Leaf phenological shifts and plant-microbe-soil interactions can determine forest productivity and nutrient cycling under climate change in an ecosystem model

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Supporting Information

First, ESM 1 describes the mathematical formulas for our model in detail. Next, ESM 2 and Fig. S1 explain how the sensitivity analysis was conducted.

ESM **1** Detailed mathematical formulas of the model

First, we use two different parameters for time: t for a continuous value and J for the Julian day of year as $t \in [0.0, 365.0)$ and $J \in [1, 365]$ with the relationship $J = \lfloor t \rfloor + 1$, where $\lfloor t \rfloor$ is the integer part of t. Table S1 shows all parameter definitions and default values.

Carbon and nitrogen biomass in growth tissues of the plant

The dynamics in carbon (C) and nitrogen (N) biomass in growth tissues of the plant at time t ($C_G[t]$ and $N_G[t]$, respectively) are governed by Eqs. (S1) and (S2) respectively:

$$\frac{dC_G[t]}{dt} = (1 - f_R)GPP[t] + r_C[J] - s_C[J] - R_{PG}[t] - f_{LC}[t] \tag{S1}$$

= [GPP – excretion of organic C from root] + [regrowth from storage] – [reallocation to storage part] – [respiration of growth part] – [litter production],

$$\frac{dN_G[t]}{dt} = u_P[t] + r_N[J] - s_N[J] - f_{LN}[t] \tag{S2}$$

= [uptake from soil] + [regrowth from storage] – [reallocation to storage part] – [litter production],

where gross primary production at time t ($0.0 \leq t < 365.0$) $GPP[t]$ is calculated by Eqs. 1–3 in the main text and the fraction f_R of GPP is released from root to soil.

The uptake of inorganic N from soil only occurs in the growth phase (Phase 3), which is proportional to the plant C biomass and concentration of inorganic N in soil, and is given by Eq. (S3):

$$u_P[t] = \begin{cases} u_{PN0}N_I[t]C_G[t] & \text{if } J \in \text{Phase 3} \\ 0 & \text{else} \end{cases}. \tag{S3}$$

The regrowth from storage tissues only occurs in Phase 2 ($D_B - S_{RG} + 1 \leq J \leq D_B$), and the function is given by Eq. (S4):

$$r_X[J] = \begin{cases} \dfrac{X_R[D_B - S_{RG}]}{S_{RG}} & \text{if } J \in \text{Phase 2} \\ 0 & \text{else} \end{cases} \quad (X = C \text{ or } N), \tag{S4}$$

where C and N stocks, C_R and N_R, respectively, at the end of Phase 1 ($t = D_B - S_{RG}$) are allocated again for growth at a constant rate over S_{RG} days in Phase 2. At the end of Phase 2, the storage tissues have exhausted their supplies of C and N by simply neglecting to accumulate C and N over time.

The reallocation to storage occurs only in Phase 4 ($D_F - S_L + 1 \leq J \leq D_F$), and the function is given by Eq. (S5):

$$s_X[J] = \begin{cases} \dfrac{r_X X_G[D_F - S_L]}{S_L} & \text{if } J \in \text{Phase 4} \\ 0 & \text{else} \end{cases} \quad (X = C \text{ or } N), \tag{S5}$$

where the fraction r_C (or r_N) of C (or N) stocked in the growth tissues at the end of the Phase 3 ($t = D_F - S_L$) is reallocated to storage in a constant rate over S_L days in Phase 4. In general, the optimal allocation schedule of photosynthetic products to growth, storage, and reproductive tissues should be considered (Iwasa 2000). However, to avoid more complex phenological events, we assumed that reallocation does not occur during the growing season.

The respiration rate, which is proportional to biomass and occurs in the regrowth and growing phases (phases 2 and 3) ($D_B - S_{RG} + 1 \leq J \leq D_F - S_L$), follows the Arrhenius equation (Davidson and Janssens 2006) shown in Eq. (S6):

$$R_G[t] = \begin{cases} b_0 \exp\left[-\dfrac{E}{RT_A[J]}\right]C_G[t] & \text{if } J \in \text{Phase 2, Phase 3} \\ 0 & \text{else} \end{cases} \tag{S6}$$

where b_0 is the reaction rate constant, E is the required activation energy, R is the gas constant (8.314 J·K^{-1}·mol^{-1}), and $T_A[J]$ is the aboveground temperature in degrees Kelvin.

The litter production rate during the growth phase (Phase 3) is proportional to C (or N) biomass, whereas it is constant in the autumn season (Phase 5), and is given by Eq. (S7):

$$f_{LX}[t] = \begin{cases} f_{L0}X_G[t] & \text{if } J \in \text{Phase 3} \\ \dfrac{X_G[D_F]}{F_L} & \text{if } J \in \text{Phase 5} \ (X = C \text{ or } N). \\ 0 & \text{else} \end{cases} \tag{S7}$$

Carbon and nitrogen biomass in storage tissues of the plant

The dynamics in C and N biomass in the storage tissues of a plant at time t ($C_R[t]$ and $N_R[t]$, respectively) are governed by the processes illustrated in Eqs. (S8) and (S9), respectively:

$$\frac{dC_R[t]}{dt} = -r_C[J] + s_C[J] - R_R[t]$$

= – [regrowth from storage] + [reallocation to storage] – [respiration of storage],

(S8)

$$\frac{dN_R[t]}{dt} = -r_N[J] + s_N[J]$$

= – [regrowth from storage] + [reallocation to storage].   (S9)

The respiration rate, which is proportional to biomass and occurs throughout the year, except during the regrowth phase (Phase 2), follows the Arrhenius equation (Eq. S10):

$$R_R[t] = \begin{cases} 0 & \text{if } J \in \text{Phase 2} \\ b_0 \exp\left[-\dfrac{E}{RT_B[J]}\right] C_R[t] & \text{else} \end{cases}$$

(S10)

where $T_B[J]$ is the belowground temperature in degrees Kelvin. Because the period of the regrowth phase is relatively short (= 5 days, Table S1), respiration at this phase is negligible.

Carbon and nitrogen stocks in soil

The dynamics of C and N stocks in soil at time t ($C_S[t]$ and $N_S[t]$, respectively) are given by Eqs. (S11) and S12), respectively:

$$\frac{dC_S[t]}{dt} = f_R GPP[t] + f_{LC}[t] - DEC_C[t] + m_M C_M[t]$$

= [excretion from root] + [litter production] – [decomposition] + [microbial mortality],

(S11)

$$\frac{dN_S[t]}{dt} = f_{LN}[t] - DEC_N[t] + m_M N_M[t]$$

= [litter production] – [decomposition] + [microbial mortality],   (S12)

where the decomposition rate follows Eq. 4. More specifically, the decomposition rate of C and N follows the (modified) Arrhenius equation (Eq. S13):

$$DEC_X[t] = k_{L,293} \exp\left[-\frac{E}{R}\left(\frac{1}{T_B[J]} - \frac{1}{293}\right)\right] C_M[t] X_S[t] \quad (X = C \text{ or } N) \quad (S13)$$

where $k_{L,293}$ is the decomposition constant at 20 °C and the decomposition rate changes with belowground temperature $T_B[J]$.

Population dynamics of soil microbes

As is explained in the main text, the amount of C (and N) assimilated by microbes depends on the potential assimilation rate of C $pASIM_C$ (that of N $pASIM_N$), and the fixed ratio of microbial C to N $(C:N)_M$. These potential assimilation rates are given by Eqs. (S14) and (S15), respectively:

$$pASIM_C[t] = e_{MC} DEC_C[t], \hspace{4cm} (S14) \text{ and}$$

$$pASIM_N[t] = e_{MN} DEC_N[t] + k_I C_M[t] N_I[t], \hspace{2.5cm} (S15)$$

where e_{MC} and e_{MN} are the potential assimilation efficiency of decomposed C and N, respectively, and k_I represents the maximum affinity for inorganic N uptake in soil. The

realized assimilation rate of C to meet the fixed ratio of microbial C:N (to maintain

homeostasis) is given by Eq. (S16):

$$rASIM_C[t] = \begin{cases} (C:N)_M \, pASIM_N[t] & \text{if } pASIM_C[t] > (C:N)_M \, pASIM_N[t] \\ pASIM_C[t] & \text{else} \end{cases} \quad \text{(S16)}$$

The rate of microbial respiration θ_C and net mineralization rate θ_N are given by Eqs. (S17) and

(S18), respectively:

$$\theta_C[t] = DEC_C[t] - rASIM_C[t], \tag{S17}$$

$$\theta_N[t] = DEC_N[t] - \frac{rASIM_C[t]}{(C:N)_M}. \tag{S18}$$

The dynamics of microbial C biomass at time t, $C_M[t]$, is given by Eq. (S19):

$$\frac{dC_M[t]}{dt} = rASIM_C[t] - m_M C_M[t]$$

= [assimilation through decomposition] - [microbial mortality], (S19)

noting that we do not need to prepare a dynamic equation for $N_M[t]$ because of the fixed C:N,

i.e., $N_M[t] = C_M[t]/(C:N)_M$.

Dynamics of inorganic nitrogen in soil

The dynamics of inorganic N at time t, $N_I[t]$, is given by Eq. (S20):

$$\frac{dN_I[t]}{dt} = \theta_N[t] - u_P[t] + n_{INPUT} - l_N N_I[t]$$

= [net mineralization] – [uptake by plant] + [nitrogen deposition] – [leaching], S(20)

where n_{INPUT} and l_N represent a constant deposition and specific leaching rates, respectively.

ESM **2** Sensitivity Analysis

This ESM explains how to conduct the sensitivity analysis (Fig. S1). Note again that we obtained results shown in Fig. 2 with the default parameter values (Table S1) and that the sensitivity of our model behavior with a single parameter changed is shown in Fig. 3. For evaluating the sensitivity to changes in all of parameters shown in Fig. 3, we chose 1000 sets of parameter values that were randomly selected from a range of −50% to +50% of the default value (using a uniform distribution in default value x [0.5, 1.5]), and then conducted numerical simulations for each parameter set. Because the variations in parameter values are very large, some of simulations show unrealistic values. When we focused on the leaf area index (LAI), 294 combinations in 1000 simulations resulted in LAI > 20 (and the maximum LAI is 37.2). We then excluded these 294 combinations prior to generating the boxplots showing the range and variations of values predicted by our model (Fig. S1).
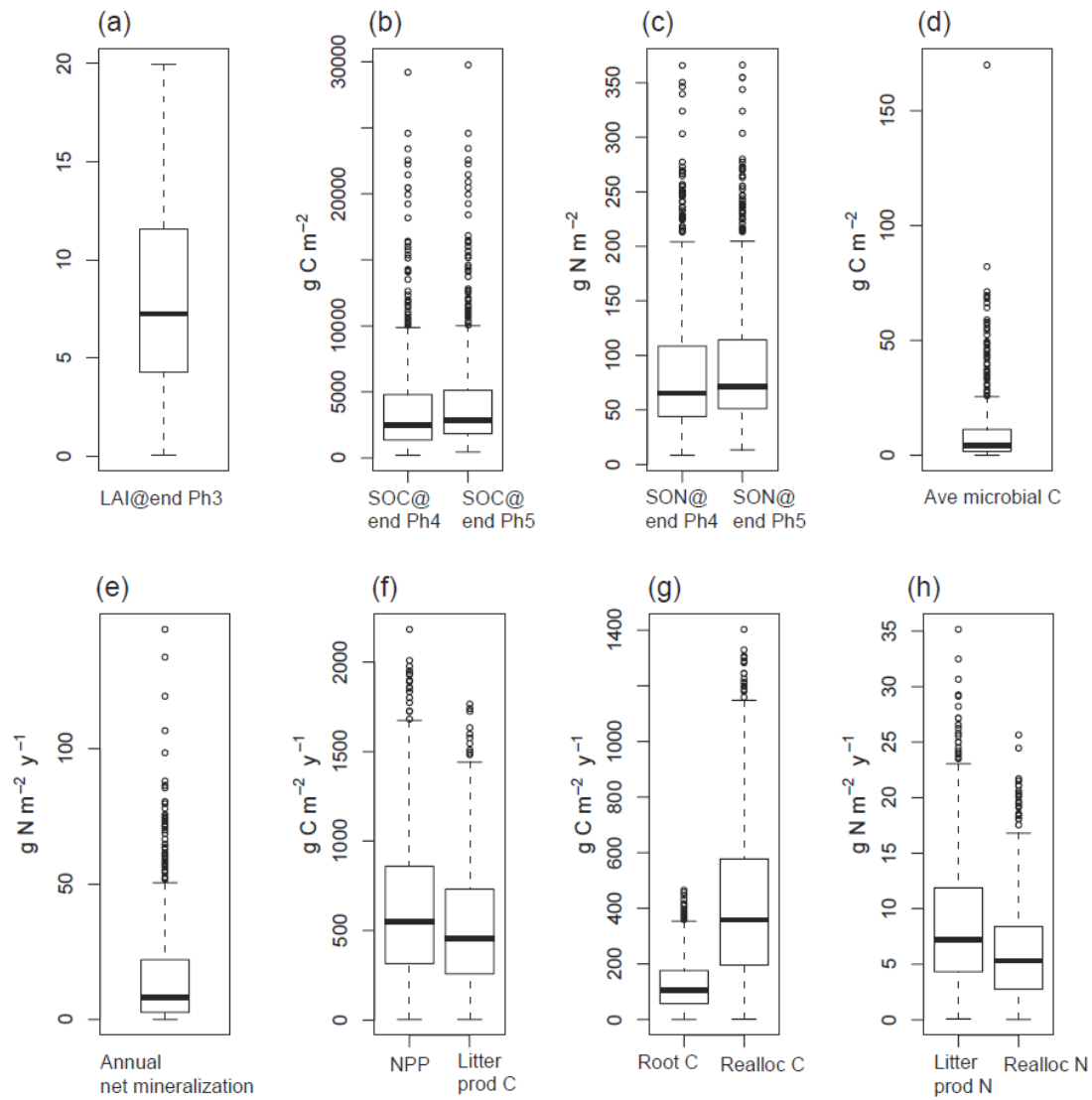
Figure S1. Box plots of sensitivity analysis. (a) Leaf area index (LAI). (b) and (c) Accumulated soil organic carbon (C) and nitrogen (N) at the end of phases 4 and 5, respectively. (c) Accumulated soil organic N at the end of phases 4 and 5. (d) Annual average C biomass of microbes. (e) Annual net mineralization rate. (f) Annual net primary production and annual production of litter C. (g) Annual rate of release of organic C from the plant root and reallocation of C into the storage tissues of the plant. (e) Annual production of litter N and annual rate of reallocation of N into the storage tissues of the plant.

Table S1 List of variables, parameters, and default values

Symbol	Definition	Abbreviation	Unit	Default value
C_G	Carbon biomass of new growth of plant	-	g m^{-2}	-
N_G	Nitrogen biomass of new growth of plant	-	g m^{-2}	-
C_R	Carbon biomass of storage part of plant	-	g m^{-2}	-
N_R	Nitrogen biomass of storage part of plant	-	g m^{-2}	-
C_S	Soil organic carbon	-	g m^{-3}	-
N_S	Soil organic nitrogen	-	g m^{-3}	-
N_I	Soil mineral nitrogen	-	g m^{-3}	-
C_M	Carbon biomass of microbes	-	g m^{-3}	-
N_M	Nitrogen biomass of microbes	-	g m^{-3}	$(C{:}N)_M C_M$
D_B	Initial day of expanding leaves	-	day of year	100[a]
D_F	Initial day of litter fall in autumn	-	day of year	300[b]
S_{RG}	Period of regrowth phase	-	day	5[*]
S_L	Period of reallocation phase	-	day	14[*]
F_L	Period of litter fall in autumn	-	day	14[*]
GPP	Gross primary production	-	µgC s^{-1}	Eq. 1
ϕ	Quantum efficiency	-	µgC J^{-1}	2.73[c]
θ	Curvature parameter	-	dimensionless	0.75[c]
a	Photosynthetic capacity per N	-	µgC gN^{-1} s^{-1}	52.5[c]
I_0	Incident PAR above the canopy	-	J s^{-1} m^{-2}	200[c]
L	Leaf area index	-	m^2 m^{-2}	$C_G \cdot LAR$
LAR	Leaf area ratio	-	m^2 g^{-1}	0.01[*]
k	Canopy light extinction factor	-	dimensionless	0.45[c]
N_{min}	Constant for nitrogen biomass	-	gN m^{-2}	0.4[c]
b_0	Reaction constant for respiration	-	gC d^{-1} g^{-1}	3.05×10^6[d]

29	E	Activation energy	-	kJ mol^{-1}	50.0[e]
30	R	Gas constant	-	J K^{-1}	8.314[e]
31	n_{INPUT}	Nitrogen deposition rate	N_deposition	gN m^{-2} d^{-1}	0.001[f]
32	l_N	Leaching rate of nitrogen	N_leaching	d^{-1}	0.01[*]
33	r_N	Reallocation efficiency of nitrogen	ReAllocN	dimensionless	0.5[*]
34	r_C	Reallocation efficiency of carbon	ReAllocC	dimensionless	0.5[*]
35	f_{L0}	Litter production rate in growing phase	frac_Litter0	d^{-1}	0.001[g]
36	f_R	Fraction of GPP excreted from root	frac_rootC	dimensionless	0.1[h]
37	u_{PN0}	Affinity of nitrogen uptake of plant	UptakeN_P	d^{-1} (gC m^{-2})$^{-1}$	0.01[*]
38	$(C{:}N)_M$	Carbon to nitrogen ratio of microbes	CNratio_M	gC gN^{-1}	8.0[i]
39	$k_{L,293}$	Decomposition constant at 20 °C	Decomp_293	d^{-1} gC^{-1}	1.0/(365 × 20)[j]
40	e_{MC}	Carbon growth efficiency of microbes	GrowthEffC_M	dimensionless	0.5[*]
41	e_{MN}	Nitrogen growth efficiency of microbes	GrowthEffN _M	dimensionless	0.5[*]
42	m_M	Microbial mortality	Mortality_M	d^{-1}	1.0/30.0[*]
43	k_I	Affinity of nitrogen uptake of microbes	UptakeN_M	d^{-1} (gC m^{-3})$^{-1}$	0.005[*]

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45 Note: GPP, gross primary production; PAR, photosynthetically active radiation.
46 a) Assuming the date used for typical temperate forest with regard to data from Japan (Matsumoto et al. 2003, Doi 2012)
47 b) Assuming the date used for typical temperate forest with regard to data from temperate regions (Matsumoto et al. 2003; Menzel et al.
48 2006; Doi 2012)
49 c) Franklin (2007)
50 d) Calculated by the average of samplings data (Table 2) in Reich et al. (2006).
51 e) Davidson and Janssens (2006)
52 f) Kjonnas and Wright (1998)
53 g) 0.1% if daily net primary production is assumed to be consumed by herbivores
54 h) Bardgett et al. (2005)
55 i) Manzoni and Porporato (2007)
56 j) Assuming that the turnover rate is in the order of 20 years with 1 gC of microbes.
57 *) Reasonable values are assumed

58   **References**

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61   linking aboveground and belowground ecology. Trends Ecol Evol 20:634–641.

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65   latitudinal pattern in Japan. Int J   Biometeorol 56: 895–902.

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71   in soil carbon and nitrogen cycles. Soil Biol.Biochem 39, 1542–1556.

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73   of the *Ginkgo biloba* L. growing season in Japan. Global Change Biol 9: 1634–1642.

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75   climate change matches the warming pattern. Global Change Biol 12: 1969–1976.

76   Reich PB, Hobbie SE, Ellsworth DS, West JB, Tilman D, Knops JMH, Naeem S, Trost

77   J, (2006) Nitrogen limitation constrains sustainability of ecosystem response to CO_2.

78   Nature 440: 922–925.

Table S2 Summary of the observed values used in Figure 2

Parameters	Values/Unit	Values/Unit	References	Note
NPP	$g \cdot m^{-2} \cdot y^{-1}$			
	638.5		Greco et al. (1996) *Glob Change Biol* 2, 183–197	Oak temperate forest, annual mean of 1993
	585		Waring et al. (1998) *Tree Physiol,* 18, 129–134	
	457		Waring et al. (1998) *Tree Physiol,* 18, 129–134	
	540		Turner and Long (1975) *Canadian J of For Res,* 5, 681–690	
	442.7		Harvard forest database (http://harvardforest.fas.harvard.edu)	
	555.125			Average was used in Fig. 2
LAI	$m^2\, m^{-2}$			
	0–5		Greco et al. (1996) *Glob Change Biol,* 2, 183–197	Oak temperate forest, annual mean of 1993
	5–6		Hollinger et al. (1994) *Ecology,* 75, 134–150.	
	2–10		Franklin (2007) *New Phytologist,* 174, 811–822	From the model
	0.2–7.1		Harvard forest database (http://harvardforest.fas.harvard.edu)	
SOC	$g \cdot m^{-2}$	$g \cdot kg^{-1}$		With assuming 1 m depth, the value is equivalent to $g \cdot m^{-3}$
	2998		Drake et al. (2011) *Ecol Letters,* 14, 349–357	Data were compiled across multiple years (2003–2007)
	1340		Raich and Schlesinger (1992) *Tellus,* 44, 81–99	review
	1895	37.9	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–5 cm
	3190	63.8	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–5 cm
	857.5	34.3	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–10 cm
	2700		Forest Science Data Bank, Corvallis, OR.	0–20 cm
	2056.10			Average was used in Fig. 2

SON	g·m^{-2}	g·kg^{-1}		With assuming 1 m depth, the value is equivalent to g·m^{-3}
	164		Drake et al. (2011) *Ecol Letters,* 14, 349–357	Data were compiled across multiple years (2003–2007)
	112	2.24	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–5 cm
	179	3.58	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–5 cm
	29.8	1.19	Ellerbrock et al. (2005) *Soil Sci Soc of Am J,* 69, 57–66	0–10 cm
	14.1	0.9	Garten et al. (2011) *Ecology,* 92, 133–139	0–16 cm
	15.9	1.02	Garten et al. (2011) *Ecology,* 92, 133–139	0–16 cm
	14.1	0.9	Garten et al. (2011) *Ecology,,* 92, 133–139	0–16 cm
	179.9		Harvard forest database (http://harvardforest.fas.harvard.edu)	
	310		Forest Science Data Bank, Corvallis, OR.	0–20 cm
	75.54			Average was used in Fig. 2
Microbial C	g·m^{-2}	g·kg^{-1}		
	55		Drake et al. (2011) *Ecol Letters,* 14, 349–357	Data were compiled across multiple years (2003–2007)
	28		Ekelund et al. (2001) *Soil Biol and Biochemistry,* 33, 475–481	surface layer
	2.5	0.001	Wallenstein et al. (2006) *For Ecol and Manage,* 222, 459–468	
	13.75	0.0055	Wallenstein et al. (2006) *For Ecol and Manage,* 222, 459–468	
	20	0.008	Högberg and Högberg (2002) *New Phytologist,* 154, 791–795	
	23.85			Average was used in Fig. 2
Microbial Respiration	g·m^{-2}·y^{-1}			
	544		Greco et al. (1996) *Glob Change Biol,* 2, 183–197	Oak temperate forest, annual mean of 1993
	463.08		Raich and Schlesinger (1992) *Tellus,* 44, 81–99	Microbial respiration is assumed to be 68% of soil respiration
	491.9616		Heinemeyer et al. (2007) *Glob Change Biol,* 13, 1786–1797.	
	470		Kelting et al. (1998) *Soil Biol and Biochemistry,* 30, 961–968	
	1131.792		Fernandez et al. (1993) *Soil Sci Soc of Am J,* 57, 1115–1121	Microbial respiration is assumed to be 68% of soil

			respiration
	1906.176	Fernandez et al. (1993) *Soil Sci Soc of Am J,* 57, 1115–1121	Microbial respiration is assumed to be 68% of soil respiration
	473.28	Bowden et al. (2004) *For Ecol and Manage,* 196, 43–56	Microbial respiration is assumed to be 68% of soil respiration
	658.92	Bowden et al. (2004) *For Ecol and Manage,* 196, 43–56	Microbial respiration is assumed to be 68% of soil respiration
	563.04	Bowden et al. (2004) *For Ecol and Manage,* 196, 43–56	Microbial respiration is assumed to be 68% of soil respiration
	51–978	Harvard forest database (http://harvardforest.fas.harvard.edu)	
	744.6944		Average was used in Fig. 2
Microbial C:N	$g \cdot g^{-1}$		
	7.35	Cleveland and Liptzin (2007) *Biogeochemistry,* 85, 235–352	Review, Calculated from C:N = 60:7 (mol:mol)
	6.0	Wright and Coleman (2000) *Pedobiologia* 44, 2–23.	Calculated from C:N = 900:150 (g:gl)
Plant C_G	$g \cdot m^{-2}$		
	8650.8	Kjønass and Wright (1998) *Hydrology and Earth Syst Sci,* 2, 415–429	Sum of structural and active pools
	5700	Harvard forest database (http://harvardforest.fas.harvard.edu)	
Plant N_G	$g \cdot m^{-2}$		
	63.14	Kjønass and Wright (1998) *Hydrology and Earth Syst Sci,* 2, 415–429	Sum of structural and active pools
	77.0	Martin and Aber (1997) *Ecol Applications*, 7 431–443.	Harvard forest
Litter C	$g \cdot m^{-2} \cdot y^{-1}$		
	685.2	Kjønass and Wright (1998) *Hydrology and Earth Syst Sci,* 2, 415–429	
	360	Harvard forest database (http://harvardforest.fas.harvard.edu)	
Litter N	$g \cdot m^{-2} \cdot y^{-1}$		
	12.292	Kjønass and Wright (1998) *Hydrology and Earth Syst Sci,* 2, 415–429	

	14.4	Harvard forest database (http://harvardforest.fas.harvard.edu)	Harvard forest, calculated from 2.0% N contents.
N Deposition	$g \cdot m^{-2} \cdot y^{-1}$		
	1.0	Currie et al. (1996) *Biogeochemistry* 35, 471–505	Harvard forest
	1.176	Kjønass and Wright (1998) *Hydrology and Earth Syst Sci,* 2, 415–429	

80   Note: C, carbon; LAI, leaf area index; N, nitrogen; NPP, net primary production; SOC, soil organic carbon; SON, soil organic nitrogen.