Adding an empirical factor to better represent the rewetting pulse mechanism in a soil biogeochemical model

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ABSTRACT

The rewetting of a dry soil causes a pulse in decomposition of soil organic matter (SOM). This mechanism may dominate carbon (C) and nitrogen (N) cycles in arid, semi-arid and Mediterranean ecosystems. Existing biogeochemical models perform poorly for systems characterized by pulsed events. In this study, we added a rewetting factor into the DAYCENT soil biogeochemical model to better represent the drying–rewetting pulses. Based on a 4-month laboratory incubation from a parallel study, we developed a simple rewetting factor for representing the enhanced mineralization pulse by rewetting stimulation. The rewetting factor was then incorporated into DAYCENT by modifying the soil moisture factor. The DAYCENT modification significantly improved model performance in predicting soil C respiration rates in drying–rewetting treatments through the capture of rewetting pulses. The modification also improved prediction performance for net N mineralization in treatments with shorter rewetting intervals, but did not improve predictions in treatments with longer rewetting intervals. The model modifications were validated by using a laboratory incubation data set from a different field site. The modified DAYCENT predictions showed that active and slow SOM pools were major contributors to mineralization pulses while the contribution from the passive pool was minimal. The modifications we made improved model performance and should be considered in future field representations of biogeochemical processes.

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1. Introduction

Xeric ecosystems, such as those dominated by chaparral species, often experience abrupt shifts from dry to wet conditions due to variability in rainfall. Therefore, the influence of soil moisture on soil carbon (C) and nitrogen (N) dynamics is particularly important in arid and semi-arid ecosystems because the rapid rewetting of a dry soil can cause a large pulse in soil C and N mineralization rates (Birch, 1958; Borken and Matzner, 2009; Fierer and Schimel, 2002; Miller et al., 2005). After soil rewetting, CO₂ production rates can be elevated by as much as 500% compared with samples kept continuously moist, with the CO₂ pulse persisting for 2 to 6 days following the rewetting event (Fierer and Schimel, 2003). Borken and Matzner (2009) summarized mechanisms of C and N mineralization and fluxes in soils under drying and wetting effects. Accumulated microbial and plant necromass, lysis

of live microbial cells, release of compatible solutes and exposure of previously protected organic matter may explain the additional mineralization in soils. The organic substrates causing wetting effects may originate from different sources produced, accumulated or exposed during the drying period. C and N could be released from both microbial biomass and nonmicrobial substrates. C and N mineralization will increase during wetting with increasing pool of accessible C and N substrates (Borken and Matzner, 2009). A major question, however, has been how important these pulses are in overall C and N cycling through their effects on all active, slow and passive pools.

Quantitative relationships have been established between soil moisture status and C and N mineralization rates in previous studies (De Neve and Hofman, 2002; Goncalves and Carlyle, 1994; Myers et al., 1982; Stanford and Epstein, 1974), and various empirical functions have been used to describe the impact of soil moisture on mineralization. For example, De Neve and Hofman (2002) applied parabolic, logistic and Gaussian-type functions to explain the relationship between N mineralization rates and soil water content, percent water-filled pore space (%WFPS) or water potential (pF). These kinds of empirical functions are usually used in C and N

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biogeochemical models for quantifying the effect of soil moisture on respiration and mineralization fluxes.

Several studies have tried to quantify the C and N rewetting pulse that occurs on the order of days to weeks after a dry soil is rewetted (Cabrera, 1993; Franzluebbers et al., 2000; Inubushi and Wada, 1987). However, empirical equations from these studies have not been associated with the dynamics of C or N state variables of different soil organic matter (SOM) pools, and have not been incorporated into C and N biogeochemical models. For this reason, it has been argued that current biogeochemical models should do poorly under drying–rewetting dominated conditions (Lawrence et al., 2009; Schimel, 2001). This point is particularly important, since if rewetting only accelerates the release of active C that is normally a small pool with a fast turnover, then rewetting pulses are unlikely to have long-term effects on soil C dynamics. If on the other hand, rewetting also stimulates the release of slow or passive C, large pools with slower turnover, then rewetting pulses may play a significant role in regulating long-term C dynamics and C sequestration. Therefore, frequent drying–rewetting events could bring different SOM pools into a new steady state with C and N transformation rates.

The idea that rewetting pulses affect both short and long-term C dynamics is supported by an experimental study where rapid rewetting of a dry soil influenced soil C cycling in the short-term, by increasing the microbial mineralization of cytoplasmic solutes in the active organic pool, and in the longer-term, by decreasing the total amount of SOM physically protected within microaggregates based on laboratory incubation experiments (Fierer and Schimel, 2003). Also, recent modeling work at the field scale for the chaparral ecosystems of California suggested that both short and long-term influences of drying–rewetting pulses need to be considered in biogeochemical models when they are applied to xeric ecosystems (Li et al., 2006).

In this study, we added an empirical rewetting factor to better reflect C and N release pulses in multiple drying–rewetting cycles in a biogeochemical model, DAYCENT under laboratory controlled conditions. We addressed the following aspects: (1) developing the rewetting pulse representation and modifying the DAYCENT model for better representing the drying–rewetting pulse mechanisms; (2) validating the rewetting pulse representation using modified DAYCENT model and independent incubation data; (3) investigating how the rewetting pulse representation captured the C and N dynamics through multiple drying–rewetting cycles.

2. Materials and methods

2.1. Drying–rewetting experiment for model development

An incubation experiment was conducted to determine whether episodic stress alters the timing and magnitude of carbon and nitrogen release from rewetted soils using a series of control and rewetting treatment experiments on California chaparral soils (Miller et al., 2005).

Table 1
Laboratory incubation treatments.

Treatment Number	Substrate	Rewetting interval (weeks)	Water hold capacity (%) ^a	Initial soil moisture (% volumetric base)
Control1	Soil	N/A	4	2.2
Control2	Soil	N/A	8	4.3
Control3	Soil	N/A	16	8.6
Control4	Soil	N/A	60	32.1
Control5	Soil + litter	N/A	4	2.2
Control6	Soil + litter	N/A	16	8.6
Control7	Soil + litter	N/A	60	32.1
Rewet1	Soil	4	8	32.1
Rewet2	Soil	2	16	32.1
Rewet3	Soil + litter	2	16	32.1

^a Water hold capacity (WHC) here is defined as moisture content at saturation.

The top 10 cm of soil from under chamise canopy on a toe slope was collected for the experiment from the Chamise Creek watershed in the southwestern Sierra Nevada within Sequoia and Kings Canyon National Parks, California (36°30'42" N, 118°42'23" W). Mean maximum and minimum temperatures at Ash Mountain, approximately 3 km from the study site, are 36.4 and 2.2 °C. Mean annual precipitation is 670 mm, with the majority of rainfall occurring between November and April. The soil is an Ultic Haploxeralf (Huntington and Akeson, 1987), and is a sandy clay with a pH of 6.2, SOM content of 6.6%, and C and N contents of 2.3% and 0.1%, respectively. The vegetation is dense chaparral dominated by *Adenostema fasciculatum* with subdominants of *Cercocarpus betuloides*, *Ceanothus cuneatus* and *Eriodictyon californicum*, and with an understory of sparse annual grasses. The watershed has not been burned for 43 years. The climate is variable from year to year with a typical Mediterranean-climate pattern, with short, wet winters and long, dry summers.

Surface soils (0–10 cm) were sieved to 4 mm and stored at 20 °C and field moisture (4% of water-holding capacity (WHC)) until the initiation of the rewetting treatment. 100% WHC from the gravimetric water content of soil that was saturated and then allowed to drain over 6 hours. The laboratory rewetting incubation experiment consisted of seven control and three rewet treatments (see Table 1), with rewetting treatment soils being wetted and dried at 2-week and 4-week intervals. This rewetting frequency is equivalent to eight and four rewetting events, respectively, over the 16-week experimental period, respectively. Each of the seven control treatments were maintained at one of following moisture levels over the course of the experiment: 4%, 8%, 16% or 60% of WHC. Rewetting treatments consisted of soils that were periodically brought to 60% WHC and then allowed to dry to 4% WHC over a period of 5–6 days. Rewetting frequencies of 2 and 4 weeks were used to simulate the natural range of storm frequency, as determined from local meteorological records (Sequoia and Kings Canyon National Parks, Division of Natural Resources, 1948–2002, unpublished data). Litter treatments (soil + litter) consisted of 2 mg C/g soil as *Adenostema* litter, equivalent to a 10% increase in soil C or a 10% increase in mean annual litterfall C (approximately 100 g m^{−2} y^{−1}). Litter was collected in August–September of 2002, air dried and ground to pass through a 40 mesh (420 μm) screen, and was added to soils prior to the start of the incubation experiment. The incubation experiment was conducted at a constant temperature 25 °C.

Net N mineralization and nitrification were determined by the differences between the initial (T0) and final (T1) inorganic N pools during incubation periods for each treatment in Table 1. Ten days (T0) following the start of the experiment and the first wetting–drying event, a subset of soils from each treatment was harvested for determination of initial inorganic N pools. Following a 16-week incubation (T1), a subset of soils from each treatment was harvested for determination of final inorganic N pools, and net N mineralization and nitrification rates. Soils were harvested following the final wetting–drying event (T1), when rewet soils had returned to 4% WHC. During the entire incubation time period, only accumulated net N mineralization and nitrification were estimated. Soil respiration was measured on rewet soils at daily intervals during each rewetting event, beginning approximately 4 h following wet-up and continuing through the dry down period until soils again reached 4% WHC. Respiration rates in control soils were measured every 2 weeks. More details about the incubation experiment can be found in Miller et al. (2005).

2.2. Dry rewetting experiment for model evaluation

For model validation purposes, we used separate data from a different incubation experiment derived by (Xiang et al., 2008). The top 5 cm of soil was collected from a freshly exposed soil profile in a California grassland (34°41'29.4"N; 120°02'42.7"W) at the University of California Sedgwick Reserve in April 2006. The sampling site has a

similar Mediterranean-climate pattern with above model development site. The soil is a Pachic Argiustoll. We used data from two treatments: (1) six cycles of rewetting events separated by 7-day dry periods (6C), and (2) twelve cycles where soils were rewet immediately upon drying (12C). One rewetting/drying cycle consisted of rewetting to 35% WHC and incubating moist for 3 days, followed by a 3-day dry-down period before soils were dried to 5% WHC. The total incubation time 75 days in addition to the initial period following the initial dry down and pre-equilibration. The incubation temperature was constantly maintained at 20 °C. Carbon dioxide production was measured after the 3-day rewetting period for the multiple dry/wet cycle treatments, and at regular intervals for the continuously moist treatments. Both cumulative CO₂ production and the immediate CO₂ production rate over each time interval were calculated. Accumulated net N mineralization and nitrification during the incubation were measured and estimated in the same way in Miller et al. (2005). More details about the description of the incubation experiment for model validation can be found in Xiang et al. (2008).

2.3. Model description

The DAYCENT biogeochemical model (Del Grosso et al., 2001; Parton et al., 1998) is the daily time step version of the CENTURY model (Parton et al., 1994). DAYCENT and CENTURY both simulate the biogeochemical processes of C, N, phosphorus, and sulfur cycling associated with soil organic matter (SOM) dynamics for grasslands, agricultural lands, forests and savannas. In addition to modeling decomposition, nutrient flows, soil water, and soil temperature on a finer time scale than CENTURY, DAYCENT also has increased vertical resolution of soil layers. DAYCENT includes sub-models for plant productivity, decomposition of dead plant material and SOM, soil water and temperature dynamics, and trace gas fluxes. Required inputs to the model include daily maximum/minimum temperature and precipitation, site specific soil properties, and current and historical land use. Disturbances and management practices such as fire, grazing, cultivation, harvest, irrigation, and organic matter or fertilizer additions can be predicted. The daily outputs in the original DAYCENT codes include soil moisture, temperature, trace gases of N₂O, NO, and CH₄. We recently developed the daily outputs for stream flow, stream NO₃⁻ export, net N mineralization, and soil CO₂ for DAYCENT (Li et al., 2006). The detailed descriptions of model structure and functions for DAYCENT and its new daily outputs can be found in the literature (Del Grosso et al., 2001; Li et al., 2006; Parton et al., 1998).

2.4. Site data sources for model development

Before DAYCENT could be used to simulate the incubation experiment, we ran the model under field conditions to obtain the initial parameters for the incubation predictions (see section of Parameterization of Incubation Predictions). Field data required in DAYCENT include daily climate data, soil physical properties and external nutrient input. The long-term daily meteorological data used in our predictions were maximum temperature, minimum temperature and precipitation. These climate data (1949–2002) were collected from a meteorological station at Ash Mountain in Sequoia and Kings Canyon National Parks, 4 km from the Chamise Creek catchment. The soil parameters are listed in Table 2. Annual N deposition was set at 0.77 g m⁻² y⁻¹, and the wet and dry N deposition was 0.28 g m⁻² y⁻¹ and 0.49 g m⁻² y⁻¹, respectively. Symbiotic and non-symbiotic N fixation were set at 0.2 g m⁻² y⁻¹ and 0.1 g m⁻² y⁻¹, respectively (Gray and Schlesinger, 1981; Kummerow et al., 1978). We assume that fires occur every 45 years based on expert opinion. The last observed fire at the study site occurred in 1960. The system was predicted with field data and results were used to establish initial conditions (Li et al., 2006).

Table 2
Initial biomass and soil parameters of the chaparral ecosystem.

Parameter	Values	Sources
Initial soil carbon pools		
Litter	595 g C m ⁻²	Gray and Schlesinger, 1981
Mineral soil	3509 g C m ⁻²	Huntington and Akeson, 1987
Initial C/N		
Litter	50.5	
Mineral soil	18.6	
Initial biomass		
Aboveground biomass	630 g C m ⁻²	Rundel and Parsons (1979)
Belowground biomass	378 g C m ⁻²	Kummerow et al. (1978)
Kummerow et al. (1977)		
Root:shoot	0.6	Kummerow et al. (1978)
Nitrogen concentration		Rundel and Parsons (1980)
N in leaves	1.38 g N m ⁻²	
N in fine branch	22.73 g N m ⁻²	
N in large wood	9.74 g N m ⁻²	
N in fine root	18.81 g N m ⁻²	
N in coarse root	2.35 g N m ⁻²	

2.5. Site data sources for model evaluation

The initial parameter values for the incubation predictions were obtained from a field prediction at the Sedgwick ranch site (Xiang et al., 2008). Through a long simulation (2006 years), DAYCENT was executed to reach steady state. We estimated initial parameter values for the simulation at the field condition from published studies. These parameter values are not required to be accurate (Li et al., 2006) as they are recalculated during the long calibration run. We assigned these initial values as: carbon content in litter 264 g m⁻², in mineral soil 2923 g m⁻²; C/N ratio in litter 10.7, in mineral soil 8.4 (Xiang et al., 2008); initial carbon content in aboveground live plant 97.4 g C m⁻², belowground 43.6 g C m⁻², root: shoot ratio 0.51 (Hooper, 1998) and initial nitrogen content in aboveground live plant 5.7 g N m⁻², belowground 5.0 g N m⁻², litter 2.0 g N m⁻² (Eviner and Firestone, 2007). Final conditions from the 2006 year simulations were utilized as the initial conditions for the model evaluation simulations using the laboratory incubation study of Xiang et al. (2008) since soil samples were taken in 2006.

2.6. Parameterization of incubation predictions

We derived the initial parameter values for the incubation predictions from a field prediction at the Chamise Creek site. This step is important because the incubation prediction requires initial parameter values at the time when we took incubation samples and the location where the samples were taken from. Another issue is the system cannot reach steady state status within short prediction time periods. The initial biomass and soil biogeochemical parameters for the Chamise watershed were estimated from literature or observed data (Table 2). Through a long run (2002 years), DAYCENT was executed to reach steady state of the modeled field chaparral ecosystem. September of 2002 was the time when soil samples were taken. The outputs of soil organic matter (SOM) pool sizes and C to N ratios in September of 2002 were used as their parameter values of the incubation predictions (Table 3). In the control soil treatment (without litter addition), the ratio among different SOM pools are as follows: active SOM: slow SOM: passive SOM = 1: 17.5: 7.5, and C/N ratio is 20.0, 31.3 and 16.2, respectively. In the litter addition treatment, we set the added litter as a soil litter pool (Table 3). In all rewetting treatments, each water addition was treated as a precipitation event.

In the incubation predictions, all of the plant C pools were set to 0.0 with the exception of the large wood biomass parameter, which was set to 5000 g C m⁻². Although there was no tree growth during the incubation prediction, the large wood biomass needed to be included

Table 3

Initial parameter values of soil organic matter pools and their C/N ratios for the incubation simulation.

Parameter	Treatment	
	Soil	Soil + litter
Active soil organic matter pool: g C m ⁻²	146.6	146.6
Slow soil organic matter pool: g C m ⁻²	2567.6	2567.6
Passive soil organic matter pool: g C m ⁻²	1072.4	1072.4
C/N ratio of active soil organic matter pool	20.0	20.0
C/N ratio of slow soil organic matter pool	31.3	31.3
C/N ratio of passive soil organic matter pool	16.2	16.2
Soil litter pool: g C m ⁻²	0.0	170.6
C/N ratio of soil litter pool	50.0	50.0

These parameters are obtained from the 3rd week outputs in September 2002 after a 2002 year simulation to reach equilibrium.

to provide the shading effect required to keep the soil surface temperature unchanged during the prediction.

2.7. Calculation of rewetting factor

We hypothesized that the incorrect estimations of C and N mineralization rates during rewetting were caused by the lack of a representation of rewetting pulses in DAYCENT in our application of DAYCENT to Chamise Creek (Li et al., 2006). In order to capture the drying–rewetting pulses in DAYCENT, a rewetting factor (*R*) was developed to modify the moisture factor. The rewetting factor is defined as the increased effect of the drying–rewetting transition on the moisture factor beyond the normal impact of soil moisture. The original moisture factor is a coefficient that represents the soil moisture effect on SOM deposition (Parton et al., 2001). It is calculated as:

$$W = \left(\left(\frac{WFPS_i - b}{a - b} \right)^{d \cdot \frac{b-a}{a-b}} \right) \cdot \left(\left(\frac{WFPS_i - c}{a - c} \right)^d \right) \quad (1)$$

where *W* is moisture factor (value varies from 0 to 1), *a*, *b*, *c*, *d* are coefficients that are influenced by soil texture, and *WFPS_i* is water-filled pore space on day *i*.

$$WFPS_i = \frac{W_g \cdot D_b}{1 - \frac{D_b}{D_p}} \quad (2)$$

where *W_g* is soil gravimetric water content, *D_b* is soil bulk density, and *D_p* is soil particle density.

The rewetting factor was built on the basis of the relationship between increased CO₂ release rate and incubation days after each rewetting event. Using the data from the 4 month rewetting incubation treatments (treatment “control 4”, “rewet1” and “rewet2”), a first order equation was developed to represent the rewetting factor (Fig. 1):

$$R = A \cdot e^{(-B \cdot T)} \quad (3)$$

where *R* is the rewetting factor (value varies from 0 to *A*), *T* is incubation time (days) within each rewetting event since the initial rewetting date. *A* is the increased proportion of SOM decomposition by the rewetting stimulation compared to SOM decomposition with constant soil moisture content at the initial rewetting date. We assumed that the SOM decomposition rate is proportional to the respiration rate. In our incubation experiment, parameter *A* was calculated as the difference of respiration rate between the rewetting treatment at each initial rewetting date and the control treatment with constant soil moisture content at the initial rewetting date, and then divided by the respiration rate in the control treatment.

Fig. 1. The change of normalized value of observed CO₂ evolution rate with incubation time. Normalized value of CO₂ evolution rate refers to the ratio of CO₂ evolution rate at any calculated point divided by the value at initial date of the rewetting event (see Fig. 2). Data that were used to fit the equation were from incubation treatment “rewet1”, “rewet2” and “rewet3” (see Table 1).

Parameter *A* represented a fraction of how much enhancement of SOM decomposition during a rewetting event that could not be represented in the original moisture factor. The constant soil moisture is 60% WHC in our experiment. *B* is a rate constant. From the incubation data, we derived *A* = 2.99, *B* = 0.2035 (Figs. 1 and 2).

Then, the modified soil moisture factor *W'* was indicated as:

$$W' = W + R \quad (4)$$

To calculate carbon flow in DAYCENT, the modified soil moisture factor *W'* was incorporated into the following equations:

$$\begin{aligned} \frac{dC_i}{dt} &= C_i \cdot K_i \cdot W' \cdot T_s \cdot P \cdot e^{(-3L_s)} \quad (i = 1, 2) \\ \frac{dC_i}{dt} &= C_i \cdot K_i \cdot W' \cdot T_s \cdot T_m \quad (i = 3) \\ \frac{dC_i}{dt} &= C_i \cdot K_i \cdot W' \cdot T_s \quad (i = 4, 5, 6, 7, 8) \end{aligned} \quad (5)$$

where *C_i* = the carbon in state variable; *i* = 1, 2, 3, 4, 5, 6, 7, 8 for surface and soil structural material, active SOM, surface microbes, surface and soil metabolic material, slow and passive SOM fractions; *W'* = modified soil moisture factor; *T_s* = soil temperature factor; *P* = pH effect on decomposition; *T_m* = effect of soil texture on active SOM turnover; *L_s* = lignin content of structural material; *K_i* = maximum decomposition rate for the *i*th state variables (*K_i* = 3.9, 4.9, 7.3, 6.0, 14.8, 18.5, 0.2, 0.045 year⁻¹).

2.8. Statistical analyses

Model prediction error was indicated with the sum of squared residuals (SS), which is calculated by

$$SS = \sum (y_i - \hat{y}_i)^2$$

where *y_i* is observed value and *ŷ_i* is predicted value. The proportionate reduction in error by the model modification was calculated by

$$RR = \frac{SS_0 - SS_1}{SS_0} \times 100\%$$

where *RR* is the proportionate reduction in error. *SS₀* is the sum of squared residuals produced by the unmodified model and *SS₁* is the sum of squared residuals produced by the modified model.

Fig. 2. The comparison of observed CO₂ evolution rates between control and rewetting treatments showing the calculation of the coefficient of rewetting factor *A*. The calculation of coefficient *A* is: the difference of CO₂ evolution rates between rewetting and control treatment at each initial rewetting date divided by each initial value of rewetting treatment. Data that were used to calculate coefficient *A* were from incubation treatment “control4”, “rewet1”, “rewet2” and “rewet3” (see Table 1).

3. Results

3.1. Model predictions for soil respiration

Since the rewetting factor *R* in control treatments with constant soil moisture contents was 0, the model modification did not change the predictions for any of the control treatments.

In all control treatments, unmodified DAYCENT overall was capable of reflecting the average level of CO₂ release rate under different water holding capacities, but fluctuations in respiration observed in the incubated soils were not captured by the model

(Fig. 3). In the treatments with 60% WHC, the model captured the declining trend of CO₂ release rate (Fig. 3).

In the incubation experiments, for a higher soil moisture level, respiration should consume more labile carbon. For example, the average CO₂ release rate in the treatment of soil at 60% WHC was as high as 14.2 µg C g⁻¹ day⁻¹, which was 226 fold higher than that in the treatment of soil at 4%WHC. The higher respiration rate apparently consumed labile C, and as a result, the decline in the labile carbon pool caused a decrease in CO₂ release at 60% WHC. In the treatments with medium soil moisture content (16% WHC), a declining trend still existed during the incubation which was not captured by DAYCENT.

Fig. 3. Observed and predicted CO_2 evolution rate of the control treatments of the incubation experiment. The modified DAYCENT did not change the outputs of the control treatments. The average predicted values were generally consistent with the observed values, but fluctuations in predictions were lower than that in observations. In the control treatments with high water hold capacity (WHC) values, the model captured the declining trend.

The litter addition increased the CO_2 release rate in 4%, 16% and 60% WHC control treatments by 140%, 30% and 60%, respectively. The model captured this increase (Fig. 3), but the impact of litter addition was less than the impact of changes in soil moisture. The model predictions at constant soil moisture content appeared to be inferior to the model predictions at fluctuating soil moisture (Figs. 3 and 4). This may not be a surprise. Since both temperature and soil moisture were constant in the control incubations, soil respiration rate should decline (in higher soil moisture treatments) or appear to be constant (in lower soil moisture treatments). The fluctuations in the control treatments could be explained by measurement errors and variations (Fig. 3).

The unmodified DAYCENT underestimated the rewetting pulses of CO_2 release rate in all rewetting treatments (Fig. 4). In model predictions, each peak in respiration at each initial rewetting event represented a high level of respiration at a high level of soil moisture, but

the transition effect from dry to wet was not represented. Unmodified DAYCENT underestimated CO_2 release rate by 68%, 58% and 52% for the rewetting treatment of soil with each 4-week rewetting interval, soil with 2-week rewetting interval and soil plus litter with 2-week rewetting interval, respectively. In the incubation experiment, litter addition increased observed average CO_2 release rate by 50%; from $21.7 \mu\text{g C g}^{-1} \text{ day}^{-1}$ to $32.8 \mu\text{g C g}^{-1} \text{ day}^{-1}$. The DAYCENT predicted value also increased in the litter addition treatment, but the modeled increase was smaller than the observed increase.

The modified DAYCENT significantly improved the prediction of the rewetting pulses (Fig. 4). The prediction error was reduced by 51.5%, 71.2% and 70.3% for CO_2 release in the rewetting treatment of a 4-week rewetting interval, 2-week interval and 2-week interval with litter addition, respectively (Table 4).

The observed average peak value of CO_2 release rate decreased from $89.0 \mu\text{g C g}^{-1} \text{ day}^{-1}$ to $48.0 \mu\text{g C g}^{-1} \text{ day}^{-1}$ when the rewetting

Fig. 4. Observed and predicted CO₂ evolution rate of the rewet treatments of the incubation experiment. The modified DAYCENT significantly improved predictions while DAYCENT significantly under estimated CO₂ evolution rate for each rewetting pulse.

interval decreased from 4 weeks to 2 weeks, and increased to 82.4 $\mu\text{g C g}^{-1} \text{ day}^{-1}$ with litter addition under the 2-week rewetting interval (Fig. 4). The increase in rewetting frequency had little effect on cumulative CO₂ release (Table 5). Litter addition significantly enhanced cumulative CO₂ release from 1348.4 $\mu\text{g C g}^{-1} \text{ day}^{-1}$ to 2034.3 $\mu\text{g C g}^{-1} \text{ day}^{-1}$ (Table 5). While unmodified DAYCENT underestimated the influence of litter addition on CO₂ release, the model modification captured this influence (Table 5).

Table 4
Reduced prediction errors (%) by the model modification.

Number	Treatment	CO ₂ respiration	Net N mineralization
Rewet1	Soil + 4 week rewet interval	51.2	None ^a
Rewet2	Soil + 2 week rewet interval	71.2	95.2
Rewet3	Soil + litter + 2 week rewet interval	70.3	98.4

^a The model modification did not reduce the prediction error for the simulation of the net N mineralization.

3.2. Model predictions for N mineralization and nitrification

Overall, net N mineralization increased when soil moisture increased, and litter addition reduced net N mineralization during the 4 months incubation (Fig. 5 and Table 5). For example, cumulative net N mineralization was 5.0 $\mu\text{g N g}^{-1}$ for the treatment without litter addition at 4% WHC, little higher values at 8% and 16% WHC, but increased to 16.9 $\mu\text{g N g}^{-1}$ at 60% WHC. Litter addition decreased cumulative net N mineralization by 46%, 67% and 64% at 4%, 16% and 60% WHC. Unmodified DAYCENT correctly captured this trend, but overestimated N mineralization at 60% WHC. Our model modification did not change the predictions in all control treatments. For the rewetting treatments, observed cumulative net N mineralization increased by 553% when rewetting interval changed from 4 weeks to 2 weeks. Litter addition decreased net N mineralization by 25% at 2-week rewetting interval treatment. While unmodified DAYCENT underestimated mineralization in all rewetting treatments, modified DAYCENT significantly improved their predictions (Fig. 5). For net N

Table 5Simulated cumulative net N mineralization and CO₂ release from soil organic matter.

Treatment	Cumulative net N mineralization from different SOM pools ¹ $\mu\text{g N g}^{-1}$ soil					Cumulative CO ₂ release from different SOM pools $\mu\text{g C g}^{-1}$ soil				
	Litter	Active	Slow	Passive	Total	Litter	Active	Slow	Passive	Total
Observations										
Rewet1	N/A	N/A	N/A	N/A	6.0 (2.2) ²	N/A	N/A	N/A	N/A	1291.1 (283.7) ²
Rewet2	N/A	N/A	N/A	N/A	39.4 (5.2)	N/A	N/A	N/A	N/A	1348.4 (213.9)
Rewet3	N/A	N/A	N/A	N/A	29.5 (1.2)	N/A	N/A	N/A	N/A	2034.3 (228.1)
DAYCENT simulations										
Rewet1	0.0	5.9	−0.6	0.0	5.4	0.0	220.8	192.3	1.8	415.0
Rewet2	0.0	20.2	−1.2	0.1	19.1	0.0	291.4	267.6	2.5	561.5
Rewet3	−0.7	16.8	−1.9	0.1	14.3	183.3	168.0	134.4	1.3	487.0
Modified DAYCENT simulations										
Rewet1	0.0	18.0	−9.6	0.1	8.5	0.0	806.5	909.6	8.7	1724.7
Rewet2	0.0	64.2	−29.4	0.3	35.1	0.0	828.2	1050.8	10.2	1889.1
Rewet3	−8.3	68.5	−29.0	0.2	31.4	601.2	1102.0	1162.6	11.2	2877.0

Positive values indicate mineralization while negative values indicate immobilization. Numbers in parentheses indicate standard errors.

mineralization in rewetting treatments, modified DAYCENT reduced prediction error in the 2-week treatment without and with litter addition by 95% and 98%, respectively, but slightly overestimated mineralization in the 4-week interval treatments.

Similar to the trends in mineralization, nitrification increased when soil moisture increased, but litter additions reduced net nitrification. Unmodified DAYCENT underestimated nitrification for all control treatments without litter addition, but slightly overestimated for control treatments with litter addition (Fig. 5). For the rewetting treatments, unmodified DAYCENT underestimated net nitrification. Modified DAYCENT increased prediction values for net nitrification in all rewetting treatments, but resulted in no improvement in the predictions except for the treatment of a 2-week interval without litter addition.

3.3. Model evaluation

Using the incubation experiments from the Sedgwick ranch soil experiment (Xiang et al., 2008) indicates that the modification made to the model for the Chamise Creek samples is transferable to other locations (Fig. 5). The type of ecosystem, the soils and the design and implementation of the incubation experiments differs significantly from the original experiments from (Miller et al., 2005). Modified DAYCENT was superior to the original DAYCENT for validations of soil carbon release and cumulative net N mineralization from both 12 and 6 rewetting cycle experiments (Fig. 6.). The original DAYCENT model under predicted higher respiration rate for both 12 and 6 rewetting cycle experiments while the modified model improved the performance (Fig. 6a & b). The prediction performance of the original and modified models at the Chamise Creek site (Fig. 5c) has similar pattern with that at the Sedgwick ranch site. The modified model improved a lot in predicting cumulative net N mineralization while the model modification little under estimated N mineralization in 12 cycle experiment and overestimated in 6 cycle experiment (Fig. 6c).

4. Discussion

4.1. Adding a rewetting factor improves explanation of overall C and N patterns

We established a modified moisture factor and made the simple assumption that it applies to the decomposition rates of all C pools. The question was then whether this simple approach would adequately explain the overall dynamics of C and N in an experiment with episodic drying and rewetting. This experiment presented two surprising results that posed a test for the modified model: (1) the 2-week and 4-week rewetting treatments released the same cumulative amount of CO₂, despite average moisture contents differing by a factor of two, and (2) despite releasing very similar amounts of C, net-N

mineralization was significantly greater in the 2-week rewetting cycle than in the 4-week rewetting cycle soils. We then further tested our model modification with a completely different set of laboratory incubation experiments (Fig. 6). The results from these experiments further confirm the usefulness of the dry-rewetting model modification and show that the changes are likely suitable for a variety of conditions.

A simple single C-pool model would not be able to explain these apparently contradictory results. However, with just a simple modification, DAYCENT did an adequate job of capturing both the C and N dynamics through multiple drying-rewetting cycles. The modified DAYCENT reproduced both the amounts and timing of respiration (Fig. 4). The nitrogen results are more interesting and compelling. For the control treatments, DAYCENT reasonably predicted net N mineralization, except in the 60% WHC + litter treatment, where it overestimated mineralization; it slightly overestimated mineralization in the 60% WHC control as well. DAYCENT underestimated nitrification consistently in the minus-litter control treatments, but this is not a major failing. What is notable is that the modified DAYCENT model was able to accurately predict net N mineralization in the rewetting treatments, both with and without added litter. It accurately estimated the low net mineralization in the 4-week rewetting treatment and the high rates of N mineralization in the 2-week rewetting treatments. DAYCENT's ability to get the different C and N dynamics right lies in the balance of C and N pools and their differing mineralization/immobilization patterns.

4.2. The rewetting factor impacts C and N releases from multiple SOM pools

Previous studies have suggested that both microbial biomass and non-biomass SOM pools contribute to the rewetting CO₂ pulse (Fierer and Schimel, 2003; Lawrence et al., 2009; Van Gestel et al., 1991; Vanveen et al., 1985). Fierer and Schimel (2003) suggested that the microbial biomass pool is the major contribution to the rewetting CO₂ pulse in the short term, but the physically protected SOM will be more labile in the long term by the release of SOM from drying-rewetting events. After a rewetting factor was incorporated into DAYCENT, the model captured the rewetting CO₂ pulse through increasing CO₂ release from active and slow SOM pools and soil litter pool (Fig. 7). The CO₂ release from the passive pool had minimal contribution. In the 4-week rewetting interval treatment, compared with unmodified DAYCENT predictions, CO₂ release in modified DAYCENT predictions from the active, slow and passive pool increased 2.7-fold, 3.7-fold and 3.8-fold, respectively, accounting for 45%, 55% and 0.5% of the total increased contribution. In the 2-week rewetting interval treatment, the increase from active, slow and passive pool was 1.8-fold, 2.9-fold and 3.0-fold, accounting for 40%, 59% and 0.6% of the total increased contribution. In the 2-week rewetting interval with litter addition

Fig. 5. Observed and DAYCENT predicted cumulative net N mineralization and nitrification during 4 months incubation period. (a) DAYCENT well predicted cumulative net N mineralization for all control treatments except for the treatment with litter addition at 60% of water hold capacity level. (b) Model under-estimated cumulative net N nitrification in all soil control treatments, but slightly over-estimated the cumulative net N nitrification in all soil plus litter control treatments. (c) Modified DAYCENT enhanced prediction values of cumulative net N mineralization for all rewet treatments. (d) Modified DAYCENT significantly increased the predicted cumulative net N nitrification for all rewet treatments.

Fig. 6. Validation of modified DAYCENT: correlations between observed and model predicted soil respiration rate. Solid line is the 1:1 line. The soil samples were collected from California grassland data from Xiang et al. (2008). (a & b) Observed versus original and modified DAYCENT predicted soil respiration rates for 12 and 6 drying-rewetting cycle treatments. (c) comparison among observed and original and modified DAYCENT predicted cumulative net N mineralization for 12 and 6 drying-rewetting cycle treatments.

treatment (validation data), the increase from soil litter, active, slow and passive pool was 2.3-fold, 5.6-fold and 7.7-fold, accounting for 17%, 39%, 43% and 0.4% of the total increased contribution. The incorporation of the rewetting factor reduced the CO_2 release

contribution from all pools when rewetting frequency was increased from one time to two times per month (Fig. 7). This change with rewetting frequency by rewetting modification in DAYCENT agreed with the deduction by Fierer and Schimel (2003): soils rarely exposed to drying and rewetting cycles will exhibit a larger CO_2 pulse on rewetting than soils which are frequently dried and rewetted. The model modification captured the influence of litter amendment (Fig. 4). The enhancement of CO_2 release by litter amendment in the modified DAYCENT prediction was produced by increases from all pools (Fig. 7). Although the rewetting factor incorporated in the model is exactly same for all SOM pools, it has very different effects on the C release from different SOM pools. We can easily understand different effects of the modified moisture factor from the calculation of C fluxes from different SOM pools in Eq. (5). In Eq. (5), eight C pools are classified as three groups and their C fluxes are calculated by three different equations. The difference of carbon content, decomposition rate, soil temperature, soil texture, soil pH and lignin content of structural material in different groups of C pools change the effect of the same modified moisture factor on C releases from different pools. The difference of the accessibility to micro-organisms should be already considered in the difference of carbon content, decomposition rate, soil texture. We ignored more details about the differences of the modified moisture factor effects within each group of SOM pools.

The model modification produced more complex results with N mineralization, since the respiration of the active pool contributes to net mineralization while the slow pool respiration immobilizes N. Decomposition of the passive pool is too limited to have much effect over the time scale of this study (Fig. 7). Compared with unmodified DAYCENT predictions, the modified DAYCENT increased N mineralization from the active pool by 2–3 fold, but increased immobilization into the slow pool by 15- to 25-fold. The net effects of the different pool dynamics caught the overall patterns of N mineralization. In the 4-week rewetting treatment, the absolute increases in mineralization from the active pool and immobilization into the slow pool were very similar in magnitude. Thus, modified DAYCENT predicted the limited increase in overall net mineralization with drying/rewetting that was observed in the data. In the case of the 2-week rewetting treatment, modified DAYCENT produced absolute increases in active fraction mineralization substantially greater than the increase in slow pool immobilization, thus producing a stimulation of overall net mineralization, as was observed in the data. In DAYCENT, N fluxes are linked with C fluxes through C/N ratios. Each of the eight SOM pools (defined in Eq. (5)) has its own C/N ratio value. The N flux value from each group of SOM pools is changed with the C flux value. The effect difference of modified moisture factor among three different group of C pools (in Eq. (5)) causes difference of moisture effects on N dynamics. Therefore, adding the same simple rewetting factor can indirectly change N fluxes through its different effects on C fluxes and different C/N ratios among SOM multiple pools.

One question that this modeling exercise does not address is the mechanism by which rewetting produces the pulses of microbial activity affecting the active and slow pools. The model highlights the importance of the slow pool in explaining differential mineralization results with different rewetting frequencies. This result is certainly consistent with the models proposed by Fierer and Schimel (2003), that there is some immediate release of C on rewetting from microbial biomass (active pool) but that physical disruption also exposes physically protected, slow C to attack. A combination of effects is certainly consistent with the extensive literature on drying/rewetting which has proposed release of microbial materials (Halverson et al., 2000; Kieft, 1987) and physical disruption of aggregates (Appel, 1998; Denef et al., 2001; Tisdall and Oades, 1982).

The value of the rewetting factor could be altered by several factors in the real environment, such as rewetting intensity, rewetting frequency, litter amendment or SOM quality. This study showed that the modified model could capture the influence of rewetting

Fig. 7. Comparisons of CO₂ release and cumulative net N mineralization modeled by DAYCENT and modified DAYCENT. Modified DAYCENT enhanced prediction values of N mineralization, immobilization and CO₂ release in different pools. Active organic matter pool is the major contributor to N mineralization while slow organic matter pool causes N immobilization. Active and slow organic matter pools are the major contributors to CO₂ release. Litter pool contributes to N immobilization and CO₂ release only in the treatment with the litter addition. The increases predicted with modified DAYCENT compared with DAYCENT are indicated for each pool.

frequency and litter addition, but the rewetting intensity or soil moisture difference between before and after a dry-rewetting event needs to be considered in the field application of our model modification. These factors need to be considered in the calibration when the model is applied to the field prediction.

5. Conclusions

In the DAYCENT biogeochemical model, the empirical equation with a direct relationship between moisture factor and soil moisture content failed to capture the rewetting pulses, which resulted in underestimation of C and N release from SOM in the context of drying-rewetting cycles. Based on a 16-week incubation experiment with treatments of different rewetting frequency and litter addition, the rewetting factor, a first-order dynamic equation $R = A \cdot e^{(-B \cdot T)}$ was developed to represent the increase of CO₂ respiration rate stimulated by rewetting events of a dry soil vs. incubation days. The DAYCENT model was modified through incorporating the rewetting factor into the moisture factor. The rewetting consideration improved the

simulations of CO₂ respiration rate. More importantly, perhaps, incorporating the modified moisture factor allowed the modified DAYCENT to capture the complex N dynamics that were observed across the different drying-rewetting treatments. No single pool model could explain the different N mineralization dynamics in the different rewetting treatments. It is interesting and perhaps surprising that even a multi-pool model that applies the same modified moisture factor to all soil pools was able to capture these dynamics.

Clearly, the next step in the application of this model is to explore whether it can better capture the dynamics of C and N fluxes in the field, under different climate regimes. This application is important, as the climate in California (and other xeric regions as well) is extremely variable, with annual rainfall varying by as much as a factor of four. Wetting/drying cycles in the field do not necessarily follow the clean, reproducible pattern used in the experiment of Miller et al. (2005) and Xiang et al. (2008) that we used to develop the modified DAYCENT. However, its ability to reproduce complex dynamics under controlled conditions suggests that it should be a substantial improvement in describing ecosystem dynamics in rainfall-pulse-driven, arid and

semi-arid ecosystems that are common around the globe and that are extremely sensitive to changing rainfall regimes associated with climate change.

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