Modeling the incorporation of corn (Zea mays L.) carbon from roots and rhizodeposition into soil organic matter


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Abstract

Experimental data reported in the literature over the last decennium indicate that roots and rhizodeposition are important sources of carbon for the synthesis of soil organic carbon. Our objective was to verify the capability of the simulation model NCSWAP to reproduce the general conclusions from the experimental literature, and to gain some insight about the processes that control the incorporation of corn below-ground production into the soil organic matter. The model was calibrated against the experimental data gathered from a long-term field experiment located near St. Paul, Minnesota. The simulation model updated daily the soil conditions to reproduce over a 13 year period the measured kinetics of seven variables: above-ground corn production, and the total soil organic matter, soil d value, and the soil organic matter derived from corn in the 0–15 and 15–30 cm depth. The simulation gave a root-plus-rhizodeposition 1.8 times larger than stalks plus leaves. The translocation efficiency of corn-C into soil organic C at the 0–15 cm depth gradually decreased to 0.19 of the below-ground deposition. The sensitivity of below-ground photosynthate incorporation into the soil organic matter was analyzed relative to variations in the parameters that control the formation and decay of roots and rhizodeposition. Roots had a greater effect than rhizodeposition on the soil organic matter, though more photosynthates were translocated to rhizodeposition than to roots. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Roots and rhizodeposition are important sources of carbon for the synthesis of soil organic carbon (SOC). The translocation of plant C into SOC is quantitatively documented with tracer C. For example, Johnen and Sauerbeck (1977) working with 14C enriched mustard and wheat showed that tracer C in soil at harvest was 20–50% higher than that mechanically isolated from roots, and that only 20% of the 14C mineralized to CO2 originated from root respiration. Experiments with 13C require elaborate methods that limit measurements to plants maintained in growth chambers for a short period. By contrast, the different natural 13C enrichments in C3 and C4 plants facilitate the estimation in situ of the long term transformation of corn photosynthates into SOC (Cerri et al., 1985; Balesdent and Balabane, 1996; Huggins et al., 1998; Clapp et al., 2000).

The amount of SOC originating from corn increases as annual crops of corn are grown continuously. It nevertheless represents only a fraction of the corn-C incorporated into the soil as some is lost, mostly as CO2, during the decay processes of the corn residues and the SOC of corn origin. Experimental results summarized by Bolinder et al. (1999) suggest that the percentage of the below ground corn-C incorporated into SOC (range 16–30%) is higher than that from the above ground corn biomass (range 7.7–20%). The multiplicity and interdependence of C and N transformations make it difficult to appreciate the origin of the percentage range, as well as the predominance of below ground over above ground contribution, without a process oriented simulation model. Several computer models are available to describe crop growth and nutrient cycling in soil, water and plant (Molina and Smith, 1998). One such model, NCSWAP, simulates below and above ground photosynthetic input into soil layers. It distinguishes between mechanically harvested roots and rhizodeposition. Total and tracer C and N released from plant are incorporated into the soil processes as computed with the model NCSSOIL (Molina et al., 1997). These two models have been tested...
(23 references in Current Contents 1993 to date), and are registered with the Soil Organic Network of the Global Change and Terrestrial Ecosystem of the International Geosphere–Biosphere Programme.

A long-term field experiment located near St. Paul was initiated in 1980 to investigate the effect of N and tillage management on the incorporation of corn residues into the SOC. Information from this experiment documents the origin of the SOC (corn or soil), and the partition of inorganic fertilizer N between the plant and the soil fractions through the use of total and tracer elements (Clapp et al., 2000).

Our objective was to gain some insight about the processes that control the incorporation of corn below-ground production into the soil organic matter. In this paper, we focus on C transformations and a field treatment (no above-ground residues returned, no fertilizer N added) that limited inputs to the SOC from roots and rhizodeposition. We ascertained the ability of NCSWAP to reproduce the experimental data, and a sensitivity analysis was performed to quantify the influence of roots, rhizodeposition, and soil C transformations on the system over 13 years.

2. Materials and methods

2.1. Field experiment and measured data

Data were obtained from one of the 12 treatments — the chisel-plough tillage with no inorganic N addition and stover-residue plus grain removed — from a long-term continuous corn cultivation (Zea mays L.) study, which took place during the years 1980–1993 at the University of Minnesota Research and Outreach Center, Rosemount, MN (Clay et al., 1989; Clapp et al., 2000). The soil at the site is a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, mesic Typic Hapludolls). Soil depth to gravel is about 100 cm, and the climate is sub-humid. Chisel ploughing to a depth of about 17 cm was conducted annually in the fall. Soil samples were taken from 0 to 15 and 15–30 cm layers, sieved (2 mm), the retained organic debris ground and returned to the soil sample, and analyzed for δ13C value. Thus, plant organic debris are included in the SOC data. Above-ground corn production was measured annually from 1980 to 1993 (Linden et al., 2000). Specific field management, analytical techniques, and results were detailed in Clapp et al. (2000) and Linden et al. (2000).

2.2. Simulation model

The model NCSWAP simulates N and C — total and tracer — transformations and the flow of water in the soil profile (Molina et al., 1997). The above-ground plant growth is described by a generalized form of the logistic equation. It is parameterized for mass increase measured during a year (the reference year, 1981) that gave maximum production with minimal or no N and water stress. For other years on the same site with the same crop, growth is adjusted daily to account for the soil conditions (N and water availability) and air temperature. The N and C transformations are simulated by the model NCSOIL included as a subroutine in NCSWAP (Molina et al., 1983; Nicolardot et al., 1994; Hadas et al., 1998). The soil organic matter is represented in each 5 cm layer of the 100 cm deep soil profile by four pools: labile and resistant Pool I, Pool II, and Pool III. NCSWAP identifies in each soil layer the following organic debris: (1) roots and (2) rhizodeposition from the current year; (3) roots and (4) rhizodeposition from the preceding years; (5–7) three different above-ground crop residues; and (8–11) four different organic amendments. Each debris is described by two pools, each defined by its first-order decay-rate-constant and C to N ratio. NCSWAP requires several input files: the initial soil conditions, and yearly files for the driving variables (crop, management, temperature, and precipitation). The soil conditions, roots and rhizodeposition included, are updated daily or every 0.2 d during water infiltration and redistribution. The source and executable code of NCSWAP and NCSOIL with the description of the variables in the input files are available at the web site (http://www.soils.umn.edu/research/ncswap-ncsoil/).

Since this work focuses on the dynamics of roots and rhizodeposition, some specifics are given in reference to the simulation of the below-ground crop.

Root and above-ground daily mass increase are linked by the shoot-to-root mass ratio (SR); SR = R1 + R2 × t, where R1 and R2 are constants and t is the time (d) from emergence. Repartition of the root mass in the soil layers is controlled by two parameters: the fraction (R3) of the daily root mass increase that is added to the top R4 layers of the profile. The parametric value of R3 is defined for different physiological stages of the crop. The left-over daily-root-mass increase is distributed below the R4th layer according to an algorithm that considers the vertical depth of root penetration. Rhizodeposition is computed as R5 times the root mass formed per day at each layer. Roots grow until they start to decay at crop maturity or harvest, whichever comes first. Rhizodeposition decays as soon as formed. Roots and rhizodeposition decay as a two-component material (labile and resistant) with the rate constants k1 and k1 (per day), modified by reduction factors to account for edaphic conditions.

2.3. δ value and SOC from corn

Tracer and total C concentrations are simulated in parallel. At each time step the rate of change in tracer concentration in any pool (Δtr) is given by the equation, Δtr = Δtot × E × μ; where Δtot is the rate of change in total concentration, E = [13C]/[12C + 13C] is the tracer
concentration at the beginning of the time step, and \( \mu \) the discrimination factor, set to 1.0 in this study. Tracer and total concentrations are both updated, and the process repeated. Simulations were performed with the same initial \( \delta^{13}C \) assigned to the resistant and labile corn-debris pools.

The initial SOC-\( ^{13}C \) tracer concentrations were set to their measured values against the Pee Dee Belemnite standard \( R_{pdb} = \delta^{13}C_{db}/\delta^{12}C_{db} = 0.0112372 \): \( E_s = \delta^{13}C_s/\delta^{12}C_s = 0.0108926 \) corresponding to a \( \delta^{13}C_s = (R_s/R_{pdb}) - 1 \) 1000 = -19.99\%e, and \( E_s = 0.0109157 \) or \( \delta^{13}C_s = -17.89\%e \) in the 0–15 and 15–30 cm layers, respectively at \( t = 0 \). The root \( ^{13}C \) concentration was taken as that of the measured corn stover residues: \( E_c = 0.0109804 \) or \( \delta^{13}C_c = -12.00\%e \).

The fraction (\( f \)) of SOC from corn in the SOC at time \( t \) is usually computed as

\[
f = (\delta^{13}C_t - \delta^{13}C_s)/ (\delta^{13}C_c - \delta^{13}C_s),
\]

where \( \delta^{13}C_t = (R_t/R_{pdb}) - 1 \)1000 is the measured value at time \( t \). It is an approximation of equation

\[
f = (E_t - E_s)/(E_c - E_s),
\]

where \( E_t = \delta^{13}C_t/\delta^{12}C_t \) and linearity between \( f \) and the \( ^{13}C \) tracer concentrations is implied. It is defined for \( f = 0 \) when \( E_t = E_s \), the measured tracer concentration of the SOC at the beginning of the experiment (\( t = 0 \)), and \( f = 1 \) for \( E_t = E_c \) when the tracer concentration is equal to that of the corn (\( E_c \)), after the experiment has been maintained long enough to obtain complete saturation of the SOC with corn-\( ^{13}C \). The potential error induced by assuming linearity between \( f \) and \( ^{13}C \) tracer concentrations (or \( \delta^{13}C \)) was estimated by computing SOC from corn without the use of \( f \). This was achieved by setting 100% tracer enrichment in the photosynthates (\( E_c = 1.0 \)), and no tracer in the SOC at \( t = 0 \) (\( E_s = 0.0 \)). With these initial conditions, the simulated tracer concentration in the SOC for \( t > 0 \) is the concentration of corn derived \( C \) in the SOC. Simulated \( ^{13}C \) and total \( C \) concentrations in the SOC were reported with corn debris included, in line with the experimental procedure that returned ground organic debris to the soil sample after sieving.

2.4. Calibration

Calibration was performed by adjusting some soil and crop parameters to obtain, by trial and error, a good visual fit of measured and simulated data during the 13 year simulation (1980–1992). The parameters of soil transformations used in previous simulations with NCSOIL were retained (e.g. half-lives of labile and resistant Pool I, and Pool II: 2, 17, and 115 d, respectively), with the exception of the initial content of Pool I plus Pool II, and the decay rate constant of Pool III.
The root parameters $R_1$ through $R_5$ were determined in two steps: first, the parameters $R_1$ through $R_4$ were calibrated against root mass production and distribution in the soil, then $R_5$ — the mass ratio of rhizodeposition-to-root daily production — was calibrated against SOC, $\delta^{13}C$, and SOC derived from corn.

2.5. Sensitivity analysis

Deviation from calibrated values of the parameters was tried one at a time. Parameters that control the formation and distribution of roots and rhizodeposition in the soil profile and their decay and assimilation into the SOC were assayed for their influence on total SOC, $\delta^{13}C$, corn-derived SOC in the top 15 cm layer, and the above-ground production.

Different $\delta^{13}C$ values were assigned to the labile and resistant pools of roots to assess the effect of $^{13}C$ depletion in lignin (Benner et al., 1987). Simulations were also performed to estimate the contribution of non-decayed root and rhizodeposition debris to the total SOC, $\delta^{13}C$, and SOC from corn; it corresponds to the experimental error incurred when these organic debris are removed from the soil sample prior to analysis.

3. Results

3.1. Computation of $\delta$ values and SOC from corn

It was verified that errors caused by the use of Eq. (1) instead of Eq. (2) were low (<1% on SOC from corn), as expected since natural $^{13}C$ concentrations are low enough to maintain $[^{13}C]/[^{12}C + ^{13}C] \approx [^{13}C]/[^{12}C]$.

The potential error induced by assuming linearity between $f$ and $^{13}C$ tracer concentrations was estimated by computing SOC from corn with and without the use of $f$. The discrepancy of results between the two methods was low: it peaked for a few days to <10% in 1980, <4% from 1981 to 1984, and <2% in subsequent years.

3.2. Calibration and simulated kinetics

The initial content of Pool I plus Pool II (385, 300, 150, and 50 $\mu g \text{ N g}^{-1}$ in the top 0–15, 15–30, 30–50, and 50–100 cm layers, respectively) and decay rate constant of Pool III (27 year$^{-1}$) reflected the high initial fertility of the soil.

The parameters controlling root mass production and distribution in the soil profile were set to the following values: initial shoot-to-root ratio, $R_1 = 0.5$, and slope of the linear relationship with time, $R_2 = 0.07$; fraction ($R_3$) of the daily root mass increase distributed in the top 15 cm
(\(R_s = 3\)) of the soil profile: 0.65, 0.60, and 0.55 during plant growth from 0–10, 10–20, and 40 d after emergence, respectively; mass ratio of rhizodeposition-to roots daily production (\(R_s = 6.0\)). The decay rate constants for the roots were selected from Hunt (1977): root labile, 27%, \(k_l = 0.05\) d\(^{-1}\); root resistant, 73%, \(k_r = 0.0002\) d\(^{-1}\). The rate constants for the rhizodeposition were set to those of Pool I, which decays as cellular debris (Molina et al., 1983): labile pool, 56%, \(k_l = 0.332\) d\(^{-1}\); resistant pool, 44%, \(k_r = 0.04\) d\(^{-1}\). The ratio of microbial C assimilation to roots and rhizodeposition decay was set to 0.6, the same value used in connection with the decay of soil organic pools.

Simulated and measured root mass distribution in the soil profile, above ground production, total SOC, \(\delta^{13}C\), and the SOC from corn are shown in Figs. 1–5. The year-to-year change of above-ground production was correctly simulated, though the simulated levels differed from the measured ones for some years (Fig. 2). A gradual decline in SOC was observed in the soil top 15 cm, and correctly reproduced by the model (Fig. 3). In the 15–30 cm layer, measured and simulated SOC were lower than in the top 15 cm, but the simulated gradual decrease in organic matter content was not observed. Difference of \(^{13}C\) enrichment observed between the SOC of the 0–15 and the 15–30 cm layer were reproduced by the model (Fig. 4). The SOC from corn was higher — equivalently, \(\delta^{13}C\) values were lower — in the 0–15 cm layer where corn roots and rhizodeposition were more abundant than in the 15–30 cm layer (Fig. 5).

### 3.3. Incorporation of corn-C from roots and rhizodeposition into the SOC

The simulated efficiency of below-ground corn-C incorporation into the total SOC (ratio of SOC from corn-to-below-ground corn-C cumulative production), and fraction of below-ground corn-C in the SOC (ratio of SOC from below-ground corn-C-to-total SOC) in the top 15 cm of the soil are shown in Fig. 6. The efficiency of corn-C incorporation into SOC decreased as the fraction of corn-C in the SOC increased.

### 3.4. Sensitivity analysis

Deviations from the calibrated values of the parameters are shown in Table 1. The percentage change relative to the calibrated data was most pronounced for the SOC from corn; and to a lesser extent, the cumulative corn above-ground production. The simulated removal of non-decayed root and rhizodeposition debris during sampling reduced the SOC and \(\delta^{13}C\) by about 3% (Fig. 4), and the SOC from corn by about 50% (Fig. 5). Changes in the initial \(^{13}C\) root
concentrations to account for lignin $^{13}$C depletion induced a 2.9% reduction in the SOC after 13 years of continuous corn.

4. Discussion

The simulation model updated daily the soil conditions to reproduce over a 13 year period the kinetics of seven variables: above-ground corn production, and the total SOC, soil $\delta$ value, and the SOC from corn in the 0–15 and 15–30 cm depth. The parameters $R_1$ to $R_4$ were selected to obtain a simulated total root mass and percentage root mass distribution with depth that would follow the data observed from the same experiment in Rosemount in 1986 (Fig. 1). The simulated data did not correctly partition the percentage mass in the top two 15 cm depths. The measured data included the crown, the portion of the above-ground corn stalk that is not harvested and thus belongs to the roots. Simulated root dry mass production ranged from 0.95 (1992) to 1.96 (1981) t ha$^{-1}$, but the percentage mass distribution in soil remained almost the same during the 13 years (e.g. 57–59% in the top 15 cm). Measured root mass at the experimental site in 1986 ranged from 1.65 to 2.06 t ha$^{-1}$, of which 23–32% was found in the crown (R.H. Dowdy, unpublished data). Comparison with other experimental results is dubious when it is not possible to assert how much of the crown is included (Allmaras et al., 1975; Jones, 1985; Anderson, 1988; Huggins and Fuchs, 1997).

Calibration indicated the daily rate of rhizodeposition to be 6 times that of root production. By comparison, Johnen and Sauerbeck (1977) estimated with $^{14}$C that roots released the equivalent of 2.5 times the C mechanically recovered from roots. The simulated amount of photosynthate translocated below-ground was large. For example at harvest in 1984, 9.91 t dry mass rhizodeposition ha$^{-1}$ were released into the soil with an above-ground and root dry mass, productions of 12.74 and 1.65 t ha$^{-1}$, respectively, to give a shoot to root ratio (7.7) within the range of the experimental values (mean ± std. dev. = 5.31 ± 3.95) computed from the literature by Bolinder et al. (1999). Of this 1984 production, however, only 0.46 t dry mass rhizodeposition ha$^{-1}$ were left in the soil on d 365 of the same
year. The root, which decayed more slowly, totaled 1.24 t dry mass ha$^{-1}$ to give a shoot-to-root-mass ratio of 10.3.

The simulated percentages of rhizodeposition in the total net C fixed photosynthetically (above- plus below-ground production in 1984) were 40.8; or 24.4%, relative to the total CO$_2$-C fixed. Experimental estimates with $^{14}$C methods have ranged from 7 to 48% (Bottner et al., 1999; Biondini, 1988; Whipps, 1984; Wood, 1987) and 3.5–18% (Barber and Martin, 1976; Meharg and Killham, 1988) relative to the net and total C fixed phosynthetically, respectively. Bale-dent and Barabane (1996) worked with naturally $^{13}$C enriched corn to compute a below-ground average yearly production 1.5 higher than that of the stalks and leaves; "much higher than any known estimation of in situ below-ground production of C in maize or any other cereal “ and consisting "of ephemeral products such as root exudates". By comparison, the present simulation gave a root-plus-rhizodeposition production in 1984, equal to 1.8 that of stalk plus leaves (assuming a harvest index of 0.50), thus corroborating that corn may translocate more to the soil from below- than above-ground.

The kinetics of SOC from corn presented peaks caused by the abundant formation and rapid decay of rhizodeposition, which did not accumulate in soil (Fig. 5). Rhizodeposition was incorporated into the SOC through the process of microbial assimilation, thus with a 40% loss to CO$_2$ for each unit decayed. Residual root debris, however, accumulated and accounted for about 50% of the SOC from corn (Fig. 5). Roots had a greater effect on the SOC from corn than rhizodeposition, though more photosynthates were translocated to rhizodeposition than roots. This was also reflected in the higher sensitivity of the SOC from corn per unit percentage change in $R_2$ or $R_3$ than in $R_5$ (Table 1). These observations underline the necessity to include root debris — crown included — when the SOC is measured.

Information gathered from these field experiments would be richer if the rates of CO$_2$-$^{13}$C production were measured. It would allow to calibrate the parameters $R_2$ through $R_5$ with a higher weight given to the information on rhizodeposition than presently done, whereby $R_5$ is obtained after consideration of the overbearing root mass. For example, when the simulated root mass percentage in the top 15 cm was increased from 57–67% (parameter $R_3$, Table 1) to bring it up closer to the measured data (Fig. 1), the calibrated amount of SOC from corn (5.90 t C ha$^{-1}$) could be computed with $R_5 = 3.5$ instead of 6.0.

The SOC from corn was the most sensitive variable to variations of the parameters that controlled roots and rhizodeposition (Table 1). The cumulative above-ground production was also influenced by those parameters that modified the root or rhizodeposition mass: microbial efficiency $R_2$, and $R_3$. Corn with higher root and rhizodeposition
mass required more N and thus induced more N stress for growth under limited N supply, as was the case for the treatment considered in this study (no fertilizer N added).

The resistant root pool in soil accounted for about half the SOC from corn. Symmetric 10-fold variations in the decay rate constant $k_r$ (0.002 and 0.00002) around the calibrated value (0.0002) induced an uneven response: the lower decay rates affected less the SOC from corn than the higher decay rates (Table 1). Davenport et al. (1988) also modeled root decay with a double exponential equation: labile to recalcitrant ratio of 15/85 with $k_l = 0.120 \text{ d}^{-1}$, and $k_r = 0.0019 \text{ d}^{-1}$, values, which are closer to those used by Hunt (1977). The double pool model does not parallel the fractions that chemically characterize plant material (e.g. cellulose, hemicellulose, and lignin). It creates a difficulty when the effects of differences in the $^{13}$C concentration between the fractions are investigated by simulation. Benner et al. (1987) measured a 4.7% depletion in the $^{13}$C lignin content relative to the whole-plant material. It corresponds to a 0.598% depletion when it is pro-rated from the lignin dry weight percentage (9.3%) to that of the resistant pool (73%); and it induced a 2.9% decrease in the SOC from corn over 13 years, which is small relative to the effects of the other parameters.

The efficiency of below-ground corn-C incorporation into the SOC, and fraction of below-ground corn-C in the SOC are important indices used to estimate the effect of agriculture on the global C dynamic. After 13 years of continuous corn, the simulated fraction and efficiency indices in the top 15 cm depth were 0.12 and 0.19, respectively. The efficiency jumped to 1.00 at corn emergence, then dropped as decay began and some corn-C escaped the soil as CO$_2$ (Fig. 6). The fall of the index was rapid in the first year, but as the amount of SOC from corn built up, it decreased more slowly. An efficiency index of 0.38 was observed after 1 year with the input of the below-ground corn-C only (Balesdent and Balabane, 1996). The fraction index from several reports of long-term studies ranged from 0.14 to 0.30 — values computed with various approximations for the amount of rhizodeposition in the SOC (Bolinder et al., 1999). The simulated kinetics of the efficiency and fraction indices leveled off at about 0.20 when the labile pools had established a steady
state (Fig. 6). Further increase would be very slow and controlled by the dual effect of the incorporation of the C from corn into the stable SOC, and the decay of the stabilized SOC of soil origin.

References


