MODELING

Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter–Residue Module from CENTURY

Arjan J. Gijsman,* Gerrit Hoogenboom, William J. Parton, and Peter C. Kerridge

ABSTRACT

In low-input systems, where most nutrients become available from soil organic matter (SOM) and residue turnover, the applicability of DSSAT (Decision Support System for Agrotechnology Transfer) crop simulation models is limited because (i) it recognizes only one type of SOM (i.e., humus) and recently added, but not yet humified, residue; (ii) it does not recognize a residue layer on top of the soil; (iii) newly formed humus is given a fixed C/N ratio of 10; (iv) only one litter pool is recognized for N although three are recognized for C; (v) for residues with C/N ratios <25, the three litter pools for C decompose at a rate that is independent of the residue's N concentration; and (vi) SOM and residue flows are independent of soil texture. A SOM–residue module from the CENTURY model was incorporated in the DSSAT crop simulation models, and a residue layer was added on top of the soil. Modifications were also made in the senescence module of CROPGRO, a model within DSSAT, so that senesced material is now added daily to the soil. Evaluation of the model, using a data set of 40 yr of bare fallow, showed an excellent fit [product moment correlation coefficient (*r*) of 0.983] between simulated and measured values for SOM-C. Soil N from decomposing SOM and residues was evaluated with data from a Brazilian experiment with seven leguminous residue types. By incorporating the CENTURY SOM–residue module, DSSAT crop simulation models have become more suitable for simulating low-input systems and conducting long-term sustainability analyses.

IN DEVELOPING COUNTRIES, detailed and long-term field experiments are often difficult to conduct due to financial or personnel limitations. The application of simulation models, which have been developed with data measured under more accommodating conditions and whose mathematical relationships apply to a wide range of conditions, is therefore an attractive option. However, just using an *off-the-shelf* model will not necessarily lead to results that are applicable to a local situation, especially when the model is being applied in a situation that is outside its tested range of conditions and where crucial differences in agricultural systems or environmental conditions exist.

The Decision Support System for Agrotechnology Transfer (DSSAT; Tsuji et al., 1994) is a comprehensive decision support system for assessing agricultural management options. It has been widely used in both developed and developing countries (Algozin et al., 1988; Bowen and Wilkens, 1998; Jagtap et al., 1993; Lal et al., 1993; Singh et al., 1993; Thornton and Wilkens, 1998). DSSAT version 3.5 incorporates 16 crops {maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), sorghum [*Sorghum bicolor* (L.) Moench], millet [*Pennisetum typhoides* (Burm.) Stapf & Hubb.], barley (*Hordeum vulgare* L.), bean (*Phaseolus vulgaris* L.), soybean [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), chickpea (*Cicer arietinum* L.), cassava (*Manihot esculenta* Crantz), potato (*Solanum tuberosum* L.), sugarcane (*Saccharum officinarum* L.), tomato [*Lycoersicon lycopersicum* (L.) Karsten], bahiagrass (*Paspalum notatum* Fluegge), and sunflower (*Helianthus annuus* L.)}, with several more under development. The model handles management strategies that involve crop rotations, irrigation, fertilization, and organic applications. Although crops (or cultivars) and crop management (e.g., mechanization) may differ from country to country or even from village to village, the effect of fertilizer or irrigation on crop production is likely to follow similar biophysical and biochemical pathways. However, there is an important difference between high-input and low-input agricultural systems. In the former, almost all nutrients required by crops are supplied by chemical fertilizers, whereas in the latter, nutrients become available mainly through decomposition of soil organic matter (SOM) and plant residues.

The DSSAT crop simulation models include a module for simulating SOM and residue dynamics, which is based on the PAPRAN model (Seligman and Van Keulen, 1981). Godwin and Jones (1991) adapted PAPRAN's SOM–residue section for the CERES model, one of the main crop simulation models of DSSAT (see also Godwin and Singh, 1998). This module has been called the "CERES-based SOM–residue module" and was also incorporated in the CROPGRO model of DSSAT (Boote et al., 1998).

The PAPRAN model was developed for annual pastures and small-grain crops in a semiarid environment. Its SOM–residue module, therefore, may not apply to very different systems, as Seligman and Van Keulen (1981, p. 195) state "the application of the model is

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Abbreviations: AEC, anion exchange (adsorption) capacity; FOM, fresh organic matter; FON, fresh organic matter nitrogen (or residue N); HUMN, humus nitrogen; RMSE, root mean square error; SOM, soil organic matter; SOM1, active (microbial) soil organic matter; SOM2, intermediate soil organic matter; SOM3, passive soil organic matter.

limited to situations which do not differ widely from those for which the model has been calibrated." Moreover, the rather low level of resolution of the model, with a black-box approach for many processes, raises particular concern for its application to systems where decomposing SOM and residues are the main source of nutrients for a crop. Major limitations of the CERES-based SOM–residue module are:

1. It recognizes only recently added, but not yet humified, residue [fresh organic matter (FOM)] and one type of SOM (humus). Most SOM models recognize more than just one SOM pool (Jenkinson et al., 1992; Li et al., 1994; Parton et al., 1994; Van Veen et al., 1984; Verberne et al., 1990). For example, old, almost inert, organic material with a very low turnover rate vs. young, often microbial, material with a very rapid turnover. Campbell et al. (1994) split the one-pool humus into a slowly decomposing fraction and a more rapid fraction, which resulted in a closer fit between simulated and measured data.
2. Newly formed SOM is given a fixed C/N ratio of 10. This may be a good average value, yet it is too restrictive for application to any soil and all conditions of N availability.
3. It does not account for a residue layer that is located on the soil surface. Residues either have to be incorporated, or residue that is placed on the surface is not accounted for. However, in legume-based rotational systems, which are very common in the tropics and low-input agricultural systems, a thick layer of senesced shoot parts may lie on top of the soil. Although this layer is never incorporated physically by the farmer through plowing or other land preparations, it becomes the main source of N for the following crop. Moreover, small farmers often prefer not to plow because it is labor intensive, particularly if they lack adequate equipment. In addition, incorporation of residues increases the risk for soil erosion.
4. Although the CERES-based module distinguishes three litter C pools (carbohydrates, cellulose, and lignin), there is only one litter N pool. This implicitly means that decomposition of a certain amount of lignin has the same effect on litter N as decomposition of a similar amount of cellulose or carbohydrates. In reality, these components have very different N concentrations.
5. For residues with C/N ratio <25, the three litter pools decompose at a rate that is independent of the residue's N concentration. This may be too limiting as some immobilization may still be needed for the formation of SOM from high-N residue.
6. In the CERES-based module, SOM and residue decomposition are independent of soil texture. Soil texture only affects the soil water conditions and, thus, the value of the multiplier for the SOM decomposition rate. But heavy clays are well known to protect SOM particles such as microbes, which hide in small pores (Beare et al., 1994; Hassink et al., 1993; Ladd et al., 1993; Van Veen and Kuikman, 1990).

Despite these limitations, Bowen et al (1993) reported a realistic simulation of N release from legume residues with the CERES-based module. However, Gabrielle and Kengni (1996, p. 142) reported that "the original CERES mineralization submodel did not correctly simulate N supply from potentially degradable SOM." Hasegawa et al. (1999, p. 255) stated that "the N transformation submodel substantially underestimated flushes in inorganic soil N immediately after rainfall or irrigation." This clearly demonstrates the need to improve the SOM–residue module of DSSAT crop simulation models, including CROPGRO and CERES.

In a special issue of *Geoderma* (Vol. 81, 1997), nine SOM models were evaluated with 12 long-term data sets, including inorganic fertilizer, organic manures, and different rotations. Measured and simulated data were compared using an array of statistical analysis tools. The CENTURY model (Parton et al., 1988, 1994) was among the models that performed best. It consistently produced low errors for all data sets but one, showed the lowest overall bias, and was able to simulate both low- and high-N treatments (Kelly et al., 1997; Smith et al., 1997).

Many other authors evaluated the CENTURY model under a range of conditions. Powlson et al. (1996) compared several models, including CENTURY, with long-term data sets. Paustian et al. (1992) compared different types of organic inputs with the CENTURY model. Parton and Rasmussen (1994) evaluated the performance of CENTURY with a 55-yr winter wheat experiment. Metherell et al. (1995) compared the impact of different types of tillage, and Probert et al. (1995) evaluated CENTURY for a long-term fallow experiment. Because of this extensive and detailed evaluation of the CENTURY model, as well as its wide adoption by many others, this model was a good candidate for being linked to the DSSAT crop simulation models. The main objective of this paper is to present the linkage between the DSSAT crop simulation models and the SOM–residue section from the CENTURY model and especially its implementation in the grain legume model CROPGRO.

The majority of the CENTURY evaluations dealt with SOM-C but less with N. Our prime focus for the use of the DSSAT crop simulation models with an improved SOM–module is for low-input systems that are driven by nutrients from SOM and residue decomposition. Nitrogen is thus of crucial importance. The second objective of this paper is to present an initial evaluation of the linked system models for SOM-C with a long-term (40 yr) experiment and for N with a 1-yr experiment with seven different leguminous residues as well as a control.

MATERIALS AND METHODS

Model Description

The pool and flow structure of the two modules is illustrated in Fig. 1. The CERES-based module (Fig. 1a) receives newly added residues in the pool of FOM where it is divided into 20% carbohydrates, 70% cellulose, and 10% lignin. These percentages are default values but can be changed by the user. The three pools decompose daily at a rate obtained by multiplying the potential decomposition rate by rate factors for the temperature, soil water, and C/N ratio. If the N concen-

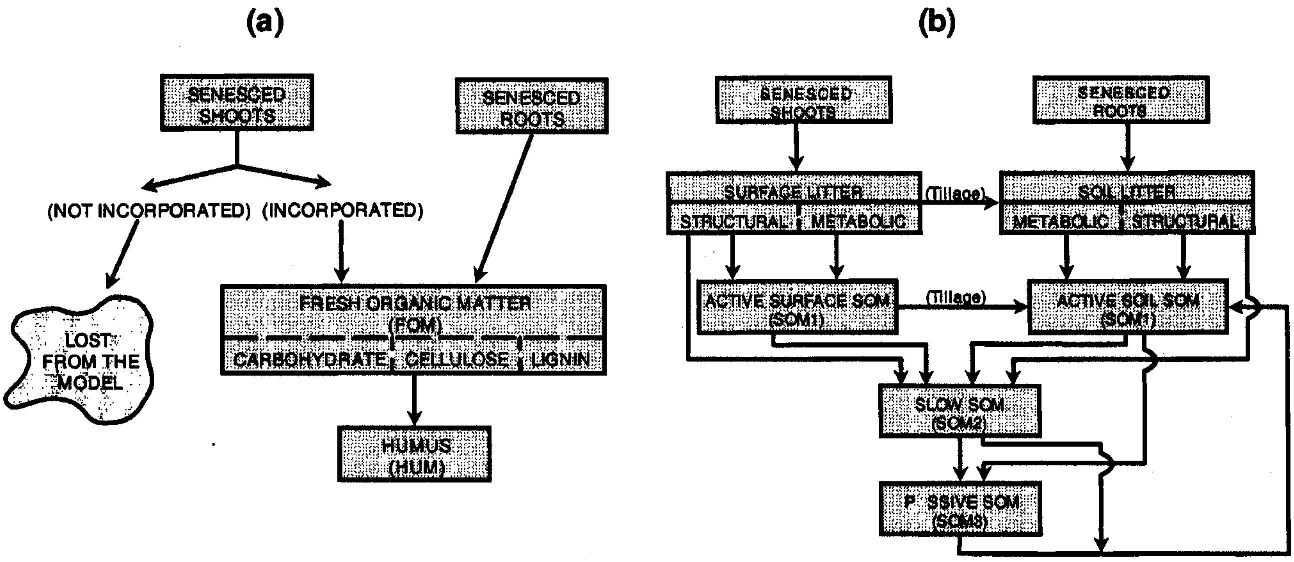

Fig. 1. The pool and flow structure of the (a) CERES-based and (b) CENTURY-based soil organic matter (SOM)–residue modules of DSSAT. Each of the decomposition flows (vertical arrows) between pools (boxes) is accompanied by either N mineralization or immobilization.

tration in the litter is <2%, N immobilization may occur. Similarly, the potential decomposition rate of the humus pool is multiplied by soil temperature and water factors. For atypical soils, an additional factor is used to either decrease or increase decomposition. During humus decomposition, no N immobilization occurs.

Immobilization of N by decomposing litter in the CERES-based module will occur if its C/N ratio is wider than 20. In the original PAPRAN model of Seligman and Van Keulen (1981), N immobilization by litter depended on the litter's *initial* C/N ratio, but in the CERES-based module of DSSAT, N immobilization depends on the litter's *actual* C/N ratio. This distinction is important because, in the latter, the critical ratio for immobilization is fixed at a value of 20 while in the original model, it depended on the type of litter entering the system. An error was found in the original DSSAT source code that stated that the litter would decompose even if there was not enough mineral N available to accommodate the immobilization. In the CERES-based module, this has been changed.

In the CENTURY-based module (Fig. 1b), organic residues are handled as either surface litter or soil litter. Both types of litter are divided into easily decomposable, metabolic materials (e.g., sugars and proteins) and recalcitrant, structural materials (e.g., lignin and other fibers). This division depends on the lignin/N ratio: metabolic fraction = 0.85 − 0.013(lignin/N). The structural material is given a fixed C/N ratio of 200, whereas the C/N ratio of the metabolic material varies with the N concentration of the litter.

After decomposition, metabolic material in the CENTURY-based module becomes part of the pool of active (microbial) SOM (SOM1), which exists in both the surface layer and in the soil (surface SOM1 and soil SOM1, respectively). Structural material is composed of fibrous material and of easily decomposable material that is encapsulated by structural fibers. The easily decomposable fraction becomes part of the surface or soil SOM1 while the fibrous fraction becomes part of the intermediate SOM pool (SOM2), which only exists in the soil. The surface or soil SOM1 decomposes into SOM2, and the soil SOM1 also decomposes into passive SOM (SOM3). The SOM2 decomposes into SOM3 or can be reactivated as soil SOM1; the SOM3 can also be reactivated as soil SOM1. All these processes are accompanied by a loss of CO_2 and by either mineralization or immobilization of N, depending on the C/N ratio of the decomposing material and the mineral N available for immobilization. Decomposition rates are, as in the CERES-based module, calculated as the potential decomposition rate multiplied by temperature and water factors and also involve factors for soil texture and cultivation, of which the latter is used to accommodate an increased decomposition rate after soil disturbance.

In the CENTURY-based module, soil texture directly affects the SOM and residue flows so that, with increasing clay content, there is:

1. A reduced decomposition rate of soil SOM1;
2. An increased partitioning of the flow out of soil SOM1 towards SOM3, and thus a reduced flow from soil SOM1 to SOM2;
3. A reduced fraction of SOM-C lost as CO_2 at decomposition; and
4. A different value for the multiplier on the optimal decomposition rate to accommodate for the effect of soil water conditions on decomposition.

Adapting the CENTURY Soil Organic Matter–Residue Module to DSSAT

For the SOM–residue section of DSSAT, two modules were developed[1]: the original CERES-based module (Gijsman et al., 2002) and a new CENTURY-based module (Gijsman and Porter, 2002). Both modules are part of the new modular version of CROPGRO (Jones et al., 2001). Though DSSAT consists of several crop models, in this paper, we only discuss the adaptation of the grain legume model CROPGRO.

We used the CENTURY version 4.0 (the so-called agroecosystem version), supplemented by updated code from versions that have not been released. Only the SOM-C and N subroutines from CENTURY were activated because the current version of CROPGRO does not handle P interactions and simulations (though P is soon to follow). CENTURY's SOM–

[1] In the new modular version of DSSAT, some variables have been renamed in a more systematic way. For example, the humus C and N content, which used to be HUM and NHUM, are now named HUMC and HUMN.

residue module was separated from the rest of the model, and its subroutines were restructured. The CENTURY model recognizes a surface litter layer and one soil layer (the top 20 cm of the soil). In DSSAT, as many as 20 soil layers can be defined; this characteristic was also applied to the CENTURY-based module.

In contrast to the monthly time intervals of the CENTURY model, the DSSAT crop simulation models use daily intervals. Decomposition rate parameters of the CENTURY-based module were thus recalculated accordingly. The CENTURY units are in g m^{-2}, whereas the DSSAT soil modules use kg ha^{-1}; these were also brought to the DSSAT standard.

The ability to simulate NH_4 was added to the CENTURY-based module so that immobilization is first *taken* from the NH_4 pool and then from the NO_3 pool while mineralized N is added to the NH_4 pool.

A new, recently developed set of equations was used for calculating the effect of soil water (Parton et al., 1996) and temperature (W.J. Parton, unpublished data, 1999) conditions on SOM and litter decomposition with the CENTURY-based module. The section on anaerobic conditions was removed.

Before conducting the decomposition of a SOM or residue pool, in the original CENTURY model, it is determined whether enough mineral N is available for the decomposition to proceed. After calculating the decomposition of this SOM–residue pool, N from mineralization is added to the soil mineral N pool, and N removed by immobilization is subtracted. Then the next SOM–residue pool is handled. This, however, means that there is a hierarchy concerning which pool has priority in accessing the mineral N. If the first pool has immobilized all N, then the pools that have lower priority cannot immobilize any more N, and thus cannot decompose. This has been changed by first calculating the net immobilization of all of the pools together, and if this is greater than the mineral N available, all immobilizing flows are reduced; the mineralizing flows can continue.

In the CENTURY-based module, soil disturbance results in a temporary enhancement of the SOM and residue decomposition rate. A new routine was added so that surface litter or surface SOM1 present on top of the soil—and already partly decomposed—will be (partly) incorporated by tillage, and thus add to the litter or soil SOM1 pool of one or more soil layers.

Parameterization

The CENTURY model includes many parameters that are stored in a *fixed-parameter* file, and users are not expected to change these parameters. All fixed parameters were recalculated to the DSSAT units, as discussed previously. One parameter value was changed to remove an inconsistency. The only new parameter needed in DSSAT for the CENTURY-based module is the long-term management history of the soil (cultivation vs. grassland, savanna, or steppe), which is used for SOM initialization. The default initial ratio SOM1/SOM2/SOM3 is 0.02:0.54:0.44 for a cultivated soil and 0.02:0.064:0.34 for a grassland soil, but it can also be set to specific values.

If no data on SOM-N are supplied, each SOM pool is initialized with its default C/N ratio: for SOM1, C/N = 10; for SOM2, C/N = 17, and for SOM3, C/N = 7. User-supplied total SOM-N data overrule these values for SOM1 and SOM2. The SOM3, which is an almost inert pool hardly affected by recent soil management or residue inputs, is left at its default C/N ratio of 7. In the CENTURY-based module, the C/N ratio of material flowing from one SOM or residue pool to another SOM pool is flexible (between a minimum and maximum value), depending on the C/N ratio of the incoming material, the C/N ratio of material allowed to enter the receiving SOM pool, and the availability of mineral N in the soil.

If the CENTURY-based module were applied with the immobilization parameters set to the values used in the original CENTURY model, a large part of the N released from the residues would be immobilized by microbes. These settings were recalibrated by modifying the minimum C/N ratio of the microbes and the critical value for the soil mineral N content at which this ratio is reached. Microbes were given a C/N ratio between 6 (conditions of ample mineral N availability) and 14 (where no mineral N is available). These values are more in agreement with the recently modified parameter settings in the CENTURY model. For this calibration, use was made of a legume experiment similar to the one used in the validation (see Experimental Data Used for Model Comparison section) but carried out in the rainy season (Bowen et al., 1993). It was checked by using one of the nine treatments [the *Cajanus cajan* (L.) Millsp. treatment] from the validation experiment. The simulated results in this paper are based on these modified parameter settings.

Senesced Material Added Daily to the Soil

The DSSAT model CROPGRO calculates daily senescence. The senesced material, however, is not added to the soil until the end of the cropping season when harvest residues are also added. When preparing the soil for a following crop, such incorporation may happen. For a simulation run that refers only to a single cropping season, senesced material is thus never added to the soil. Therefore, a surface litter layer was introduced in the CENTURY-based module. In addition, senesced material is now added daily to the soil as shoot residues decomposing in the surface litter layer or as root residues in their respective soil layers.

Experimental Data Used for Model Comparison

To validate the CENTURY-based module, two data sets were used: one for a long-term simulation of soil C and the other for a 1-yr simulation of N release from leguminous residues. The first data set was collected at the Highfield bare fallow plot located at the Institute of Arable Crops Research (IACR), Rothamsted, UK. This plot, which is located on a silty clay loam with 23.4% clay, 23% silt (2–20 μm), and 49% sand (rest is gravel), had been under grassland for several hundreds of years until it was plowed in 1959 (Jenkinson et al., 1987). Since then it has been left bare. It was plowed to 23-cm depth four times a year, with an estimated 500 kg ha^{-1} weeds per year that were plowed under. Atmospheric dry and wet N deposition plus N input by symbiosis of free-living, heterotrophic N-fixing bacteria was in the range of 40 to 50 kg ha^{-1}. Soil samples were taken in 1959, 1963, 1971, 1978, and 1987 to a depth of 23 cm and analyzed for C. The initial SOM-C content of the 0- to 23-cm layer was 76.0 t ha^{-1} (2.5% at a bulk density of 1.33 g cm^{-3}), with a C/N ratio of 12. In DSSAT, the SOM concentration for the top three soil layers (i.e., 0–5, 5–15, and 15–23 cm) was set to the same value but adapted for bulk density differences. Because the previous land use had been long-term grassland, the ratio SOM1/SOM2/SOM3 at initialization was set to 0.02:0.64:0.34 for the CENTURY-based module. Soil water retention characteristics were estimated from the texture and SOM concentration according to Rawls et al. (1982).

To evaluate the soil N component of the model, detailed data from a set of experiments conducted in the Brazilian *cerrados* (savannas) were used (Bowen et al., 1993). In this experiment, residues from leguminous green manures were added to the soil, and the pattern of mineral N in the soil at various depths was measured several times during the year. The treatments involved fallow, with or without any of seven leguminous residue types, during the (irrigated) dry season and subsequent wet season. An earlier experiment conducted at the same site (Bowen et al., 1993) was used for calibration (see Parameterization section). The soil type was a Dark Red Latosol in the Brazilian classification system, which classifies as clayey, oxidic, isothermic, Anionic Acrustox in the U.S. classification system. Soil texture was 59% clay, 22% silt, and 19% sand, and the plot had previously been under cropping, with 1.81% organic C in the topsoil. The SOM C/N ratio was not known; thus, the models' default values were used. For the CENTURY-based module, the ratio SOM1/SOM2/SOM3 at initialization was set to 0.02:0.54:0.44.

In these variable-charge soils, NO_3 leaching depends on the anion exchange (adsorption) capacity (AEC) of the soil. This parameter was not measured, but the AEC value of each soil layer was adjusted for a fallow treatment that had not received leguminous residues to fit the model's results to the measured data, as was done by Bowen et al. (1993). The same AEC values were also applied to other treatments that received residues. This fitting of the simulated data of the fallow plot to the measured values means that the estimated AEC value may implicitly correct for other inaccuracies in the model, which may have been unknown (e.g., inaccuracy in the soil temperature module, water module, and leaching module). The two modules, therefore, resulted in different AEC estimates, with rather small values for the CENTURY-based module for each successive 15-cm soil layer and bigger values for the CERES-based module, as estimated by Bowen et al. (1993):

AEC estimates for CENTURY-based module =

0.0, 0.0, 0.0, 0.1, 0.1, 0.1, 0.1, and 0.15 $cm^3\ g^{-1}$

AEC estimates for CERES-based module =

0.0, 0.0, 0.0, 0.4, 0.8, 1.0, 1.2, and 1.60 $cm^3\ g^{-1}$

Van Raij and Peech (1972) stated that the AEC value of the topsoil is generally very small (sometimes zero) and increases with depth. Estimates of AEC were thus unlikely to lead to important errors of the simulated mineral N data in the top layers of the soil, which are mainly affected by residue.

The CERES-based module requires input data to define the fraction of carbohydrates, cellulose, and lignin in residues while the CENTURY-based module requires input data on lignin. For the Brazilian experiment, the residue amounts and their N concentrations were known, but they had to be estimated for the Rothamsted experiment (which had only input of weeds). For both experiments, the carbohydrates, cellulose, and lignin fractions were set to the default values of 0.20, 0.70, and 0.10, respectively, because they were not measured during the experiment. Similar values were also used by Bowen et al. (1993) for the Brazilian experiment.

Statistical Analysis

The measured data did not include replicates. Following Whitmore's (1991) recommendation, the product moment correlation coefficient and mean difference were used as statistical analysis tools. The correlation coefficient (r) is a measure of the degree of association between simulated and measured data. The mean difference [mean difference = Σ(measured − simulated)/N] reveals a possible trend of the model to overestimate or underestimate the data (N is the number of data pairs). We also used the root mean square error {RMSE = $[\Sigma(\text{simulated} - \text{measured})^2/N]^{0.5}$}, which quantifies the dispersion between simulated and measured data (Gabrielle and Kengni, 1996; Quemada and Cabrera, 1995). Note that the RMSE is sometimes also expressed in relative instead of absolute terms, i.e., multiplying it with 100/mean of measured (e.g., Loague and Green, 1991).

THE SOIL ORGANIC MATTER–RESIDUE MODULE STRUCTURES

Soil Organic Matter Nitrogen Initialization and Carbon/Nitrogen Ratio as a Decomposition Rate Determinant

If the SOM–residue modules are initialized with the modules' default SOM-N concentrations, it may result in a very different organic N content at initialization for the two modules. In general, this is lower for the CENTURY-based module than for the CERES-based module. If the user provides the initial data, the total SOM-N at the start of the simulation is identical.

Twenty percent of the residue N that is decomposed in the CERES-based module is added to the humus pool, taking with it an amount of C that gives the newly formed humus a C/N ratio of 10. The fraction of litter C added to humus or lost to microbial respiration is thus a function of the litter's N concentration. In contrast, in the CENTURY-based module, decomposing soil litter will only become part of soil SOM1 and SOM2 if its C/N ratio after decomposition is below 14 and 20, respectively, or if it can immobilize enough N to bring (part of) the litter to such a C/N ratio; for the surface litter, these values are variable, depending on the litter's N concentration.

In the CERES-based module, the SOM decomposition rate depends only on environmental conditions and not on the humus' C/N ratio. The amount of humus that decomposes is calculated as a fraction of the humus N pool (HUMN). Thus, 100 units of SOM with 2% N mineralizes the same amount of N as 200 units with 1% N, but it gives has half as much C decomposition. In contrast, in the CENTURY-based module, the *receiving* SOM pool determines what kind of material can enter, and thus which material may decompose. This means, for example, that for the flow from SOM2 toward SOM3, mineral N availability is the rate determinant because the material goes from a pool with a relatively wide C/N ratio to a pool with a narrower C/N ratio; N immobilization may thus be needed. The flow from SOM3 toward SOM1, in contrast, goes from a pool with a relatively narrow C/N toward a pool with a wider C/N, and thus is never N limited.

Temperature and Water as Decomposition Rate Determinants

The two modules use different mathematical relationships to describe the effects of soil water conditions and soil temperature on the decomposition. For the soil temperature factor (Fig. 2a), the CERES-based module uses a linear relationship, with its optimum at 35°C or higher, while the CENTURY-based module uses a curvilinear relationship, reaching its optimum at 30°C. The soil water factor with the CERES-based module (Fig.

2b) decreases from optimal at field capacity to zero at wilting point for all layers, except for the topsoil (response not shown). The CERES-based module allows the topsoil layer to dry out to a water content below wilting point because of water evaporation from the soil surface. The equations used for this layer, however, are such that the soil water factor differs from those of the other layers, even if the soil water content is the same. The CENTURY-based module distinguishes two soil classes for the soil water factor: fine-medium and coarse (Fig. 2c). The soil water factor is at its optimum at a water-filled porosity of 60% (fine- or medium-textured soil) or 55% (coarse soil), equaling a volumetric water content of about 0.32 and 0.21 cm^3 cm^{-3}, respectively (depending on the bulk density). Above field capacity, both modules let the soil water factor decline because of the excess of available water.

Both the CERES- and CENTURY-based modules assume that the SOM decomposition rate decreases under very wet soil conditions. But, as Greenland et al. (1992) pointed out, SOM decomposition in the tropics may be sufficiently rapid so as not to be limited by poor soil aeration. The low SOM content of many wetland paddy rice soils is testimony to this suggestion (Kyuma, 1985). For such soils, both modules have to be used with caution.

Litter Decomposition

The CERES-based module calculates the daily decomposition of the three litter (FOM) pools—i.e., carbohydrates, cellulose, and lignin. It then reduces the litter C and N by the relative contribution of each pool to the total amount of litter × its fraction that decomposes. For C, this is correct, but for N, it ignores the fact that the N concentration of the three litter pools will not be the same. In the CERES-based module, fresh litter, which is relatively rich in carbohydrates, has the same N concentration as old litter of the same type, which consists mainly of lignin (unless immobilization has occurred, adding N to the litter).

From a 6-mo incubation study with various crop residues, Quemada and Cabrera (1995) concluded that allowing the user to vary the relative size of the residue (FOM) pools greatly improves the simulation compared with having fixed fractions of the three pools. The present version (3.5) of the DSSAT crop models has such flexible settings as a standard option.

Earlier calibrations and validations with the CERES-based SOM model resulted in different estimates of the decomposition rate constant of the three litter pools under nonlimiting conditions. For carbohydrates, it ranged from 0.05 to 0.8 d^{-1}; for cellulose, 0.0034 to 0.05 d^{-1}; and for lignin, 0.00095 to 0.0095 d^{-1} (Bowen et al., 1993; Quemada and Cabrera, 1995; Vigil et al., 1991). The currently used values are 0.2, 0.05, and 0.0095 d^{-1}, respectively, while for the humus pool, the rate constant is 0.000083 d^{-1}.

The pattern of residue decomposition, simulated by both modules, was similar in dry matter terms until about 80 d, after which the CENTURY-based module resulted in a slower decomposition of the remaining residues than did the CERES-based module. An example for *C. cajan*, one of the residue types from the Brazilian experiment, is shown in Fig. 3. Although the CENTURY-based module was slower in residue decomposition (Fig. 3a), it was faster in releasing N from the residues (Fig. 3b, top two lines). The CENTURY-based module calculated the metabolic fraction of the residues at 79%, based on the lignin/N ratio, but this fraction took up 98.3% of the residue's N, as the structural pool is given a fixed C/N ratio of 200. However, in the CERES-based module, no distinction is made between the N concentrations of the various residue fractions. The slowly decomposing lignin fraction, which made up 10% of the residue, thus also took up 10% of the residue N.

Although the rate of N release from the residues was faster with the CENTURY-based module than with the CERES-based module, this does not mean that this N is

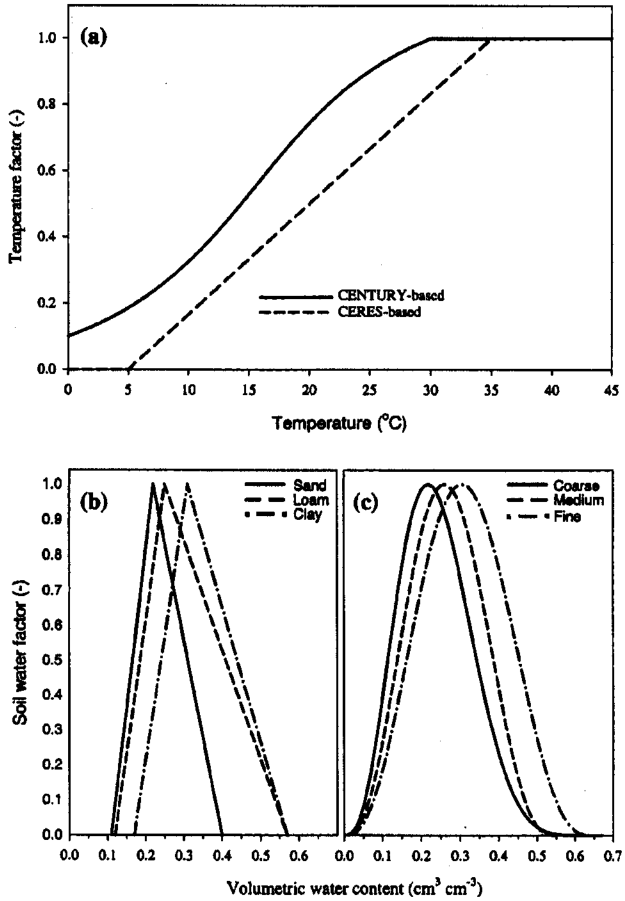

Fig. 2. (a) Soil temperature and (b and c) soil water factors in the (b) CERES-based and (c) CENTURY-based soil organic matter (SOM)–residue modules. For both modules, the curves of the soil water factor will be different for each soil as they vary with the soil water parameters field capacity and wilting point (CERES-based module) and soil texture plus bulk density (CENTURY-based module). The curves presented here are just examples. For the CENTURY-based module, "coarse," "medium," and "fine" have been given bulk densities of 1.6, 1.5, and 1.3 g cm^{-3}, respectively.

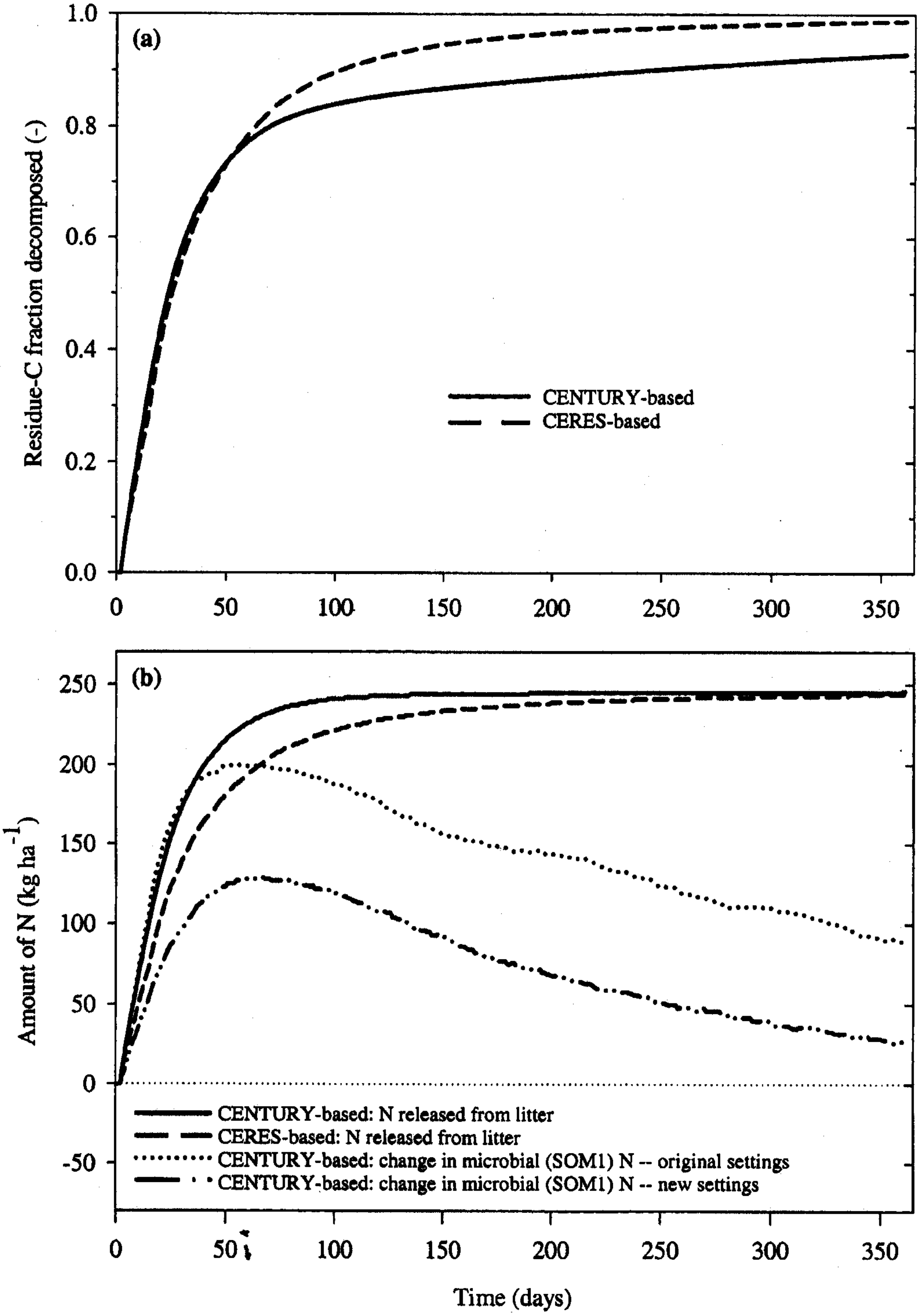

Fig. 3. (a) Decomposition pattern of *Cajanus cajan* residues as simulated with the CERES-based (dashed line) and CENTURY-based (solid line) soil organic matter (SOM)–residue modules. (b) Nitrogen mineralized from *C. cajan* residues as simulated with the CERES-based (dashed line) and CENTURY-based (solid line) SOM–residue modules, and N immobilized by microbes with the original parameter settings (dotted line) and with the modified parameter settings (dashed-dotted line), as simulated by the CENTURY-based SOM–residue module. Residues with a N concentration of 2.35% were applied at 10 495 kg ha^{-1}; they were incorporated at a 20-cm depth.

available in the soil as mineral N. With the CENTURY-based module, part of the N released from decomposing residues was immobilized by the microbial biomass, thus ending up in SOM1. This N was gradually released again after 50 to 100 d (Fig. 3b, dotted line). As described in the Parameterization section, we recalibrated the microbial N immobilization to limit its impact (dash-dot line).

The CERES-based module does not recognize a mi-

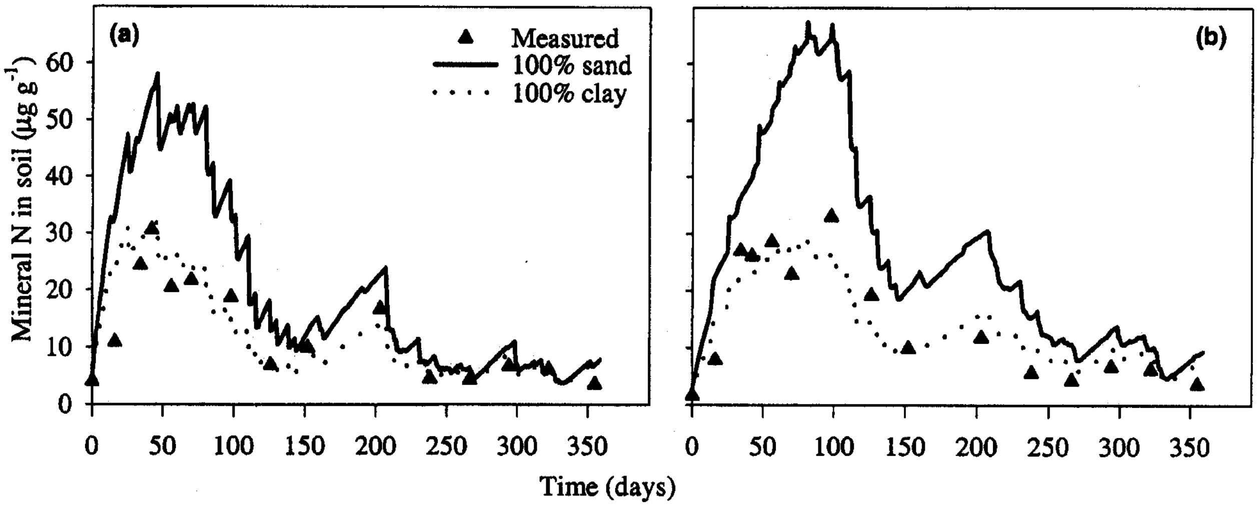

Fig. 4. Mineral N concentration of the (a) 0- to 15- and (b) 15- to 30-cm soil layers under fallow with *Cajanus cajan* residues, as measured (▲) and as simulated with the CENTURY-based soil organic matter (SOM)–residue module with the soil texture of all layers set to 100% sand (solid line) or 100% clay (dotted line). The residues applied were 10 495 kg ha^{-1} of *C. cajan* tops with a N concentration of 2.35%.

crobial biomass pool as microbes are assumed to be part of the FOM (Seligman and Van Keulen, 1981). Immobilization is then handled by adding N to the residue N pool (FON) during its decomposition, instead of adding it to the HUMN that is derived from FON. Although this is theoretically not correct, it is one way of overcoming the limitation that in the CERES-based module, the fractions of FOM and FON that decompose are the same. The residue's C/N ratio would thus always remain constant over time. Residue with a high C/N ratio would thus always remain recalcitrant to decomposition. Adding N from immobilization to FON, however, gives a gradually narrowing C/N ratio.

In the CERES-based module, a fixed 20% fraction of N from decomposing residues is transferred to the humus pool while the remaining 80% is released as mineral N. This amount may be reduced by the N needed for immobilization to bring the decomposing litter to a 2% N concentration. For SOM decomposition, there is no N immobilization in the CERES-based module. In the CENTURY-based module, net N mineralization or immobilization during SOM–residue decomposition depends on the C/N ratios of the decomposing material and of the material allowed to enter the receiving pool.

Soil Texture

In the CENTURY-based module, the flows between the various SOM–residue pools depend on the soil texture, whereas in the CERES-based module, texture does not play a role. Figure 4 shows the impact of the two extremes in soil texture—100% clay and 100% sand—on simulated pattern of soil mineral N with an example from the Brazilian experiment. For this, only the soil texture effect on the SOM–residue decomposition was taken into account. Its effect on the soil water conditions was not dealt with. This figure clearly shows the importance of accurate soil texture data for the CENTURY-based module.

EVALUATION

Long-Term Soil Organic Matter Carbon

For the long-term bare fallow experiment, the CENTURY-based module resulted in a close fit between simulated and measured SOM-C (Fig. 5), with a mean difference of 1.48 t ha^{-1} C, a RMSE of 3.36 t ha^{-1} C, and a product moment correlation coefficient (r) of 0.983. Despite the very good congruence, the shape of the curve compared with the measured values suggests that some of the rate parameters (particularly of SOM2) may have to be increased to obtain a steeper decline and the fraction of SOM3 be increased to obtain the correct platform level. There are, however, a number of other parameters that should be considered, especially for long-term experiments.

The CERES-based module did not simulate SOM-C very well and gave a poor fit to the measured data. The CERES-based module has only one SOM pool with a maximum decomposition rate of 0.000083 d^{-1}, whereas the three SOM pools in the CENTURY-based module have rates of 0.02, 0.00054, and 0.000012 d^{-1}, respectively, for SOM1 (soil pool, not the surface pool), SOM2, and SOM3. The SOM2 pool, which at initialization occupied 64% of the total SOM content, thus had a maximum decomposition rate that was almost seven times higher than that of the SOM in the CERES-based module. Even the lower maximum decomposition rate for SOM3 did not even this out as this pool occupied only 34% of the total SOM content at initialization.

One element of uncertainty is that the soil texture data that were used as inputs for the simulation were expressed in European (or ISSS) textural units, in which silt is the 2- to 20-µm class while DSSAT and CENTURY use the American unit system with silt equal to 2 to 50 µm. This not only affects the SOM decomposition process directly, as the fractions of sand and clay influence the SOM decomposition rate and the flows between pools in the CENTURY-based module, it also

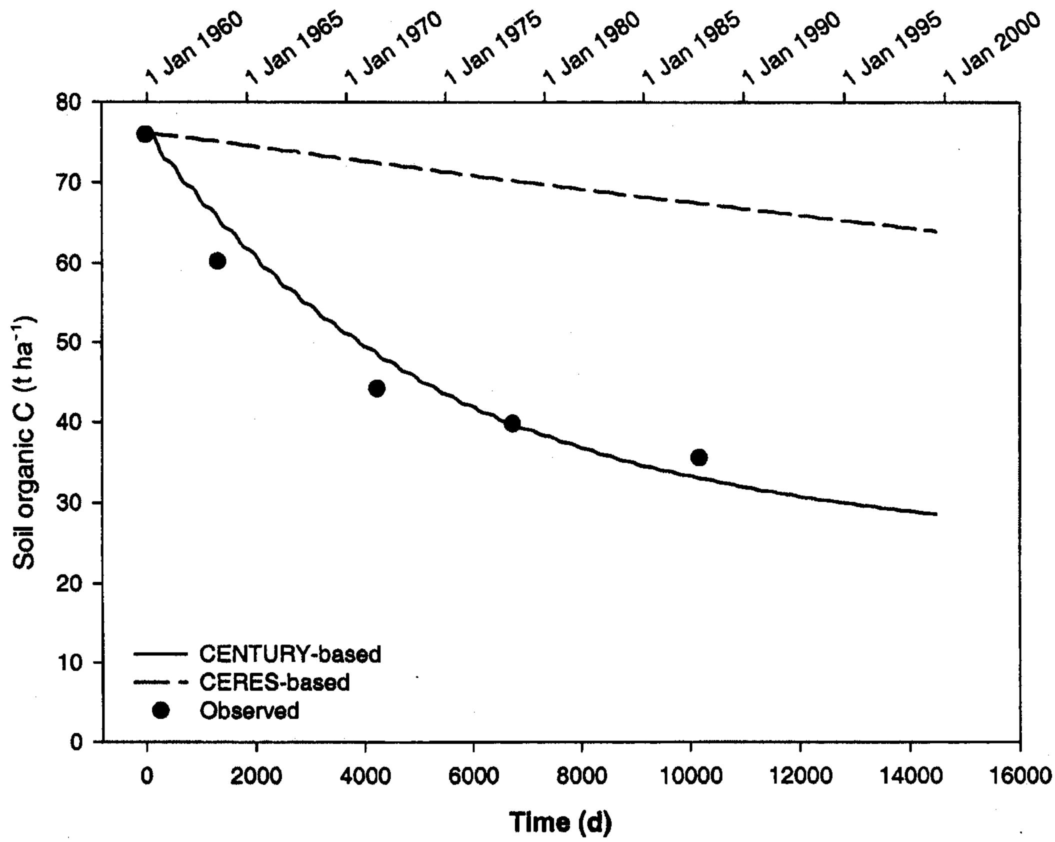

Fig. 5. Soil organic C content of the 0- to 23-cm layer of the soil under bare fallow in the Rothamsted Highfield bare fallow experiment, as simulated with the CERES-based (dashed line) and CENTURY-based (solid line) soil organic matter (SOM)–residue modules.

affects it indirectly as texture was used for estimating the soil water retention characteristics. A sensitivity analysis was conducted in which the model was run for both the measured silt (2–20 μm) fraction of 23% and an estimated silt (2–50 μm) fraction of 30% and, thus, a reduced sand fraction. This analysis showed that the percentage of silt hardly affected the results: After a simulation of 40 yr, the SOM-C level differed <95 kg ha^{-1}.

Nitrogen Profile in the Soil with Various Types of Residues

The leguminous residues in the Brazilian experiment were incorporated to a 20-cm depth while the mineral N content of the soil was measured in 15-cm increments. The top layers of the soil (0–15 and 15–30 cm) should thus be most affected by the residue application. The mineral N concentrations for these layers, as estimated by the application of the two modules to bare fallow plots and fallow plots with seven different leguminous residue types, are shown in Fig. 6. The high mineral N values between Day 30 and 70 reflect the flush of N from the decomposing residue. The second (smaller) peak around Day 200 is due to the start of the rainy season when decomposition of the remaining residue sped up again.

Both modules gave a reasonable-to-good fit between simulated data and measured data for some treatments and soil layers but a poor fit for others. The CENTURY-based module resulted in better estimations of soil mineral N for the topsoil layer of bare fallow, *C. cajan*, *Calopogonium mucunoides* Desv., *Canavalia brasiliensis* Mart. ex Benth., *Pueraria phaseoloides* (Roxb.) Benth., and *Mucuna aterrima* (Fig. 6a, 6c, 6e, 6g, 6m, and 6o) and for the 15- to 30-cm layer of bare fallow, *C. cajan*, and *M. aterrima* (Fig. 6b, 6d, and 6p). The CERES-based module performed better for both layers of *C. ensiformis* (L.) DC. and *Crotalaria striata* Aiton (Fig. 6i, 6j, 6k, and 6l) and for the deeper soil layer of *C. mucunoides* and *C. brasiliensis* (Fig. 6f and 6h).

In general, the CERES-based module provided a better simulation for mineral N for the 15- to 30-cm layer. In the topsoil layer, estimated mineral N obtained with the CENTURY-based module gave a better agreement between simulated and measured data than that from the CERES-based module as demonstrated by the statistical parameters shown in Table 1. It should be noted that the statistics point to a different conclusion than the graphical representation for some of the treatments where the CERES-based module seemed to perform better (Fig. 6i and 6k). This suggests that, though the CENTURY-based module missed the high peaks around Day 40, in general, it provided a more accurate simulation of the mineral N for the 0- to 15-cm layer. The CERES-based module simulated the main peak in mineral N but did not simulate the decrease in mineral N between Day 40 and 80 shown by the measured data,

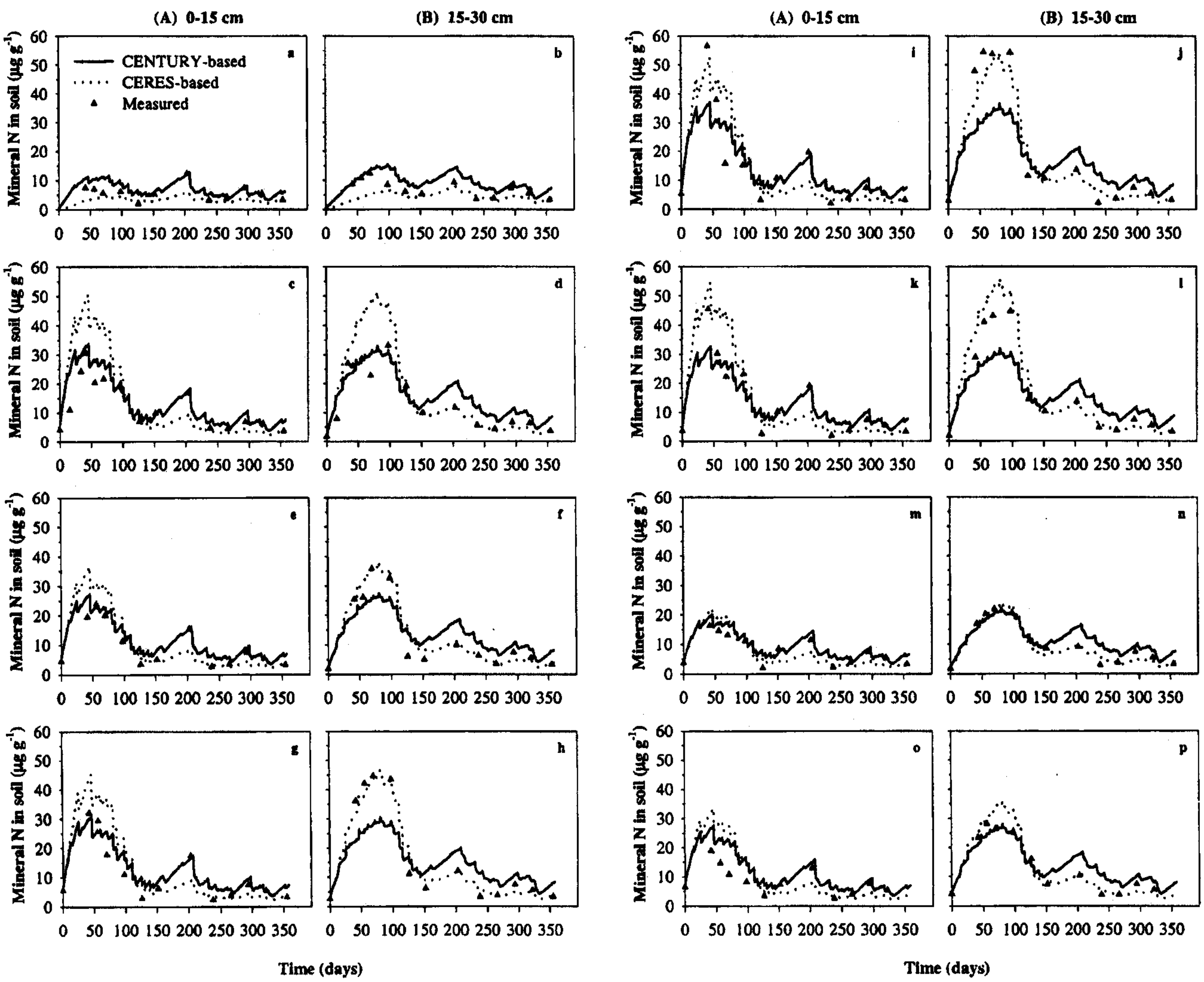

Fig. 6. Mineral N concentration of the (A) 0- to 15- and (B) 15- to 30-cm soil layers under fallow, without or with various residues, as measured (▲) and as simulated with the CERES-based (dotted line) and CENTURY-based (solid line) soil organic matter (SOM)–residue modules. The treatments applied were (a and b) bare fallow, (c and d) *Cajanus cajan* (10 495 kg ha^{-1} with a N conc. of 2.35%), (e and f) *Calopogonium mucunoides* (7586 kg ha^{-1} with a N conc. of 2.17%), (g and h) *Canavalia brasiliensis* (8214 kg ha^{-1} with a N conc. of 2.41%), (i and j) *C. ensiformis* (9514 kg ha^{-1} with a N conc. of 2.68%), (k and l) *Crotalaria striata* (12 444 kg ha^{-1} with a N conc. of 2.16%), (m and n) *Pueraria phaseoloides* (4758 kg ha^{-1} with a N conc. of 1.91%), and (o and p) *Mucuna aterrima* (5907 kg ha^{-1} with a N conc. of 2.37%).

especially for *C. striata* (Fig. 6k). The mean difference across all treatments for Day 56 and 70 was, respectively, 8.39 and 14.85 μg g^{-1} for the CERES-based module and 0.53 and 7.04 for the CENTURY-based module. The CERES-based module did not simulate the second mineral N peak around Day 200: The mean difference was −7.44 μg g^{-1} for the CERES-based module vs. 0.18 μg g^{-1} for the CENTURY-based module.

Table 1. Mean difference (Md), product moment correlation coefficient (r), and root mean square error (RMSE) of the mineral N concentration in the 0- to 15- and 15- to 30-cm soil layers, as simulated with the CENTURY-based and CERES-based soil organic matter (SOM)–residue modules. For an explanation of the treatments, see Fig. 6 caption.

	Letter in Fig. 6	CENTURY based 0–15 cm			CERES based 0–15 cm			CENTURY based 15–30 cm			CERES based 15–30 cm		
		Md	r	RMSE	Md	r	RMSE	Md	r	RMSE	Md	r	RMSE
		μg g^{-1}		μg g^{-1}	μg g^{-1}		μg g^{-1}	μg g^{-1}		μg g^{-1}	μg g^{-1}		μg g^{-1}
Bare fallow	a, b	2.04	0.78	2.69	−2.23	0.82	2.96	2.95	0.77	3.52	−2.37	0.38	3.53
Cajanus cajan	c, d	3.02	0.94	4.67	5.18	0.91	11.28	2.47	0.93	4.65	4.82	0.94	9.02
Calopogonium mucunoides	e, f	2.26	0.96	3.10	2.00	0.92	6.07	1.25	0.93	5.67	1.29	0.97	3.20
Canavalia brasiliensis	g, h	2.04	0.95	3.70	2.71	0.91	7.43	−1.49	0.95	9.37	−0.07	0.99	2.71
Canavalia ensiformis	i, j	0.49	0.90	7.71	1.21	0.87	8.61	−3.25	0.95	12.54	−1.65	0.98	5.04
Crotalaria striata	k, l	0.12	0.95	5.15	2.27	0.92	8.17	−0.89	0.96	7.84	2.56	0.99	4.48
Pueraria phaseoloides	m, n	1.90	0.95	2.53	0.27	0.89	3.27	1.84	0.93	3.31	−0.16	0.98	1.55
Mucuna aterrima	o, p	3.89	0.92	5.26	3.05	0.84	7.66	1.70	0.95	3.73	1.23	0.98	3.40

For the 15- to 30-cm layer, the statistical analysis showed similar results as the graphical representation and the CERES-based module generally performed better. The higher mean difference of the mineral N calculated by the CENTURY-based module (Table 1) was largely due to the measurements at Day 42 and 56 when the mean difference across all treatments was −6.68 and −7.54 μg g^{-1}, respectively. The CERES-based module calculated a mean difference of −0.91 and 1.04, respectively, for those dates.

For the layers below a depth of 30 cm, which were not directly affected by the added residues, the pattern of soil mineral N was mainly a function of N leaching from the top layers. The mineral N concentration at the various depths was different between the two modules (data not shown) because leaching was determined by the settings of the anion adsorption coefficients, which for the deeper layers, were different for the two modules (see Materials and Methods section). No measured data were available for anion adsorption strength, so a proper evaluation cannot be made. For the top 60 cm of the soil, the anion adsorption coefficient was set to zero for both modules; thus, the mineral N for the top two layers was not affected (Fig. 6).

Simulation of soil mineral N is inevitably prone to a larger error than simulation of soil C because mineral N is influenced by many processes besides plant uptake. Leaching, denitrification, volatilization, microbial immobilization, and adsorption onto the cation or anion adsorption complex of the soil all affect the pattern of soil mineral N. A SOM–residue decomposition model depends on the soil-water-balance and soil-temperature routines through the influence of water and temperature on the decomposition rate factor. In addition, the mineral N pattern is also affected by the impact of water and temperature on previously mentioned processes. These processes are not handled equally well by the model; therefore, soil mineral N simulation can be prone to errors. Soil C simulation does not face these problems and is thus a better measure of the quality of a SOM–residue model.

Changes in Simulated Soil Organic Matter Pools

The initial and final values of the simulated SOM pools in the 0- to 15-cm soil layer of the Brazilian experiment and the 0- to 23-cm layer of the Rothamsted experiment are shown in Table 2. In the CENTURY-based module, the most dynamic SOM pool is composed of the microbes (SOM1). These microbes feed on fresh residues or easily decomposable SOM, thereby forming new microbial biomass (SOM1) and intermediate SOM2. In the Rothamsted experiment, most of the decline of SOM simulated with the CENTURY-based module was due to losses from the SOM2 pool. The SOM2 pool decreased from from 48 645 kg ha^{-1} C at the start of the experiment to 3913 kg ha^{-1} C after 40 yr. The more resistant SOM3 pool only lost 1323 kg ha^{-1} C during this period. The C/N ratio of the total SOM decreased from 11.99 to 7.59 as the SOM3 pool that remained had a much narrower ratio than the C/N ratio of the SOM2 pool that was lost. Because the CERES-based module had only one SOM pool, the C/N ratio did not change.

In the Brazilian experiment, the CENTURY-based module simulated the largest SOM changes for the SOM2 pool, which lost between 464 and 1603 kg ha^{-1} C. The highest loss, as expected, was found in the bare fallow plot because it did not receive any residues. The SOM2 C/N ratio decreased slightly for the treatments that received legume residues. Despite the ample avail-

Table 2. Carbon and N contents and C/N ratios of the sum of all of the soil organic matter (SOM) pools (total SOM), active SOM (SOM1), intermediate SOM (SOM2), and passive SOM (SOM3) pools of the 0- to 15-cm soil layer, as simulated with the CENTURY-based SOM–residue module. Also indicated is the humus pool (HUM), as simulated with the CERES-based module. For an explanation of the treatments, see Fig. 6 caption.

	CENTURY-based module												CERES-based module		
	C				N				C/N ratio				C	N	C/N ratio
Treatment	Total SOM	SOM1	SOM2	SOM3	Total SOM	SOM1	SOM2	SOM3	Total SOM	SOM1	SOM2	SOM3	HUM	HUM	HUM
	kg ha^{-1}												kg ha^{-1}		
	Rothamsted long-term fallow														
Initialization	76 008	1 520	48 645	25 843	6 338	109	2 537	3 692	11.99	14.00	19.17	7.00	76 008	6 337	11.99
After 40 yr	28 564	131	3 913	24 520	3 765	11	244	3 510	7.59	11.80	16.07	6.99	63 960	5 347	11.96
	Brazilian legume experiment														
Initialization	27 950.9	559.0	15 093.5	12 298.4	2 700.7	55.9	887.9	1 756.9	10.35	10.00	17.00	7.00	27 951.0	2 795.1	10.00
Bare fallow	26 261.5	468.8	13 490.5	12 302.2	2 588.4	37.3	793.9	1 757.2	10.15	12.58	16.99	7.00	27 513.9	2 751.4	10.00
Cajanus cajan	27 306.0	634.2	14 340.6	12 331.2	2 675.0	55.0	857.9	1 762.1	10.21	11.53	16.71	7.00	27 839.5	2 784.0	10.00
Calopogonium mucunoides	27 122.7	610.5	14 188.4	12 323.8	2 656.0	51.0	844.2	1 760.8	10.21	11.96	16.81	7.00	27 777.1	2 777.7	10.00
Canavalia brasiliensis	27 337.4	647.0	14 361.3	12 329.1	2 673.4	55.2	856.5	1 761.7	10.23	11.71	16.77	7.00	27 851.5	2 785.1	10.00
Canavalia ensiformis	27 307.5	639.3	14 339.5	12 328.7	2 675.4	56.6	857.1	1 761.7	10.21	11.30	16.73	7.00	27 905.1	2 790.5	10.00
Crotalaria striata	27 666.78	700.0	14 629.4	12 337.4	2 699.5	60.9	875.6	1 763.0	10.25	11.50	16.71	7.00	27 943.8	2 794.4	10.00
Pueraria phaseoloides	26 810.8	559.7	13 935.1	12 316.0	2 630.6	45.4	825.7	1 759.5	10.19	12.32	16.88	7.00	27 671.3	2 767.1	10.00
Mucuna aterrima	26 933.1	579.0	14 034.9	12 319.2	2 642.6	48.3	834.2	1 760.1	10.19	11.99	16.83	7.00	27 733.2	2 773.3	10.00

ability of N-rich residues, the SOM1 C/N ratio widened somewhat, indicating that the initialization value of C/N = 10 may have been too small, as newly formed microbes had C/N ratios around 12, within the allowable range from 6 to 14. The C and N contents of the SOM3 pool were hardly affected because the SOM3 pool received little new material. Its C/N ratio therefore remained unchanged.

The CERES-based module responded far less to changes in land use for the Brazilian experiment. The HUMN content remained almost the same for the treatments that included *C. striata* residues and declined only 438 kg ha^{-1} C for the bare fallow plot. The CERES-based module's humus remained at a fixed C/N ratio of 10. The lack of a microbial pool in this module and the fixed C/N ratio of newly formed humus mean that its SOM content and composition cannot respond well to changes in residue input.

CONCLUSIONS

The CENTURY-based module did an excellent job in simulating the development of the SOM content for the long-term bare fallow experiment. The CERES-based module, which is the original SOM–residue module of the present DSSAT version, performed very poorly and clearly demonstrated that it is not suitable for long-term simulations.

For short-term simulations with fresh residues added to the field, both modules gave a fair, though inconsistent, congruence between measured and simulated data. The relatively adequate job of the CERES-based module in simulating soil mineral N is noteworthy, considering its reported limitations. However, it raises questions of how widely applicable this module is; how sensitive it is to changes in system conditions, such as SOM levels, litter type, and soil disturbance; and how it behaves with soils of very different textures.

With the incorporation of the CENTURY-based module, DSSAT has become more flexible in handling different agricultural systems and more suitable for long-term simulations. This holds particularly for low-input systems where almost all nutrients are derived from SOM–residue decomposition and systems with a litter layer on top of the soil, such as green-manure-based smallholder systems. The DSSAT models also have become more responsive to systems that have different soil texture, and they accommodate an increased decomposition rate after soil disturbance.

A thick layer of residues on top of the soil will affect the soil temperature profile and water evaporation; the same holds for topsoil loosening when the material is incorporated. There is, however, no module yet that accommodates a potential *damping* effect of surface litter or a *mulching* effect of a loosened topsoil.

A word of caution: Gijsman et al. (1996) demonstrated the limited applicability of the CENTURY model to highly weathered, strongly P-sorbing soils. This applies also for the CENTURY-based module in DSSAT (though work is underway to correct this). The CERES-based module does not handle P.

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