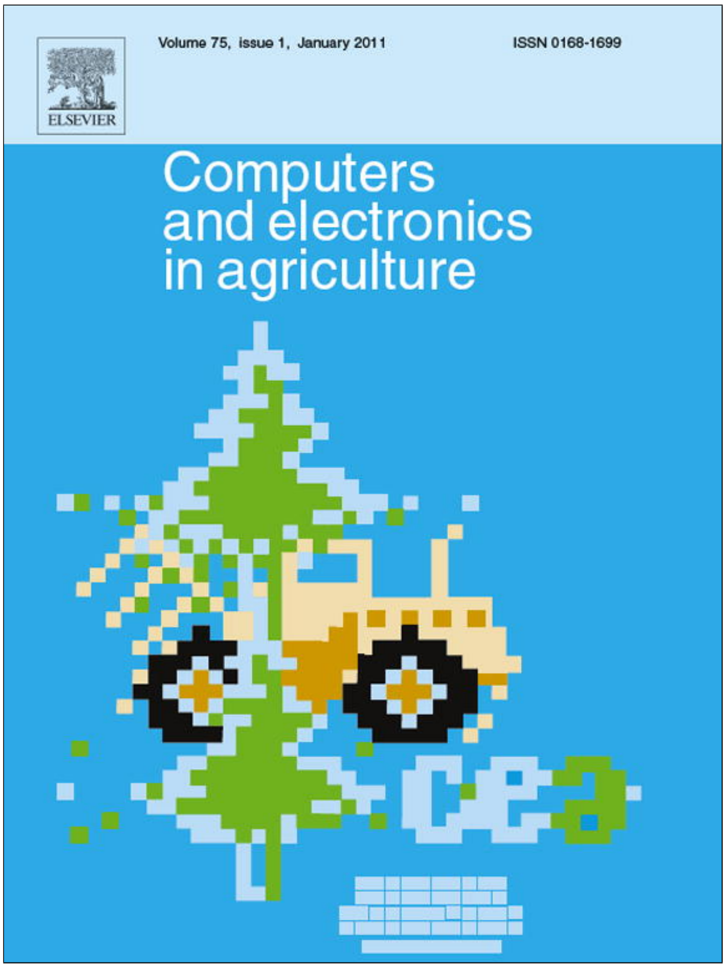
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Development and evaluation of the carbon–nitrogen cycle module for the GPFARM-Range model

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A B S T R A C T

Rangelands cover approximately 50% of the terrestrial surface of the earth. Consequently, the soil carbon and nitrogen storage and turnover in rangeland systems are becoming increasingly important for sustainable grazing management and climate change. In this study, a carbon–nitrogen (C–N) cycle module from the N Leaching and Environmental Analysis Package (NLEAP) was added into the GPFARM-Range model. This linkage was tested against a 14-year forage dataset (1993–2006) with measurements of C and N in 1993, 2003, and 2006 near Cheyenne, WY. The results showed that the peak standing crop (PSC), and changes in soil organic carbon (SOC) and total soil organic nitrogen (TON) in the rangeland were reasonably simulated by the new GPFARM-Range model. The indices of agreement (*d*) were >0.85 and the mean bias errors (MBE) were <130 kg ha^{-1} for the PSC simulation. The SOC and TON in the soil profile were simulated with relative root mean squared error (RRMSE) <5% for the calibration treatment without grazing and <20% for the validation treatments with grazing, both showing no significant bias or error from the observed values. A sensitivity analysis showed that the model responded reasonably to changes in temperature and precipitation. A long-term dataset with more soil C and N measurement events on the rangeland is needed to further test the model, but it is not available at this time. Additional investigation is needed into the adequacy of root-to-shoot ratio approaches to simulate root growth for forage groups in these systems.

1. Introduction

Approximately 50% of the terrestrial surface of the earth is covered by rangelands, where about one-third of the world's total C is stored in the above- and belowground forage biomass (Allen-Diaz, 1996). A number of computer models have been developed to simulate forage biomass and livestock gains for rangelands (Wight and Skiles, 1987; Thornley and Johnson, 1990; Donnelly et al., 1997). In the 1980s, an ARS team developed the Simulation of Production and Utilization of Rangelands (SPUR) model (Wight and Skiles, 1987; Hanson et al., 1992; Teague and Foy, 2002). Thornley and Johnson (1990) developed the Hurley Pasture Model, which was used to predict the responses of grassland in Britain to climate change (Thornley and Cannell, 1997). In Australia, the GRAZPLAN family of decision support tools was developed at CSIRO Plant Industry to help producers strategically position their enterprises for profit and sustainability (Donnelly et al., 2002), which proved to be a useful approach to determining forage management and cow–calf stocking rates when unusual dry weather occurred.

The Great Plains Framework for Agricultural Resource Management (GPFARM) decision support software was released by USDA-ARS in the early 2000s for strategic planning, and to evaluate alternative management for farms and ranches in the US Northern Great Plain area (Ascough et al., 2002). It contained separate simulations for rangeland and cropland. The GPFARM-Range model included hydrology, chemical transport, the extended Shuttleworth–Wallace potential ET model (Farahani and Ahuja, 1996), and a simplification of the SPUR2 model for forage and cow–calf production. The capability of the GPFARM-Range model in simulating rangeland forage growth and livestock development was evaluated with field data collected near Cheyenne, WY, and Nunn, Colorado (Andales et al., 2005). For the calibration year of 2001, the model predicted the dominate warm- and cool-season grass biomass with *d* (index of agreement, which gives the proportion of the variance explained by the model with respect to 1:1 line) >0.99; for the validation years of 2000 and 2002, the model explained 0.67–0.80 (*d* value) of the variances of the five functional groups and 0.66 of the total peak standing crop. Overall, the model performed well for cow and calf weights, with d values of 0.81 and

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Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; TON, total organic nitrogen; C–N, carbon–nitrogen; PSC, peak standing crop; GPFARM DSS, Great Plains Framework for Agricultural Resource Management Decision Support System; NLEAP, the N Leaching and Environmental Analysis Package.

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0.94, respectively. The GPFARM-Range model simulated the peak standing crop production in exclosure mixed grass prairie plots with $d = 0.66$ from 1983 to 2001 at the USDA-ARS High Plains Grasslands Research Station near Cheyenne, WY (Andales et al., 2006). The model was recently used to predict sandsage-bluestem production under different stocking rates at the USDA-ARS Southern Plains Experimental Range site near Ft. Supply, OK, with d value of 0.68 for the annual peak standing crop (Adiku et al., 2010).

Bryant and Snow (2008) reviewed nine models for pastoral or rangeland farm agro-ecosystems and reported that the GPFARM-Range model showed strengths in predicting forage production of five functional groups (warm-season grasses, cool-season grasses, legumes, shrubs, and forbs) and cow and calf live weights. With an increased concern for climate change, there has been a great interest in evaluating and enhancing C sequestration in rangelands. However, the GPFARM-Range package did not include a C–N cycle module for C simulation in rangelands.

There are various modules available to describe soil C–N cycles in the agricultural environments, including CENTURY (Parton et al., 1983), OMNI (Shaffer et al., 2000), and NLEAP (Shaffer et al., 1991). All of these modules include the core C–N processes, but vary in the number and complexity of their organic matter pools. The SPUR model was linked with CENTURY in SPUR2 and a better prediction in animal weight gain was obtained, but the nitrogen cycling component needed further improvement (Foy et al., 1999). For OMNI, the most detailed module, more data and special procedures are needed to initialize the pools appropriately (Shaffer et al., 2000). Based on the review by Ma and Shaffer (2001), we selected the NLEAP model for GPFARM-Range, as it has moderate complexity and a daily time scale, and has been widely accepted for water and soil quality assessment (Delgado et al., 2000; Follett, 1995; Shaffer et al., 1994). The GPFARM-Crop model contains the NLEAP based C–N algorithms and pool structures for crops such as corn, soybean, and wheat (Shaffer et al., 2004). Thus, it provided a good reference for adding the C–N module into the stand-alone GPFARM-Range model under the conditions of forage and animal growth while upgrading the FORTRAN code base to an object oriented design in Java.

The objectives of this study were to (1) develop a C–N cycle module for the GPFARM-Range model based on the C–N algorithms and pool structures of NLEAP; and (2) evaluate the performance of this C–N module in simulating soil organic carbon (SOC) and total organic nitrogen (TON), which also required calibration and validation of the model against field forage data.

2. Model development and theory

The stand-alone GPFARM-Range model was initially developed in Fortran to simulate forage growth and cow–calf production on native rangelands, and later converted to a component-based modular model in Java, under the Object Modeling System (OMS) framework at the USDA-ARS. Infiltration from rainfall or snow melt is computed by the Green-Ampt approach and water redistribution in the soil profile is simulated by Darcy's law. The upper boundaries, potential soil evaporation and plant transpiration, are estimated by the double layer model of Shuttleworth and Wallace (1985), an enhancement of the Penman–Monteith equation (Farahani and Ahuja, 1996). The forage module is phenology based, driven by heat units (growing degree days) for five functional groups of plant species: warm-season grasses, cool-season grasses, legumes, shrubs, and forbs. The weight gain or loss of cows and calves is calculated by their demand for forage, availability of forage and supplements, and forage intake. The forage and animal modules are described in detail in Andales et al. (2005, 2006).

The C–N cycle processes of GPFARM-Range are to be simulated under native conditions without additional N inputs such as fertilization (Fig. 1). Therefore, some subroutines in the NLEAP code, such as N volatilization with urea applications, are not currently included in this C–N cycle module for rangelands. Dung and urine are not added to the system because they are usually concentrated at the place where livestock congregate and animal stocking rates normally used in western rangelands are very low. For example, the recommended stocking rate for the short-duration rotation grazing was 3 ha per steer in the mixed prairie (SCS, 1986; Hart et al., 1988). Denitrification was also not included as it was not considered important under the mostly arid conditions of the rangelands in the Great Plains.

Because NLEAP was originally developed for the C–N cycle in crop fields, details on how it was adapted to the rangeland environment are shown in this section. Four components in the C–N cycle module are environmental factors (water and temperature), surface residue, and their decomposition, dead root material and their decomposition in different soil layers, and plant N uptake. All the calculations in this C–N cycle module are based on a daily time step, so are in other modules of the GPFARM-Range model. The environmental component computes the water and temperature factors affecting the processes of decomposition and mineralization of dead materials and soil organic matter. The surface residue component includes calculations of N deposition from precipitation, litter gained from dead aboveground plant material, and decomposition and C–N mineralization of surface litter. The dead root materials component computes dead root material gained for each soil layer, and their C decomposition, N mineralization, nitrification, and immobilization on a daily basis. An additional independent simulation component for N uptake uses the information on root-to-shoot ratios for different forage functional groups to calculate total N demand and uptake per soil layer.

2.1. Environmental factors

The factors of water and temperature (*wfac* and *tfac*) control most of the processes in the C–N cycle, and are calculated based on the soil water regime and air temperature. The water factor is computed as a function of percent water-filled pore space (WFPS) of each soil layer:

$$wfac = \begin{cases} 0.0075 \times WFPS & WFPS \leqslant 20 \\ -0.253 + 0.0203 \times WFPS & 20 < WFPS \leqslant 59 \\ 41.1 \times \exp(-0.0625 \times WFPS) & WFPS > 59 \end{cases} \tag{1}$$

$$WFPS = \frac{\theta_v}{1 - \rho_b/2.56} \tag{2}$$

where θ_v is the volumetric water content (cm^3 cm^{-3}), ρ_b is the soil bulk density (g cm^{-3}), and 2.56 is the particle density (g cm^{-3}). The temperature factor is based on thermodynamic principles, calculated using

$$tfac = 1.68 \times 10^9 \times \exp\left(\frac{-13.0}{1.99 \times 10^{-3} \times (TMOD + 273)}\right) \tag{3}$$

$$TMOD = \begin{cases} \frac{T-32}{1.8} & T < 86\,^\circ\mathrm{F} \\ 60 - \frac{T-32}{1.8} & T \geqslant 86\,^\circ\mathrm{F} \end{cases} \tag{4}$$

where T is the air temperature (°F).

2.2. Surface residues and their decomposition

This simulation component was constructed to compute the status of C–N on the surface soil of rangelands. Inputs include N deposition and metabolized C and N from dead material from

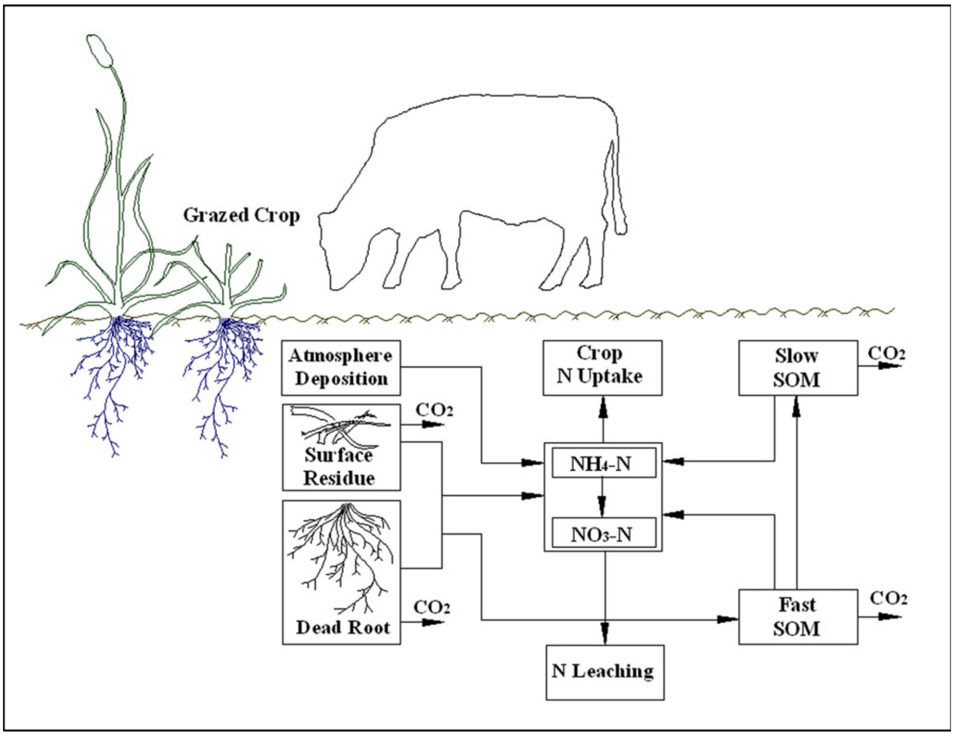

Fig. 1. Diagram of the C–N cycle module of the GPFARM-Range model.

above ground biomass. N deposition from precipitation was calculated by:

$$Nh4Surface = Precipitation \times Nh4Concentration/10 \tag{5}$$

$$No3Surface = Precipitation \times No3Concentration/10 \tag{6}$$

where *Nh4Surface* and *No3Surface* were precipitation deposition of NH_4–N and NO_3–N, respectively, onto the soil surface (kg N ha^{-1}). *Precipitation* in the equations is the amount of daily precipitation (cm); and *Nh4Concentration* and *No3Concentration* are NH_4–N and NO_3–N concentrations in precipitation (mg N L^{-1}), respectively. The denominator '10' is a factor to convert cm mg N L^{-1} to kg N ha^{-1} for the mass of N in precipitation. N concentration in forms of NO_3–N and NH_4–N in precipitation on the US continent can be obtained from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu). The NH_4–N and NO_3–N deposited from precipitation are partitioned into two parts: stored in flat surface residue and in bare ground, and added to existing amounts.

The C and N in residue are calculated by:

$$cRes = cRes + newLitterC \tag{7}$$

$$nRes = nRes + newLitterN \tag{8}$$

where *cRes* and *nRes* are total C and N in residue available for decomposition and mineralization (kg ha^{-1}), respectively; and *newLitterC* and *newLitterN* are newly added C and N from dead above ground biomass (kg ha^{-1}), respectively. Dead above ground biomass and its C:N ratio are calculated by the forage module. For the data at Cheyenne, WY, the fraction of C was set at 0.44 for dry dead residue biomass and 0.25 for dead roots according to Schuman et al. (1999). The total N content is computed from the content of C and C:N ratio. Surface residue C decomposition is calculated by:

$$cResMet = kResSurface \times rAdjust \times cRes \times tfac \times wfac \tag{9}$$

$$rAdjust = \begin{cases} 0.29 & C:N = 100 \\ 0.59 & C:N = 40 \\ 1.0 & C:N = 25 \\ 2.6 & C:N = 9 \end{cases} \tag{10}$$

where *cResMet* is the surface residue C metabolized (kg ha^{-1}), *kResSurface* is the first order rate coefficient (day^{-1}), which is set equal to 0.2 day^{-1} in NLEAP. The rate adjustment factor *rAdjust* is a tabulated function of C:N ratio in the organic matter and can be linearly interpolated for any C:N ratio between 9 and 100. The maximum C metabolized is limited by the available C source in the residue. Surface residue C is subsequently updated by subtracting the amount of C metabolized.

NH_4–N mineralized from surface crop residue (*nResR*, kg ha^{-1}) is a function of C metabolized and the C:N ratio:

$$nResR = cResMet \times (1/(C:N) - 1/30) \tag{11}$$

where the constant 30 is the critical C:N ratio for immobilization, above which immobilization will occur instead of mineralization. Total organic N is subsequently updated by subtracting N mineralized. The maximum amount of mineralized N from residue is controlled by the total amount of organic N in the residue.

When calculated *nResR* is less than 0, it means that NH_4–N immobilization will occur, and this amount is taken from the N for mineralization available from total NH_4–N and NO_3–N in the soil surface. When total available NH_4–N and NO_3–N is less than the value of *nResR*, 90% of the deficit NH_4–N for immobilization is obtained from microbial decay:

$$Nh4IM = Nh4Surface + 0.9 \times (-nResR - (Nh4Surface + No3Surface)) \tag{12}$$

where *Nh4IM* is the total amount of NH_4–N obtained from N immobilization (kg N ha^{-1}). The C and N content, and the resulting C:N ratio in the crop residue are then updated.

When the C:N ratio drops below 12 during mineralization, the decomposed surface crop residue is then incorporated in the top soil layer's (user defined) fast soil organic matter pool (*fastSOM*, kg ha^{-1}), and is calculated by the amount of N mineralization, C:N ratio, and fraction of C in soil organic matter as follows:

$$fastSOM = fastSOM + nRes \times C:N/fRes \tag{13}$$

where the fraction of C in crop residue (*fRes*) is set to 0.45. Corresponding C and N in the residue are added into the fast pools of C and N (*fastC* and *fastN*) in the surface soil layer, respectively:

$$fastC = fastC + cRes \tag{14}$$

$$fastN = fastN + nRes \tag{15}$$

Nitrification of NH_4–N in the surface residue (*nitrifN*) is calculated using a zero-order equation:

$$nitrifN = k_n \times tfac \times wfac \tag{16}$$

where k_n is the zero order rate of nitrification (kg N ha^{-1} day^{-1}), which was set to 30 kg N ha^{-1} day^{-1} according to the NLEAP Fortran code. The amount of nitrified N is also limited by total available NH_4–N in the residue.

2.3. Decomposition of dead root biomass in different soil layers

Dead plant roots are the only source of C input below ground for each soil layer. The amount of total root biomass for each functional forage group is simulated using the predicted shoot biomass multiplied by a root:shoot ratio in the forage module. The amount of dead root material is calculated for each functional forage group by the following equation:

$$DeadRoot = TotalRoot \times RootMortRate \tag{17}$$

where *DeadRoot* is the total amount of dead root material in each soil layer (kg ha^{-1}); *TotalRoot* is the amount of total live root material in each soil layer (kg ha^{-1}), and *RootMortRate* is the root mortality rate (day^{-1}), which is calibrated in this study. Dead root of each functional group is added together and partitioned between soil layers:

$$LayerDeadRoot = TotalDeadRoot \times drp \tag{18}$$

where *LayerDeadRoot* is the amount of dead root biomass in each soil layer (kg ha^{-1}); *TotalDeadRoot* is the total dead root biomass from all functional groups (kg ha^{-1}); and *drp* is the proportion of live roots in each soil layer, which is calculated in the forage module.

Subsequently, the C and N storage in each soil layer is computed. First, the dead root biomass is metabolized and mineralized according to Eqs. (9) and (11) with an increased first order decomposition rate of 0.4 day^{-1} for dead root biomass. The organic matter is subsequently added into the fast SOM pool in each soil layer when the C:N ratio drops below 12. The fast SOM in each soil layer is computed by Eq. (13) with *fRes* equal to 0.22 for dead root material, and part of the fast SOM is converted into the slow SOM pool:

$$slowSOM = slowSoM + fastSOM \times frSlow \tag{19}$$

where *fastSOM* and *slowSOM* are the total SOM in the fast and slow pool, respectively (kg ha^{-1}); and *frSlow* is the pool transfer rate of fast SOM to slow SOM pool, which is set to 0.05 in NLEAP. The simulation of immobilization processes in soil layers is identical to the simulation for the surface crop residue. Total nitrification of available soil NH_4–N is also computed using Eq. (16) as with the surface residue simulation, but was partitioned into each soil layer based on the proportion of live root in each layer. The proportion of live root is calculated in the forage module of GPFARM-Range. Other processes such as N movement and uptake are incorporated in the water chemical balance and plant growth modules.

2.4. Nutrient uptake

N uptake by each functional group is calculated based on the total N demand of shoot and root growth:

$$ShootNit = ShootGrowth * 0.45/ShootCN \tag{20}$$

$$RootNit = RootGrowth * 0.25/RootCN \tag{21}$$

where *ShootNit* is the N demand for shoot growth on a given day (kg N ha^{-1}), *ShootGrowth* is the shoot biomass increment (kg ha^{-1}), and *ShootCN* is the C:N ratio in the shoots. *RootNit* is the N demand for root growth (kg N ha^{-1}), *RootGrowth* is the root biomass increment (kg ha^{-1}), and *RootCN* is the C:N ratio of the roots. The coefficients of 0.45 and 0.25 are the fractions of C in shoots and roots, respectively, based on field observations by Schuman et al. (1999). The total potential demand of N (*TotalNitDem*) was the sum of N demand by shoots and roots, and is partitioned to every soil layer based on root distribution:

$$TotalNitDem = ShootNit + RootNit \tag{22}$$

$$PotentialNitLayer = TotalNitDem \times drp \tag{23}$$

where *PotentialNitLayer* is the potential N demand for each soil layer (kg N ha^{-1}). It is noted that the actual N uptake by the plants is partitioned to NH_4–N and NO_3–N based on the proportion of these two inorganic N forms in the soil layers, and is limited by the total available NH_4–N and NO_3–N in each soil layer.

3. Field experimental data

A field study was conducted at the USDA-ARS High Plains Grasslands Research Station (HPGRS, 41°11′N 104°53′W) near Cheyenne, WY, to investigate the long-term impacts of various grazing rates on a native northern mixed-grass prairie ecosystem. Three stocking rate treatments were established in 1982: EX, ungrazed exclosure; CL, pastures continuously grazed season-long at a light stocking rate of 0.16–0.23 steers ha^{-1}; and CH, pastures continuously grazed season-long at a heavier stocking rate of 0.56 steers ha^{-1}. Approximately 10% of the net above ground biomass was utilized by the animals in the CL treatment, and 50% was utilized in the CH treatment. Soil cores were sampled for all the treatments to 90 cm deep in 1993, and to 60 cm in 2003 and 2006 for SOC, TON, and soil bulk density. Peak standing crop (PSC) was determined for this long-term grazing study on an annual basis in late July/early August for CL and CH treatments, but for the EX treatment, above ground biomass was only sampled during the years of 2004–2006. Detailed descriptions of this field experiment can be found in Schuman et al. (1999) and Ingram et al. (2008). Additional information on the root-to-shoot ratio and initial C and N in the roots and shoots of vegetation on this research were reported by Schuman et al. (1999). Daily weather data including precipitation and maximum and minimum air temperature were site-specifically measured (Pam Freeman, personal communication); wind speed was downloaded from www.weatherunderground.com for Cheyenne, WY (Jodi Preston, personal communication). Solar radiation was not available for the site, so a dataset from Fort Collins, CO, which is about 75 km south of the site, was used.

4. Model calibration and evaluation

The main objective of this paper was to test this newly added C–N cycle module of the GPFARM-Range model in simulating SOC and TON in rangeland soils. Because decaying surface plant residues and dead root materials are the dominant source of C in this native system, the forage module was also tested using observed peak standing crop data, rather than merely evaluating the C–N cycle module.

The results from EX were selected for model calibration, and those from CL and CH were used to validate the model. The forage module of GPFARM-Range was calibrated against PSC data from

Table 1
Input parameters used in the GPFARM-Range simulations.

Parameter	Definition	Functional Group				
		Warm-season grasses	Cool-season grasses	Legumes	Shrubs	Forbs
Default						
T_{max} (°C)	Maximum temperature for growth	41	36	35	36	35
T_{opt} (°C)	Optimum temperature for growth	27	22	20	21	23
T_{min} (°C)	Minimum temperature for growth	8	3	3	4	3
SenRate (kg kg^{-1} day^{-1})	Growing degree days until senescence begins	0.018	0.013	0.005	0.001	0.001
FallRate (kg kg^{-1} day^{-1})	Rate that standing dead biomass falls and becomes residue	0.02	0.02	0.05	0.01	0.01
Calibrated						
MaxGrowthRate (kg kg^{-1} day^{-1})	Maximum relative growth rate of shoot	0.22	0.18	0.17	0.17	0.12
SenGDD (C day)	Day senescence begins	1400	1800	1858	1877	1685
rootMortRate (kg kg^{-1} day^{-1})	Root mortality rate	0.003	0.002	0.001	0.001	0.005
RSRatio	Root-to-shoot ratio[a]	28.4	28.4	28.4	28.4	28.4
Mnr	Initial root C:N ratio[a]	21	21	18	35	21

[a] Root-to-shoot ratio and root C:N ratio were taken or modified from Schuman et al. (1999).

Table 2
Measured soil parameters used in the C–N cycle module in the GPFARM-Range model.

No. layers	Depth (cm)	Bulk density (g cm^{-3})[a]			SOM (%)			C:N ratio		
		EX	CL	CH	EX	CL	CH	EX	CL	CH
1	0–3.8	1.01	1.14	1.17	4.4	5.0	4.7	14.1	13.5	14.3
2	3.8–7.6	1.01	1.14	1.17	2.7	3.0	3.3	12.1	11.0	12.8
3	7.6–15	1.36	1.36	1.42	2.1	2.5	2.5	10.8	10.3	11.9
4	15–30	1.39	1.26	1.47	1.6	2.1	1.7	10.2	9.4	11.1
5	30–45	1.39	1.26	1.47	1.9	1.8	2.0	12.3	11.7	15.0
6	45–60	1.39	1.26	1.47	1.4	1.2	1.4	11.5	12.4	14.1

EX, exclosure; CL, continuous light grazing; CH, continuous heavy grazing. Data were taken from Schuman et al. (1999).

[a] Bulk density was measured at three depths of 0–7.6, 7.6–15, and 30–60 cm in 1993.

Table 3
Measured average proportion and total peak standing crops of each functional group in 2004–2006.

Treatment	WSG (%)	CSG (%)	Legumes (%)	Shrubs (%)	Forbs (%)	Total (kg ha^{-1})
EX	0.067	0.660	0.043	0.138	0.092	1422
CL	0.110	0.669	0.034	0.068	0.119	1436
CH	0.289	0.265	0.069	0.288	0.089	1221

EX, exclosure; CL, continuous light grazing; CH, continuous heavy grazing; WSG, warm-season grasses; CSG, cool-season grasses. Data provided by the USDA-ARS High Plains Grasslands Research Station.

the EX treatment obtained in 2004–2006, including environmental and plant growth parameters for warm-season grasses, cool-season grasses, legumes, shrubs, and forbs; mortality rate of root; and the C:N ratio in the roots (Table 1). Simulations of C–N cycle were initiated using the data obtained in 1993 and run continuously from 1993 to 2006. Because SOC and TON were not measured at the 60–90 cm soil layer in 2003 and 2006, soils were only examined to the depth of 60 cm in this simulation. Soil bulk density, SOC, and the C:N ratio of SOM for each soil layer measured in 1993 were input into the model as initial conditions (Table 2). Although bulk density was measured three times (in 1993, 2003, and 2006), in this modeling study, the bulk densities in 1993 were used and not changed over the simulation years from 1993 through 2006. The default and initial forage parameters in Table 2 and cow–calf parameters were mainly adopted from Andales et al. (2006) and the mortality rate of roots and initial C:N ratio of roots were calibrated to get a good fit of SOC and TON prediction in the EX calibration treatment. The model's potential maximum forage production for the site, a required input, was set at 2700 kg ha^{-1}.

Input of the proportion of each functional group varied for each grazing treatment. Schuman et al. (1999) reported an increase in the proportion of warm-season grass (WSG) and decrease in that of cool-season grass (CSG) in the CH treatment compared with those in the CL treatment after 12 years of the grazing experiment. In 2004–2006, the sampled peak standing crop was sorted by functional groups. The proportion of the functional groups for each treatment were then computed and used as input for the plant community composition in the GPFARM-Range model (Table 3).

To evaluate the performance of the forage production module in the GPFARM-Range model, simulated and observed peak standing crop (PSC) were compared using statistics of mean bias error (MBE) and index of agreement (*d*, Willmott, 1982) which were also used by Andales et al. (2006). For total SOC and TON in the soil profile, we used the spreadsheet MODEVAL to compare simulated with observed values following the procedures given by Smith et al. (1997). Statistic variables that are employed for SOC and TON simulation include: relative root mean squared error (RRMSE), mean difference (M) evaluated by *t*-test, and the lack of fit (LOFIT) assessed by *F*-test. Because there are only 2 replications of each

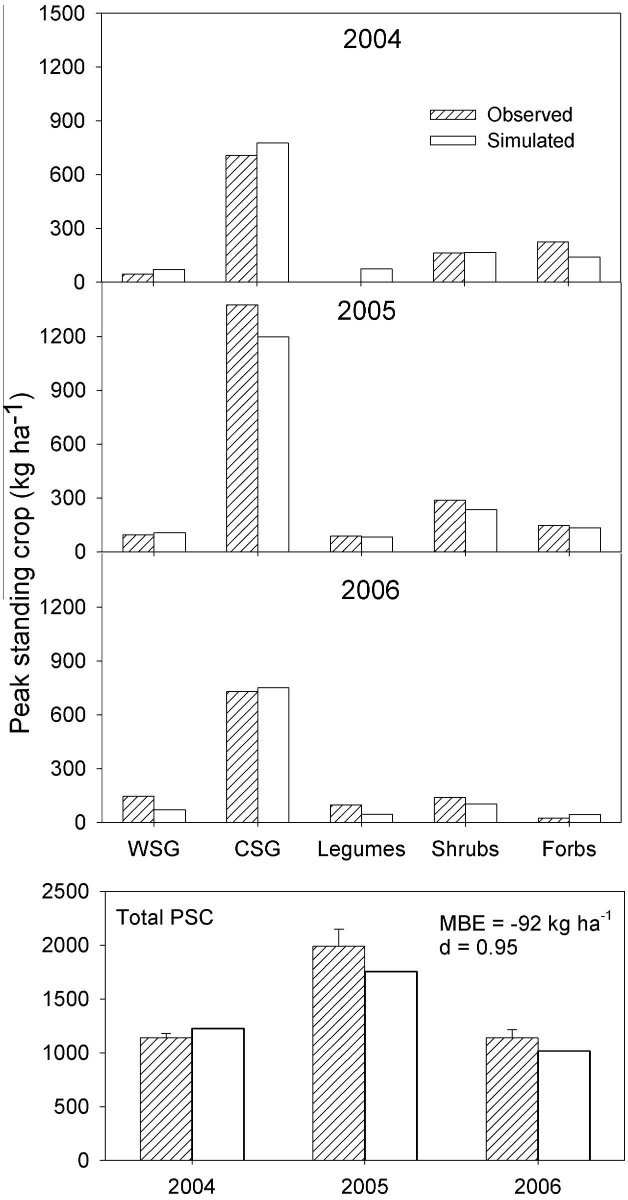

Fig. 2. Observed and simulated peak standing crops (PSC) of each functional group and the total PSC for the calibration EX treatment. Legumes were not sampled in 2004. Bars above and below each data column represent mean ± 1 standard deviation. Standard deviation of each functional group was not available. WSG, warm-season grasses; CSG, cool-season grasses.

grazing treatment and the trend in measurement was not strong, the 95% confidence limit of RRMSE, the relative error, and correlation coefficient were not used in this paper.

5. Sensitivity analysis

To analyze sensitivity of the C–N cycle module to different weather conditions, seven weather patterns with changed temperature and precipitation were established for the simulations under the CL treatment. Superimposed on the observed weather data for 1993–2006, these seven weather patterns included: (1) 5 °C lower temperature, (2) 5 °C lower temperature and double precipitation, (3) double precipitation, (4) 2.21 °C higher temperature; (5) 2.21 °C higher temperature and double precipitation, (6) double precipitation with increased maximum forage production parameter, and (7) 5 °C lower temperature and double precipitation with increased maximum forage production. The lower temperature scenarios are to mimic the weather at a location of higher latitude in the northern Great Plains, and the scenarios with double the precipitation amount are to simulate weather in eastern parts of the Great Plains. The temperature increase of 2.21 °C was adopted from the projection of the climate change model HadCM2 for 2030 in upper Colorado (Izaurralde et al., 2011). The scenarios with increased maximum forage growth were to mimic conditions of increased biomass production due to double precipitation under certain rangeland conditions.

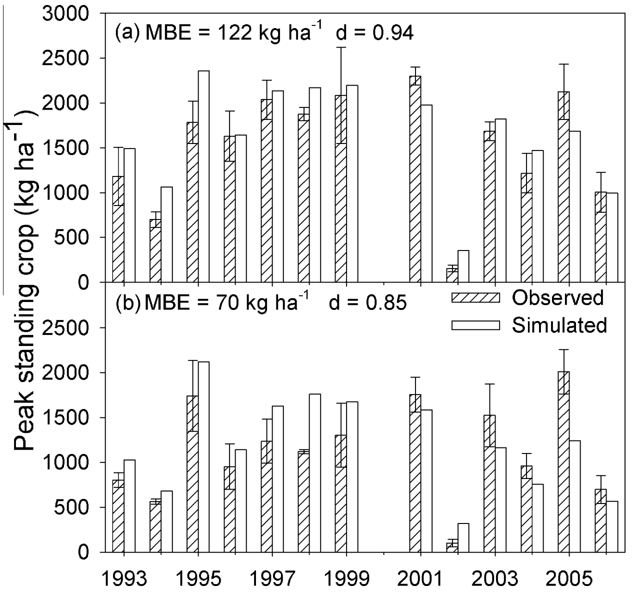

Fig. 3. Observed and simulated peak standing crops for the validation treatments of (a) CL and (b) CH. Peak standing crops were not sampled in 2000. Bars above and below each observed data column represent mean ± 1 standard deviation.

6. Results and discussion

6.1. Simulation of forage production

Predicted total PSC and PSC of each functional group were in good agreement with observed data for the non-grazed EX treatment (Fig. 2). The MBE and d values were −92 kg ha^{-1} and 0.95, respectively, which were comparable to the statistical values of Andales et al. (2006). The simulated CSG in the EX treatment was 938 kg ha^{-1}, within 5% error from the observed CSG of 945 kg ha^{-1}. The forage module responded well to weather conditions. The year of 2005 witnessed the highest amount of precipitation during April through June in 2004–2006 (Derner and Hart, 2007), and the model consequently predicted about 60% more CSG and 40–70% more total PSC in 2005 than in other years.

The model evaluation using treatments CL and CH indicated that the forage module performed well in predicting PSC (Fig. 3). The MBE values were 122 and 70 kg ha^{-1} for CL and CH treatments, respectively, which were within 10% of the observed annual average PSC. The model explained more than 80% of the variability for both treatments. Statistically, results of PSC in this study were comparable to those reported by Andales et al. (2006). The model responded well to weather variation with a yield decrease in PSC of 90% in the driest year of 2002.

However, the PSC was overestimated in 1993–1999 when the spring was wet and underestimated in 2000 when the spring was dry (Derner and Hart, 2007), in particular for the CH treatment. The model also failed to simulate the quick recovery of crop

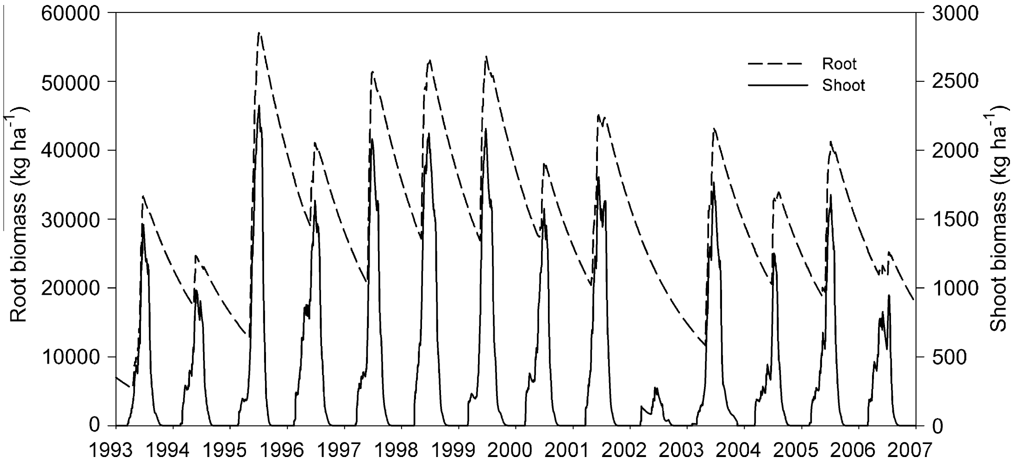

Fig. 4. Simulated root and shoot biomass for the treatment of CL.

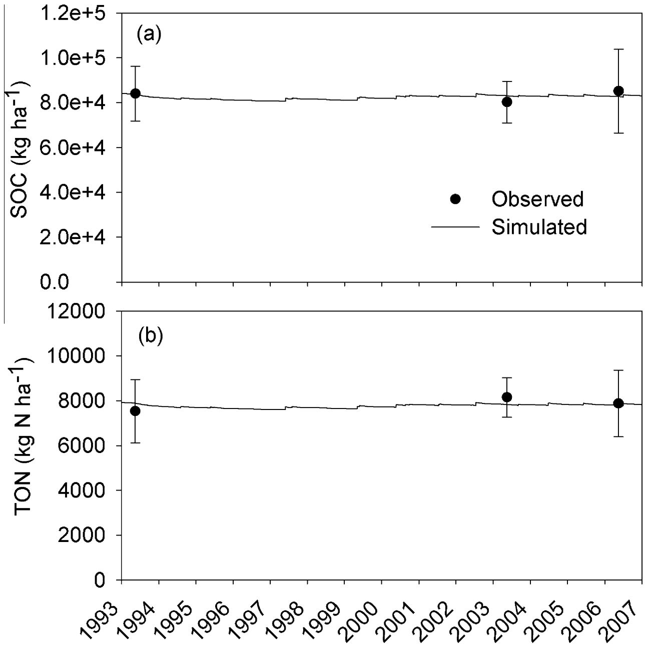

Fig. 5. Simulated and observed SOC and TON in the calibration treatment of EX. Bars above and below each observed data circle represent mean ± 1 standard deviation.

growth after a severe drought, the same as reported by Andales et al. (2005, 2006).

The predicted root biomass was in good agreement with observed data. For the calibration treatment of EX, the simulated root biomass in July 1993 was 39,443 kg ha^{-1}, with 2% overestimation of the observed 38,608 kg ha^{-1} (Schuman et al., 1999). For the validation treatments of CL and CH, the simulated root biomass in July 1993 was 30,455 and 33,770 kg ha^{-1}, respectively, which correspond to 2% and 15% overestimation. Such overestimation of root biomass was due to the overestimation of above ground biomass in 1993 for all treatments. Unfortunately, there was no root biomass to compare to in other years.

The root dynamics and total above ground biomass in the CL treatment are shown in Fig. 4. Although the simulated root biomass in 1993, the only year with observed root biomass, was within 2% error from the observed value, the simulated root biomass in other years was much higher than the data reported in the literature. Sims and Singh (1978) documented root biomass of ten grasslands in western North America. For a mixed-grass prairie, which is similar to our experiment site, the observed peak root biomass in 1970 was about 30,000 kg ha^{-1} for grazed grassland. Our simulated peak root biomass in 1995, however, was 57,000 kg ha^{-1} for the CL treatment in our study, approximately twice as much as the peak value reported by Sims and Singh (1978). The high estimated root biomass by the GPFARM-Range model is attributed to a high root-to-shoot ratio, a parameter for our study site, because the root biomass was computed by the production of above ground biomass multiplied by the root-to-shoot ratio. The root-to-shoot ratio parameter was set at 28.4 (Table 1), adopted from the observed value by Schuman et al. (1999). In a short-grass steppe in northern Colorado, which is about 60 km south to our site, Derner et al. (2006) reported observed root-to-shoot ratio of 25 for grazed

Table 4
Performance of the GPFARM-Range model in predicting SOC and TON.

Statistics	Unit	Calibration		Validation			
		EX		CL		CH	
		SOC	TON	SOC	TON	SOC	TON
RRMSE	%	3%	4%	10%	12%	18%	15%
MD	kg ha^{-1}	−4	10	3764	−661	−11136	−1012
MD/M	%	0%	0%	−4%	−8%	−13%	13%
Significant bias	Yes/No	No	No	No	No	No	No
	Good/Bad	Good	Good	Good	Good	Good	Good
MSLOFIT/MSE	–	0.11	0.2	0.85	0.93	5.84	6.47
F critical at 5%	–	7.71	7.71	7.71	7.71	7.71	7.71
Significant error	Yes/No	No	No	No	No	No	No
	Good/Bad	Good	Good	Good	Good	Good	Good

EX, exclosure; CL, continuous light grazing; CH, continuous heavy grazing; RRMSE, relative root mean squared error, MD, mean difference; M, mean; MSLOFIT, mean square of lack of fit; MSE, mean square error. Formula for the statistics included in this table can be found in Smith et al. (1997).

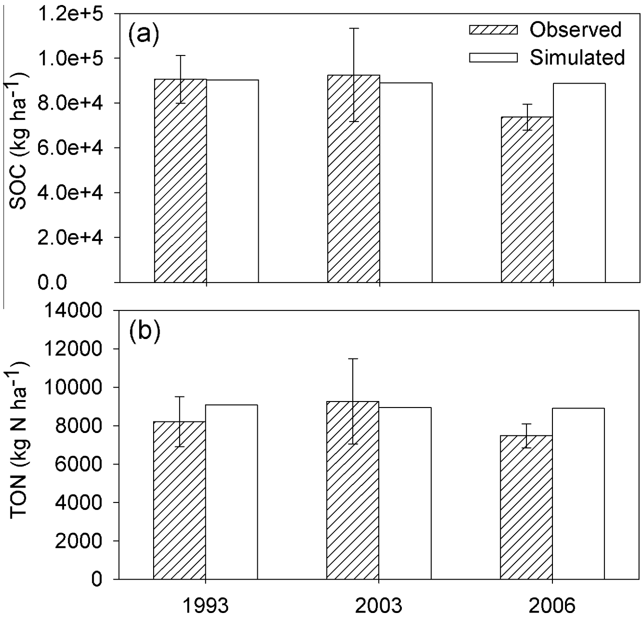

Fig. 6. Simulated and observed SOC and TON for the validation treatment of CL. Bars above and below each observed data column represent mean ± 1 standard deviation.

systems. A more complete dataset with intra-seasonal root dynamics, such as data reported by Sims and Singh (1978), is needed to further validate the calculation of root growth of this model. Since the dead roots are the major input sources of C and N in the system, the root mortality rate is a key parameter to the C and N turnover in soils.

6.2. Simulation of SOC and TON

Simulated and observed SOC and TON for the calibration treatment (EX) are illustrated in Fig. 5. There was no obvious trend in either the observed or simulated SOC or TON. The simulated and observed values were 83,100 versus 83,097 kg ha^{-1}, respectively, for SOC, and 7838 versus 7859 kg ha^{-1} for TON in the EX treatment. Statistical evaluations indicated that the simulated SOC and TON for the EX are in good agreement (Table 4). The RRMSE values were 3% and 4% for SOC and TON, respectively. There was no significant bias between the mean observed and simulated SOC and TON, nor was significant error indicated by the *F* test.

For the validation treatments of CL and CH, although some simulated values of SOC and TON were not in the range of mean observed values ±1 standard deviation (Figs. 6 and 7), results suggest that the SOC and TON were simulated reasonably well without significant bias or error (Table 3). The RRMSE of simulated SOC and TON for CL and CH were less than 20%, and the MD values were within ±15% of the observed mean.

Although simulated forage growth indicated low root growth in the extremely dry year of 2002, neither SOC nor TON was affected significantly by the simulated low biomass accumulation. This may be explained by the high belowground root biomass. For example, peak root biomass in the summer of 2001 was 44,657 kg ha^{-1} for CL, and by the end of 2002 the simulated remaining root biomass was 14,464 kg ha^{-1} after one and a half years decomposition. Therefore, even though there was not much new root growth in 2002, the large amount of root biomass in 2001 was adequate to supply C and N to the soil profile over the following two-year period.

Besides root growth and death rates, the C:N ratio of the dead root biomass is another key parameter that impacts the build-up of SOC and TON in the C–N cycle module. There is only one compartment for dead roots and the C:N ratio of soil dead root material is updated every day using the weighted average C:N ratio in the decomposing dead root and fresh dead root for that day. Because the decomposed soil residue was added into the fast organic matter pool until the C:N ratio was less than 12, a high C:N ratio of the dead roots will postpone and reduce the addition of residue to the fast organic matter pool. In this study, the root C:N ratio was adjusted from 25 to 21 or 18 to obtain better SOC and TON simulation results.

As noted above, the observed (1993) and simulated root biomass were higher than values reported in the literatures (Sims and Singh, 1978; Derner et al., 2006). Under a given root mortality rate, higher root biomass resulted in high fast SOC pool. We created a new scenario using root-to-shoot ratio value of 10 for the CL treatment based on the findings for a mix-grass prairie at Dickinson, ND by Sims et al. (1978). This low root-to-shoot ratio produced much less simulated peak root biomass, ranging from 8892 kg ha^{-1} in 2002 to 21,299 kg ha^{-1} in 1995, within the range reported by Sims and Singh (1978). The scenario under the low root-to-shoot ratio (10) led to a drastic reduction of fast SOC pool in comparison to the high root-to-shoot ratio (28.4). The fast SOC reduced from 3450 kg ha^{-1} for high root-to-shoot ratio to 1318 kg ha^{-1} after 14 years of cycle in the CL treatment. However, this difference in the fast SOC pool did not affect the total SOC very much (was within 5%), since the slow SOC pool had a much higher magnitude. The simulated total SOC was 86,522 kg ha^{-1} for the low root-to-shoot ratio after 14 years, compared with 88,978 kg ha^{-1} for the high root-to-shoot ratio.

6.3. Sensitivity test

The sensitivity test of the C–N cycle module indicates that increased temperature or double rainfall only led to a net organic carbon loss in soils (Fig. 8). Increased temperature slightly reduced biomass accumulation under the structure of functional groups in this study, but increased the soil mineralization rate. For example, the simulated PSC under 2.21 °C higher temperature was

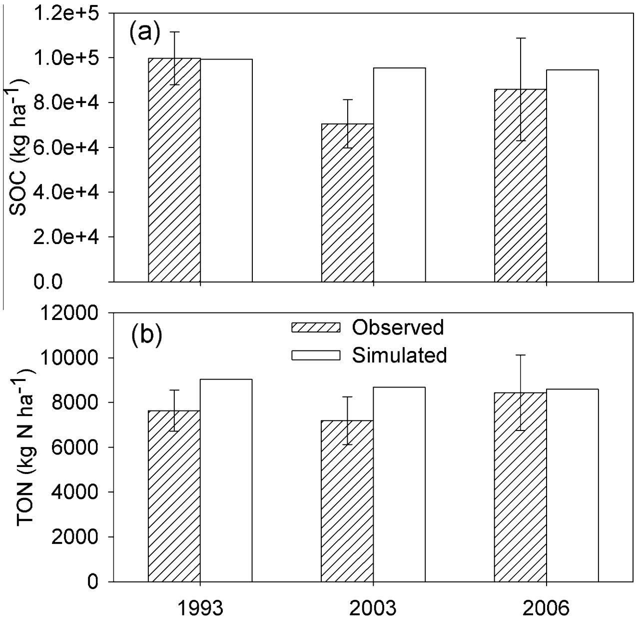

Fig. 7. Simulated and observed SOC and TON for the validation treatment of CH. Bars above and below each observed data column represent mean ± 1 standard deviation.

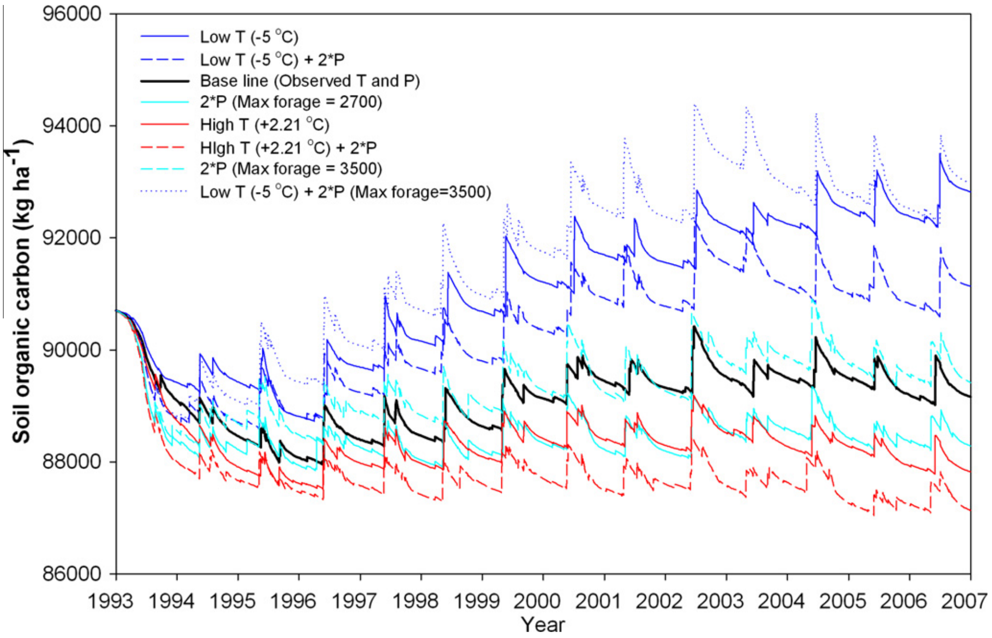

Fig. 8. Sensitivity of predicted soil organic carbon to various weather patterns. Low *T* (−5 °C): 5 °C lower temperature than observed; 2 ∗ P: double precipitation; High *T* (+2.21 °C), 2.21 °C higher temperature than observed.

1579 kg ha^{-1} which was about 4% lower than the baseline, while the *tfac* for mineralization in Eq. (9) was 0.195, which was 20% higher than that of 0.163 under the baseline conditions. Double rainfall only increased the PSC by 26%, however, the *wfac* in Eq. (9) increased by 59%, which indicated that the loss of SOC due to increased mineralization outpaced the gain of SOC due to increased dead root material input.

Lower temperature, with or without double precipitation, resulted in an increase of SOC in the soil profile. The biomass was not affected by the 5 °C lower temperature because the slight decreases in warm-season grass biomass was offset by the increased PSC of cool-season grasses, but the *tfac* for mineralization was reduced by 33%. Under the scenario of lower temperature combined with double precipitation, the increase of SOC in the soil profile was less than that under the condition of lower temperature only because the mineralization reduced by lower *tfac* was offset by increased *wfac* under increased precipitation.

It should be noted that the above simulations were conducted using fixed maximum potential forage of 2700 kg ha^{-1} for the CL treatment from the calibration. However, the maximum potential forage growth under double precipitation may be much higher than the calibrated value under certain rangeland and weather condition. The simulations indicated that stored SOC increased under increased potential maximum biomass production. For example, when potential maximum biomass increased from 2700 to 3500 kg ha^{-1}, SOC increased by 1846 and 1133 kg ha^{-1} for 5 °C lower temperature combined with double precipitation and double precipitation only, respectively.

7. Conclusions

The observed peak standing crop was successfully simulated using the forage module of GPFARM-Range, with reasonable outputs in surface and sub-surface biomasses contributing to the C–N cycle. Predicted SOC and TON in the rangeland soils by the newly developed C–N cycle module for the GPFARM-Range model were in reasonably good agreement with field measured data. The sensitivity analysis showed that the model responded reasonably to weather scenarios in simulating SOC. This study suggests that the NLEAP C–N algorithms and organic and inorganic pool structures can be used as a C–N cycle module in the GPFARM-Range model to investigate soil organic matter turnover in rangelands.

The C–N cycle module needs further testing against long-term data with more frequent SOC and TON measurements. The available dataset used in this study only included three sampling times over a 14-year period for each treatment plot. Unfortunately, longer term data for rangelands are not available at this time. Because root mortality rate is a key parameter that determines residue input to the soil, detailed annual root dynamics data would also be helpful to improve the simulation. Furthermore, an enhancement of the algorithms and/or accounting of dead root material influencing their fate to soil organic matter fast pools should be explored.

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