\ \text{bias} = (O_i - P_i) * 100\% / O_i \tag{8}$$

MAE and RMSE include the difference between simulated and measured values, and the closer they are to zero, the better is the goodness of fit. ME compares the difference between simulated and measured values against the variance of the measured values over a period. The value ranges from minus infinite to 1, where 1 indicates a perfect fit. If the values are negative, the simulated results are worse than using the mean of the measured data. CRM and % bias indicate a tendency of overestimating (positive values) or underestimating (negative values) the measured data. For a perfect model, fit the values should be equal to zero. During the calibration, achieving the values of MAE < 0.3, RMSE < 0.3, ME > 0.5 and $-0.3 <$ CRM < 0.3 was considered acceptable, and further parameter adjustment was then stopped. For evaluation of the predictions of measured data in the field trial, the same ranges of target values were used for the statistical indices.

3. Results

3.1. Incubation of organic resources in soil at 15 °C and constant temperature

During incubation of the organic resources (Table 1) in soil, initial C mineralization differed substantially between treatments but eventually converged towards slower rates after about 20 days. Overall,

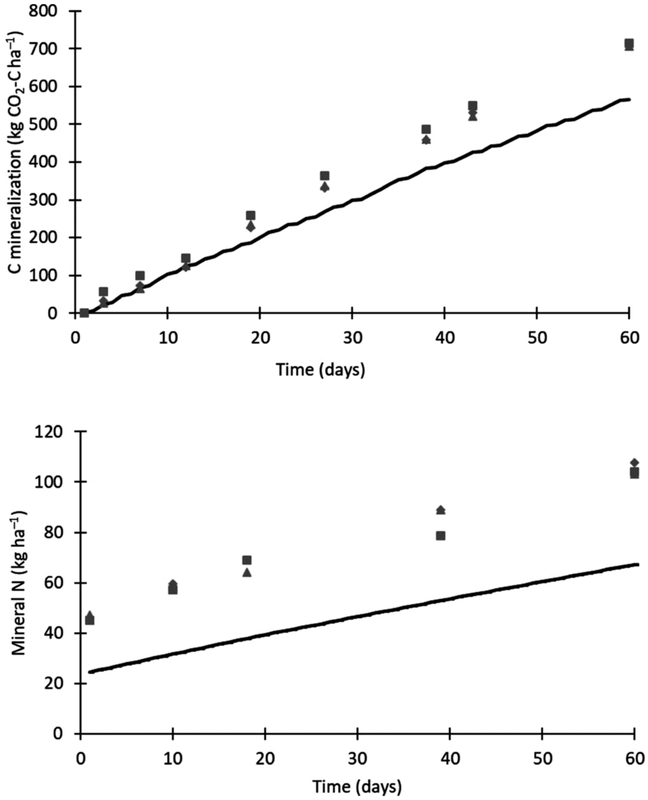

Fig. 3. Simulated (lines) and measured (dots) rates of CO_2-C evolution and mineral N accumulation in soil without added organic resources.

mineralization of added C, as calculated by the difference method, ranged from –10 to 68% after 60 days (Fig. 1A). For N mineralization, the materials fell into the following main categories (Fig. 1B): 1) SL, LD and AM were initially immobilizing mineral N, followed by a slow release after 10 days for SL and LD but not AM, 2) SSM, SSP, MBM and FW were initially releasing mineral N rapidly, followed by a decline in release rate after 20 days, and 3) AD and SM showed high availability of mineral N initially with little change during the incubation. After 60 days, 40 to 80% of the added N was present as mineral N for all materials except LD (16%), SL (9%) and AM (–25%). There was a significant negative relationship (Fig. 2; $R^2 = 0.93$) between the C:N ratio of the organic amendment and the N mineralization (expressed as % of added N) after 60 days.

3.2. Model calibration with measured C and N mineralization data

With some exceptions, initialization and calibration of the N mineralization module of EU-Rotate_N produced reasonably good fits with the observed C and N mineralization (Table 5 and Fig. 4). For SL, LD and AM, the ME values indicated satisfactory calibrations for C mineralization (ME value ranged from 0.90 to 0.99). Fig. 4 illustrates satisfactory ME values for N mineralization for SL (ME = 0.53) and LD (ME = 0.69), but negative ones for AM. However, the MAE and RMSE values for N mineralization were far from zero for all seaweeds tested. For N-rich organic resources originating from industry (MBM, SSP, SSM and FW), MAE, RMSE and CRM were close to zero and ME close to 1 (Table 5), however, for SSP there was poor correlation (ME = 0.04) between measured and simulated C mineralization (cf. Fig. 4). For some of the other materials, it was difficult to match the measured C and N mineralization equally well by adjusting the decay rate constants and C:N ratios. For SM, calibration resulted in a satisfactory fit with measured C mineralization (ME = 0.97), but correlation indices for N mineralization were poor (ME=–5.51). For AD, the opposite was the case, with poor fit with C mineralization data (ME=–0.37). In unamended control soil, C mineralization, measured as accumulated evolution of CO_2-C, was slightly underestimated, particularly towards the end of the experiment (Fig. 3). The measured mineral N in control soil was underestimated already at day zero, and the further accumulation of mineralization was so as well.

3.3. Evaluation of model performance against crop data from the field trial

Predicted and mean observed values for broccoli and potato yield, DM of yield (DM_{yield}) and total plant material (DM_{total}), N in the entire plant (N_{total}), and soil mineral N (N_{soil}) are presented in Table 6 and for broccoli fertilized with 80 kg N ha^{-1} in Appendix Table A1. The statistical indices describing goodness of fit are given in Table 7 and Appendix Table A2. The measured values for broccoli responded significantly to the type of organic resource and the N fertilizer rate, whereas potato did not. The yields were within the expected range for both crops and are presented in detail by Øvsthus et al. (2015 and 2017). The adjustment of critical %N (see the Materials and Methods section) improved the statistical agreement for potato. ME-values for N_{total}, DM_{yield} and DM_{total} were improved from negative to positive (0.34, 0.44 and 0.39). For broccoli, when using default critical N% values, ME values ranged from 0.53 to 0.62 for DM_{yield}, DM_{total} and N_{total}.

In general, the model tended to underestimate the observed potato and broccoli data, as indicated by negative CRM values. Broccoli and potato fertilized with mineral fertilizer, AD, SSP and SM, and some of the AM-fertilized potato had MAE and RMSE values close to zero (lowest for mineral fertilizer, AD and SSP). Also, the correlation indices (ME) for AD, SSP and SM showed approximately the same patterns as for broccoli and potato with mineral fertilizer, and for AM in potato. For unfertilized (NF) broccoli, there was a substantial lack of fit, but the predictions of observed potato values were satisfactory.

The percentage bias (equation 8) between predicted and observed values for fresh-weight yield was 19% for broccoli fertilized with mineral fertilizer at 170 kg N ha^{-1}, while for potato at 80 kg N ha^{-1}, it was 11% (Table 7). The corresponding bias values for the organic fertilizers ranged from 1 to 49% in the order of AD < SSP < SM < AM < NF for broccoli and from 2 to 21% in the order of AD = SM < SSP < AM < NF for potato. The bias of DM_{total} ranged from 2 to 80% (lowest for AD and highest for AM) and from 0 to 26% (lowest for SM and highest for unfertilized) for broccoli and potato, respectively. Other noteworthy biases were found for potato and for N_{soil} in the case of broccoli, all of which were poorly predicted. These bias observations between predicted and observed values were also reflected in the other statistical indices.

4. Discussion

4.1. Model calibration with measured C and N mineralization

The markedly different patterns of C and N mineralization from the organic materials fell into three groups similar to those identified by Jensen et al. (2005) in a similar, but more comprehensive study on plant residues. The first group consisted of the very N-rich materials of industrial origin (MBM, SSP, SSM and FW), which showed high initial C and N mineralization rates in accordance with results obtained in experiments with similar organic materials (Brod et al., 2012, 2014, 2017; Jeng et al., 2004, 2006; Thuriès et al., 2001, Cayuela et al., 2009). The calibrations were successful for MBM, SSM and FW, but it was difficult to match simulated with measured C mineralization for SSP, as the model does not explicitly include effects of physical quality of the organic materials other than indirectly through fractionation into slow and fast pools and adjustment of their decay rate constants. Despite being similar in chemical composition, the pelleted shrimp shell product SSP showed lower initial C mineralization rate than the powdered SSM. Also, N mineralization differed. These differences can most likely be explained

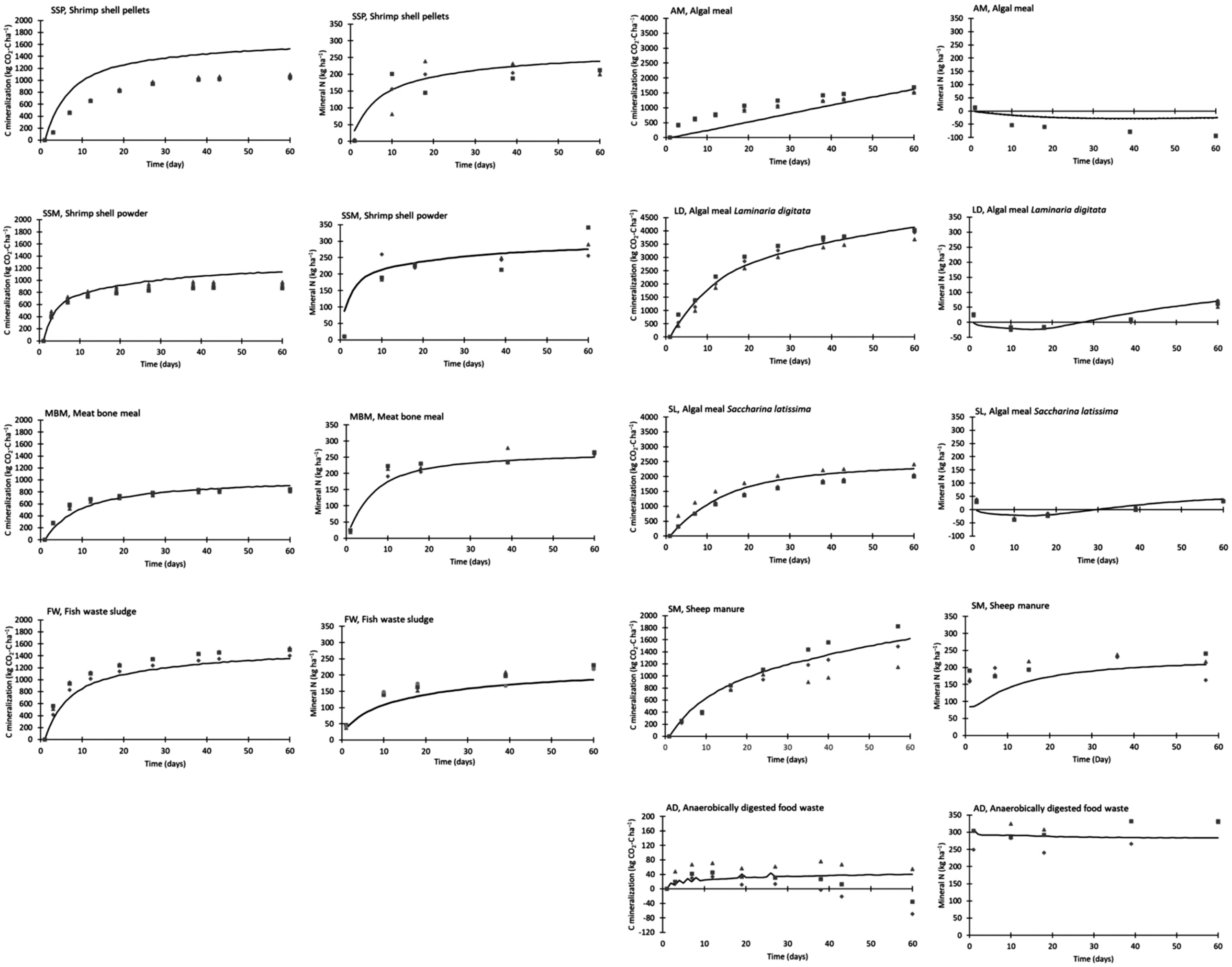

Fig. 4. Measured (replication dots: □, Δ and ◇) and simulated (lines) C and N mineralization (kg ha^{-1}) from organic resources during 60 days of incubation at 15 °C and constant soil moisture.

by the physical properties of the pellets compared to those of powder. Pellets has a much smaller surface area, which most likely makes pellets more resistant to microbial attack. Moreover, pellets may create concentrated hotspots of organic material in the soil, which may lead to locally anoxic conditions favoring N dissimilation by denitrification (Cabrera et al., 1994; Breland, 1994; Johansen et al., 2019).

The second group of organic materials comprised the brown algae materials, which showed initial immobilization of N followed by a slow mineralization. The partitioning of C to the fast pool AOMf, guided by the amounts of structural compounds in brown algae as taken from the literature (Øverland et al., 2018; Schiener et al., 2015), seems to be adequate for SL and LD, however, not for AM. The decay rate constants for AOMf estimated by calibration ranged from 0.005 to 0.100, lowest for AM and highest for LD. The low k values for AM are atypical, whereas the estimates of the decay rate constants for SL and LD are similar to the values used for plant residues with low decomposability (Mueller et al., 1997; de Neergaard et al., 2002). The atypically low value for AM may be due to biochemical properties not accounted for, but N-limitation may also be a factor, as very low concentrations of inorganic N were measured in soil with AM. Henriksen and Breland (1999c) found that C mineralization from straw was substantially reduced when soil inorganic N became depleted by microbial immobilization and introduced in their model a rate-modifying factor reducing the decay rate constant of structural material (cellulose and hemicellulose) under N-limiting conditions. The EU-Rotate_N model has a similar routine, but it might not be restrictive enough for the conditions in our experiment. The chosen pool sizes and calibrated decay rate constants resulted in satisfactory simulation of cumulative CO_2-C evolution from SL and LD, but not from AM (Fig. 4). The atypically low k value that had to be set for AOMf of AM in order to match C mineralization towards the end of the incubation period, resulted in a linear increase in amount of simulated C mineralization, whereas the measured values showed curvilinearity. This is consistent with the assumption that C mineralization from AM was N-limited after depletion of soil inorganic N and that the model's factor for modifying the decay rate due to N limitation may not have been restrictive enough. Simulated N mineralization from LD and SL visually showed very good fits with measured values (Fig. 4). However, the statistical indices of goodness of fit were poor. The reason is that the observed values (O_i) represent or are included in the denominator of the formulae of the statistical indices (equations 4–8), and the low values for N mineralization from LD and SL, therefore, rendered their indices more sensitive to experimental error than for treatments where observed values were higher. For AM, simulated values were less negative than measured values, probably because of the low value of the AOMf decay rate constant set to match the values of accumulated C mineralization at the end of the incubation period. In addition to a likely effect of different availability of immobilizable N, as suggested above, the observed differences in C and N mineralization between AM, SL and LD were likely due to species-specific differences in chemical composition (Schiener et al., 2015), e.g., the content of polysaccharides (laminarin, mannitol, alginate, fucoidan, cellulose), monosaccharides, polyphenols, protein, ash, and total C and N. Of these, the contents of laminarin and

Table 6

Observed (O) and predicted (P) values for fresh-weight yield, DM yield (DM_{yield}) and DM of total above-ground plant materials including tubers for potato (DM_{total}), and N content in plant biomass (N_{total}) and mineral N in soil (N_{soil}) for potato and broccoli without fertilizer (NF) or fertilized with mineral fertilizer (MF), anaerobically digested food waste (AD), shrimp shell pellets (SSP), sheep manure (SM), and commercial algal meal (AM) at rates of 80 and 170 kg N ha^{-1} for potato and broccoli, respectively. Observed values are average of three replicates.

Fertilizers		Potato 2009		Broccoli 2009		Potato 2010		Broccoli 2010	
	Variables (unit)	O	P	O	P	O	P	O	P
AD	Yield (Mg ha^{-1})	41.0	40.8	10.1	10.7	31.5	30.3	6.6	6.1
	DM_{total} (Mg ha^{-1})	10.7	10.3	5.5	5.3	8.8	7.7	2.5	2.9
	DM_{yield} (Mg ha^{-1})	8.7	9.2	1.4	1.3	7.6	6.9	0.5	0.7
	N_{total} (kg N ha^{-1})	139	138	169	186	99	122	80	103
	N_{soil} (kg ha^{-1})	ND	6.0	50	12	24	43	99	79
SSP	Yield (Mg ha^{-1})	46.6	38.9	9.8	9.9	31.5	29.5	7.4	6.0
	DM_{total} (Mg ha^{-1})	12.0	9.8	5.9	4.6	8.2	7.4	3.0	2.8
	DM_{yield} (Mg ha^{-1})	9.9	8.8	1.2	1.2	7.3	6.7	0.7	0.7
	N_{total} (kg N ha^{-1})	143	124	162	144	91	120	92	95.6
	N_{soil} (kg ha^{-1})	ND	6.1	19	11	25	25	31	46
SM	Yield (Mg ha^{-1})	40.1	38.9	6.1	9.7	29.9	29.5	5.9	5.8
	DM_{total} (Mg ha^{-1})	9.9	9.8	4.8	4.5	7.3	7.4	2.6	2.6
	DM_{yield} (Mg ha^{-1})	8.3	8.8	0.8	1.2	6.6	6.7	0.5	0.7
	N_{total} (kg N ha^{-1})	111	125	107	139	73	120	72	89
	N_{soil} (kg ha^{-1})	ND	6.1	14	11	20	25	24	48
AM	Yield (Mg ha^{-1})	38.9	26.1	3.2	1.9	15.2	19.0	1.2	0.9
	DM_{total} (Mg ha^{-1})	8.2	6.4	4.8	0.8	3.2	4.7	1.1	0.4
	DM_{yield} (Mg ha^{-1})	6.9	5.9	0.5	0.2	2.8	4.3	0.1	0.1
	N_{total} (kg N ha^{-1})	91	71	77	24	41	69	19	10.9
	N_{soil} (kg ha^{-1})	ND	6	22	14	25	14	14	17
MF	Yield (Mg ha^{-1})	47.4	42.0	10.5	10.7	35.9	32.1	9.9	5.9
	DM_{total} (Mg ha^{-1})	11.6	10.6	5.6	5.4	9.0	8.3	3.6	2.9
	DM_{yield} (Mg ha^{-1})	9.5	9.5	1.3	1.3	8.0	7.3	0.8	0.7
	N_{total} (kg N ha^{-1})	156	145	181	199	100	126	117	104
	N_{soil} (kg ha^{-1})	ND	12	47	15	37	87	40	94
NF	Yield (Mg ha^{-1})	37.1	25.3	5.0	2.9	18.7	19.0	4.0	1.7
	DM_{total} (Mg ha^{-1})	9.7	6.2	4.1	1.2	5.0	4.7	1.8	0.7
	DM_{yield} (Mg ha^{-1})	8.1	5.7	0.6	0.4	4.4	4.3	0.4	0.2
	N_{total} (kg N ha^{-1})	107	67	88	32	53	66	48	21
	N_{soil} (kg ha^{-1})	ND	6	19	12	19	14	26	18

polyphenol are higher in SL compared to LD, and alginate contents are lower in SL (Schiener et al., 2015). Studies of animal digestion of brown algae suggest that a high content of polysaccharides renders the material more recalcitrant, especially in combination with phenolic compounds (Øverland et al., 2018). This might explain the lower decay constant for SL compared to LD, despite lower C:N ratio for SL.

The third group of organic materials contained SM and AD, which in absolute terms instantly and persistently showed low C mineralization rates and high mineral N availability, especially of NH_4^+-N. Expressed as percentage of added C, however, the rate of C mineralization from AD was relatively high, which is consistent with the finding that AD application to soil often leads to microbial immobilization of mineral N (Brod et al., 2017; Alburquerque et al., 2012), although no significant immobilization was observed in the present trial. Thereafter, there was a period with less CO_2 emission in AD-treated than in the control soil, leading to "negative" C mineralization for AD. This might be due to bicarbonate build-up in the AD-treated soil, which likely had a higher pH than the control soil and possibly stimulated nitrification consuming some of the produced CO_2. Moreover, small differences in C mineralization between soil with AD and control soil after the initial CO_2 flush, rendered the estimated C mineralization from AD, which was calculated by the difference between AD-treated and control soils, vulnerable to experimental error, as partly evidenced by a relatively large spread of measured values for AD (Fig. 1a). Therefore, the partitioning of C between AOMs and AOMf for AD were set at the model's default values for animal manures and slurries. For SM a somewhat larger AOMf fraction was chosen because of its content of straw. The relatively good fit between simulated and estimated C mineralization suggests that this was a right decision, but for SM, the simulated mineral N values initially are lower than the measured values. This gap might be explained by different handling and storage of manures sent to analysis and manure incubated. Some N mineralization likely took place in SM between the sampling for chemical analysis, which is the basis for the mineral N in the input file, and the start of the incubation.

The underestimated N mineralization values for unfertilized control soil might be due to N mineralization during the storage period. In unamended control soil, C mineralization, measured as accumulated evolution of CO_2-C, was slightly underestimated, particularly towards the end of the experiment (Fig. 3). The measured mineral N in control soil was underestimated already on day zero, and the further accumulation of mineralization was so as well.

4.2. Performance evaluation of the calibrated model

The yield and N uptake data of broccoli and potato used for the current evaluation experiment are discussed by Øvsthus et al. (2015, 2017). The EU-Rotate_N model predicted the observed values for crop growth, N uptake and yield quite well for broccoli using the original default values for critical %N for optimal crop growth. The ME values for broccoli with mineral fertilizer were comparable to those obtained in previous evaluations of the model's performance (e.g., Nendel et al., 2013). However, the potato yield and the other crop data could not be predicted with the model's default values for critical %N, as the model underestimated these values for all fertilizer treatments, including the predictions obtained by using the non-calibrated values for mineral fertilizer (data not shown). The adjustment of critical %N for potato increased the model's ability to simulate the potato crop variables. This approach has been used in other model evaluations (e.g., Sun et al., 2013). In an earlier model evaluation conducted in Norway, the use of default values of critical %N resulted in simulated values of yield that corresponded well with measured values for potato (Hugh Riley, personal communication). However, the critical %N for optimum growth may vary between cultivars. 'Troll' is a potato cultivar that grows fast and gives large yields with small inputs. Therefore, it seems reasonable

Table 7
Summary of statistical parameters (see explanation in Section 2.6) for goodness of fit between model-predicted and observed fresh-weight yield, DM yield (DM$_{yield}$) and DM of total above-ground plant biomass including tubers for potato (DM$_{total}$), N contents in total plant biomass (N$_{total}$) and mineral N in soil (N$_{soil}$) for broccoli and potato without fertilizer (NF) or fertilized with mineral fertilizer (MF), anaerobically digested food waste (AD), scrimp shell pellets (SSP), sheep manure (SM) or algal meal (AM) at rates of 80 and 170 kg N ha^{-1} for potato and broccoli, respectively, for three replicates in 2009 and in 2010 (n = 6). Boldface numbers indicate poor model fit according to the criteria listed in Section 2.6.

		Broccoli					Potato				
	Unit	MAE	RMSE	ME	CRM	% bias	MAE	RMSE	ME	CRM	% bias
AD	Yield (Mg ha^{-1})	0.11	0.15	0.63	0.00	–1	0.09	0.09	0.65	–0.02	2
	DM$_{total}$ (Mg ha^{-1})	0.10	0.11	0.92	0.03	–2	0.11	0.13	**0.15**	–0.07	8
	DM$_{yield}$ (Mg ha^{-1})	0.25	0.27	0.71	0.04	–5	0.11	0.13	**–0.03**	–0.01	1
	N$_{total}$ (kg N ha^{-1})	0.16	0.18	0.75	0.15	–16	0.13	0.15	**0.31**	0.09	–9
	N$_{soil}$ (kg ha^{-1})	**0.50**	**0.65**	**–0.14**	**–0.39**	39					
SSP	Yield (Mg ha^{-1})	0.26	**0.33**	**0.04**	–0.07	8	0.15	0.16	**0.38**	–0.12	12
	DM$_{total}$ (Mg ha^{-1})	0.17	0.22	0.58	–0.16	17	0.16	0.18	**0.20**	–0.15	15
	DM$_{yield}$ (Mg ha^{-1})	0.30	**0.40**	**0.32**	0.00	0	0.10	0.12	**0.46**	–0.1	10
	N$_{total}$ (kg N ha^{-1})	0.14	0.20	0.63	–0.06	–11	0.20	0.25	**0.08**	0.04	–4
	N$_{soil}$ (kg ha^{-1})	**0.46**	**0.50**	**–2.10**	0.13	–13					
SM	Yield (Mg ha^{-1})	**0.33**	**0.44**	**–15.8**	0.29	–29	0.07	0.09	0.77	0.00	2
	DM$_{total}$ (Mg ha^{-1})	0.19	0.21	0.65	–0.05	4	0.07	0.08	0.77	0.00	0
	DM$_{yield}$ (Mg ha^{-1})	**0.39**	**0.43**	**–2.99**	**0.39**	–46	0.08	0.1	0.54	0.04	–5
	N$_{total}$ (kg N ha^{-1})	0.28	**0.32**	**–0.86**	0.28	–27	**0.33**	**0.39**	**–1.85**	**0.33**	–33
	N$_{soil}$ (kg ha^{-1})	**0.70**	**0.92**	**–6.51**	**0.55**	–54					
AM	Yield (Mg ha^{-1})	**0.37**	**0.58**	**0.08**	**–0.36**	36	**0.31**	**0.36**	**0.35**	–0.17	17
	DM$_{total}$ (Mg ha^{-1})	**0.80**	**0.99**	**–1.31**	**–0.80**	80	0.29	**0.31**	0.53	–0.02	3
	DM$_{yield}$ (Mg ha^{-1})	**0.50**	**0.68**	**–0.26**	**–0.50**	50	0.26	**0.28**	0.58	0.06	5
	N$_{total}$ (kg N ha^{-1})	**0.64**	**0.82**	**–0.61**	**–0.63**	64	**0.41**	**0.44**	**–0.24**	–0.41	–6
	N$_{soil}$ (kg ha^{-1})	**0.31**	**0.51**	**–0.31**	–0.15	15					
MF	Yield (Mg ha^{-1})	0.29	**0.31**	**–3.56**	–0.19	19	0.11	0.12	**0.30**	–0.11	11
	DM$_{total}$ (Mg ha^{-1})	0.14	0.16	0.57	–0.10	10	0.09	0.10	**0.44**	–0.09	8
	DM$_{yield}$ (Mg ha^{-1})	0.18	0.24	0.53	–0.06	5	0.07	0.08	**0.39**	–0.04	4
	N$_{total}$ (kg N ha^{-1})	0.11	0.15	0.62	0.02	–2	0.21	0.21	**0.34**	0.06	–6
	N$_{soil}$ (kg ha^{-1})	**1.00**	**1.08**	**–9.23**	0.25	–25					
NF	Yield (Mg ha^{-1})	**0.49**	**0.51**	**–7.26**	**–0.49**	49	0.24	**0.32**	**0.16**	–0.21	21
	DM$_{total}$ (Mg ha^{-1})	**0.68**	**0.75**	**–2.52**	**–0.68**	68	0.27	**0.34**	**–0.04**	–0.25	26
	DM$_{yield}$ (Mg ha^{-1})	**0.43**	**0.46**	**–2.06**	**–0.43**	40	0.23	0.29	**0.13**	–0.19	18
	N$_{total}$ (kg N ha^{-1})	**0.61**	**0.65**	**–3.44**	**–0.61**	61	**0.33**	**0.39**	**–0.16**	–0.16	17
	N$_{soil}$ (kg ha^{-1})	**0.33**	**0.37**	**–1.63**	**–0.33**	33					

Table A1
Observed (O) and predicted (P) values for fresh-weight yield, DM yield (DM$_{yield}$), DM of total above-ground plant materials (DM$_{total}$), and N content in plant (N$_{total}$) and mineral N in 0–90 cm soil (N$_{soil}$) for broccoli fertilized with 80 kg N ha^{-1} of shrimp shell pellets (SSP), algal meal (AM), anaerobically digested food waste (AD) and sheep manure (SM). Observed values are average of three replicates.

Fertilizers		Broccoli 2009		Broccoli 2010	
	Variables (unit)	O	P	O	P
AD	Yield (Mg ha^{-1})	8.4	8.7	7.4	4.4
	DM$_{total}$ (Mg ha^{-1})	5.5	3.9	2.5	2.0
	DM$_{yield}$ (Mg ha^{-1})	1.1	1.0	0.6	0.5
	N$_{total}$ (kg N ha^{-1})	136	108	78	61
	N$_{soil}$ (kg ha^{-1})	16	11	31	46
SSP	Yield (Mg ha^{-1})	7.9	7.6	5.3	4.3
	DM$_{total}$ (Mg ha^{-1})	5.5	3.3	2.4	1.8
	DM$_{yield}$ (Mg ha^{-1})	1.1	0.9	0.5	0.5
	N$_{total}$ (kg N ha^{-1})	135	88	73	57
	N$_{soil}$ (kg ha^{-1})	13	11	34	31
SM	Yield (Mg ha^{-1})	5.5	7.6	4.1	4.1
	DM$_{total}$ (Mg ha^{-1})	4.3	3.3	2.3	1.7
	DM$_{yield}$ (Mg ha^{-1})	0.8	0.9	0.4	0.5
	N$_{total}$ (kg N ha^{-1})	96	88	58	54
	N$_{soil}$ (kg ha^{-1})	18	11	23	31
AM	Yield (Mg ha^{-1})	4.3	2.8	1.7	1.3
	DM$_{total}$ (Mg ha^{-1})	4.8	1.1	1.2	0.5
	DM$_{yield}$ (Mg ha^{-1})	0.6	0.3	0.2	0.2
	N$_{total}$ (kg N ha^{-1})	104	32	25	16
	N$_{soil}$ (kg ha^{-1})	28	12	18	18

Table A2
Summary of statistical parameters (see explanation in the text) for goodness of fit between model-predicted and observed fresh-weight yield, DM yield (DM$_{yield}$) and DM of total above-ground plant biomass (DM$_{total}$), N contents in total plant biomass (N$_{total}$) and mineral N in soil (N$_{soil}$) for broccoli fertilized with 80 kg N ha^{-1} of anaerobically digested food waste (AD), scrimp shell pellets (SSP), sheep manure (SM) or algal meal (AM) for three replicates in 2009 and in 2010 (n = 6). Boldface numbers indicate poor model fit.

		Broccoli				
	Unit	MAE	RMSE	ME	CRM	% bias
AD	Yield (Mg ha^{-1})	**0.37**	**0.43**	**–0.60**	–0.17	17
	DM$_{total}$ (Mg ha^{-1})	0.26	**0.32**	0.35	–0.26	26
	DM$_{yield}$ (Mg ha^{-1})	0.28	**0.36**	0.31	–0.11	12
	N$_{total}$ (kg N ha^{-1})	0.28	**0.32**	0.20	–0.21	21
	N$_{soil}$ (kg ha^{-1})	**0.43**	**0.50**	**–1.29**	0.23	–39
SSP	Yield (Mg ha^{-1})	0.15	0.18	0.51	–0.03	10
	DM$_{total}$ (Mg ha^{-1})	**0.30**	**0.37**	**0.12**	–0.03	35
	DM$_{yield}$ (Mg ha^{-1})	0.23	0.25	0.66	0.04	13
	N$_{total}$ (kg N ha^{-1})	0.24	**0.33**	**0.16**	–0.22	30
	N$_{soil}$ (kg ha^{-1})	0.16	0.21	0.81	–0.13	12
SM	Yield (Mg ha^{-1})	**0.40**	**0.44**	**–1.40**	0.26	–22
	DM$_{total}$ (Mg ha^{-1})	0.23	0.29	0.33	–0.22	24
	DM$_{yield}$ (Mg ha^{-1})	**0.33**	**0.38**	**0.00**	0.29	–17
	N$_{total}$ (kg N ha^{-1})	0.10	0.11	0.85	–0.01	8
	N$_{soil}$ (kg ha^{-1})	**0.36**	**0.43**	**–1.86**	0.06	–3
AM	Yield (Mg ha^{-1})	**0.40**	**0.53**	**–0.05**	–0.40	32
	DM$_{total}$ (Mg ha^{-1})	**0.75**	**0.91**	**–1.31**	0.75	73
	DM$_{yield}$ (Mg ha^{-1})	**0.48**	**0.65**	**–0.09**	–0.48	38
	N$_{total}$ (kg N ha^{-1})	**0.66**	**0.83**	**–0.78**	–0.66	63
	N$_{soil}$ (kg ha^{-1})	**0.34**	**0.63**	**–0.76**	–0.34	36

that it can grow with a lower N supply rate and, thus, should have a lower critical %N than other potato cultivars commonly grown in Norway. In other evaluation experiments with the EU-Rotate_N model, the model predictions have also been improved by adjusting parameters related to crop growth and critical %N for optimum growth both in field and greenhouse experiments (Sun et al., 2012; Soto et al., 2018; Suárez-Rey et al., 2016; Guo et al., 2010). Our field experiment was conducted at 67.28 N and in colder climate than in other regions where the model has been tested. It is possible that crop production at this latitude and temperature may require lower critical %N for optimum growth. However, this hypothesis has not been tested scientifically.

Provided that the adjustment of the model's critical %N for potato was justified, the model predicted the yield and crop variables quite well and better than it did for the soil N variables. The deviations between predicted and observed values were acceptable for AD, SSP and mineral fertilizer. These results are within the range of other statistical evaluations of the model (Nendel et al., 2013; Rahn et al., 2010; Soto et al., 2018). Nendel et al. (2013) similarly found that the model satisfactorily predicted DM and N contents of crops, but soil mineral N predictions were poor. The underestimation of soil mineral N in the present study is in accordance with other studies (Soto et al., 2018; Doltra and Muñoz, 2010). The poor correlation for AM in the evaluation experiment was in line with the poor fit (Tables 6 and 7) between simulated and measured C and N mineralization under controlled temperature and moisture conditions (Fig. 4 and Table 5). For AD, the model prediction of crop data was relatively insensitive to the setting of pool fractions and estimation of C:N ratio in the input file and to the estimated values of the decay constants. This is because AD is a highly processed material with little decomposable C remaining and most of its N already present in inorganic form and, therefore, low C and N mineralization rates. For SM-fertilized potato and broccoli, the poor correlation between predicted and observed values may be caused by difficulties in finding homogenous fertilizer materials for both calibration and evaluation experiments.

The DM target yield input in the model is crucial for the accuracy of the model prediction. This DM target yield approach is based on the earlier models, such as N-ABLE and WELL_N (Greenwood, 2001). In the current evaluation experiment, the measured total DM yields for broccoli and potato in the various years were used to determine the DM target yield. The need to accommodate for seasonal variation in DM target yields has been suggested earlier for improving model performance (e.g. Suárez-Rey et al., 2016). This confirms the sensitivity of the model to values of input variables and illustrates that models must be used with caution, maybe in combination with other models, as a decision support tool (Palosuo et al., 2010; Rötter et al., 2012).

Model performance may also be affected by other factors than the model itself, such as pests, diseases, weeds and other factors influencing crop growth and development. However, underestimation rather than overestimation of the observed crop values makes this an unlikely cause of lack of fit in the current study. The underestimation might rather be explained by either underestimation of N mineralization or an excessively high critical %N curve. In the model, both will contribute to N-limited crop growth. In the case of AM, overestimation of N mineralization was certainly the major explanation for the poor fit between predicted and measured values.

5. Conclusions

Based on their C and N mineralization patterns, the investigated organic resources fell into three groups: organic materials of industrial origin with high N concentrations (rapid initial C and N mineralization followed by much slower one after 20 days), brown algae (moderate C mineralization and initial N immobilization followed by a slow net N release) and digestates or manures (low C mineralization and initially high mineral N content and slow or non-detectable incubation mineralization). After 60 days of incubation, 40 to 80% of added N was present as mineral N for organic materials of industrial origin, digestate and manure, whereas N mineralized from algae ranged from –25 to 16% of added N. There was a significant negative relationship between increasing C:N ratio and the amount of mineral N.

For N-rich materials of industrial origin, the calibration of the EU-Rotate_N model with measured C and N mineralization at constant temperature and moisture was good. For shrimp shell pellets (SSP), which represented this group of fertilizer materials in the model evaluation experiment, the model predicted the crop data and plant N content well, but not mineral soil N data. The EU-Rotate_N model should be further improved to include physical properties in addition to chemical properties of the organic materials.

For the brown algae LD and SL, model calibration with C and N mineralization data produced good fits with measured data, but poorer ones for AM. As AM represented this group in the evaluation experiment, the crop and soil data were poorly predicted. We therefore need more knowledge about brown algae decomposition including effects of N limitation before including them in the model.

For SM, the model could be satisfactorily calibrated with measured C mineralization, but the ability to simulate N mineralization remained poor. For AD it was opposite, with poor fits for C mineralization and satisfactory fits for mineral N, which remained at a high and stable level throughout the incubation period. Model evaluation performance on crop data and N content in plants after AD fertilization was good, but the predictions of soil N data were poor.

The newly calibrated EU-Rotate_N model can be used as a tool for understanding the mechanisms and dynamics of C and N mineralization from organic materials relevant as fertilizers. However, as a decision tool for fertilizer management for optimum yield, economic outcome and environmental impact, it should be used in combination with other models and information from the literature. The model predicted yield and crop data quite well after fertilization with organic resources of industrial origin and AD, however, soil N was difficult to predict. The model needs further development before we can recommend it as decision tool for fertilization with seaweed. Still unresolved challenges that reduce the model's value as a decision support tool is the need for setting a target yield and the supposedly variable values of critical %N among different crops and possible growing conditions.

CRediT authorship contribution statement

Ingunn Øvsthus: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Kristian Thorup-Kristensen:** Methodology, Supervision, Writing - review & editing. **Randi Seljåsen:** Methodology, Project administration, Funding acquisition. **Hugh Riley:** Resources, Writing - review & editing. **Peter Dörsch:** Methodology, Resources, Writing - review & editing. **Tor Arvid Breland:** Supervision, Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

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