



# Supplement of

## Jena Soil Model (JSM v1.0; revision 1934): a microbial soil organic carbon model integrated with nitrogen and phosphorus processes

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This appendix includes a detailed description of the model with equations and tables of parameter values.

## S1 The SOM cycle

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The model represents different soil organic pools (woody (*wl*), polymeric (*poly*), and soluable (*sol*) litter, as well as dissolved organic matter (DOM, *dom*), microbial biomass (*mic*), microbial residue (*res*), mineral-associated DOM (*aDom*), and
mineral-associated microbial residue (*aRes*)), and the dynamics of them (X = C, N, P, <sup>13</sup>C, <sup>14</sup>C, <sup>15</sup>N) are described in general as:

$$\frac{\partial}{\partial t}X_{wl} = \sum (f_{vp \to wl}F_{L_{vp}}) - \frac{X_{wl}}{\tau_{wl}} - \frac{\partial}{\partial z}(D_b\frac{\partial X_{wl}}{\partial z}) - \frac{\partial(\omega \cdot X_{wl_{sl>1}})}{\partial z}$$
(S1a)

$$\frac{\partial}{\partial t}X_{sol} = \sum (f_{vp \to sol}F_{L_{vp}}) - \frac{X_{sol}}{\tau_{sol}} - \frac{\partial}{\partial z}(D_b\frac{\partial X_{sol}}{\partial z}) - \frac{\partial(\omega \cdot X_{sol})}{\partial z}$$
(S1b)

$$\frac{\partial}{\partial t} X_{poly} = \sum (f_{vp \to poly} F_{L_{vp}}) + \eta_{wl \to poly} \frac{X_{wl}}{\tau_{wl}} - F_{poly \to dom}^{depoly}$$

$$-\frac{\partial}{\partial z} \left( D_b \frac{\partial X_{poly}}{\partial z} \right) - \frac{\partial (\omega \cdot X_{poly})}{\partial z}$$
(S1c)

$$\frac{\partial}{\partial t} X_{dom} = \eta_{sol \to dom} \frac{X_{sol}}{\tau_{sol}} + F_{poly \to dom}^{depoly} + F_{res \to dom}^{depoly} - F_{dom \to aDom}^{sorp}$$

$$-F_{dom \to mic}^{upt} + \eta_{mic \to dom} \frac{X_{mic}}{\tau_{mic}} + \sigma_{recycle}$$

$$-\frac{\partial v_{dom} dom}{\partial \phi} - \frac{\partial}{\partial \phi} \left(D_{t} \frac{\partial X_{dom}}{\partial \phi}\right) - \frac{\partial(\omega \cdot X_{dom})}{\partial \phi}$$
(S1d)

$$-\frac{\partial v_{dom} dom}{\partial z} - \frac{\partial}{\partial z} \left( D_b \frac{\partial X_{dom}}{\partial z} \right) - \frac{\partial \left( \omega \cdot X_{dom} \right)}{\partial z}$$
(S1d)

$$\frac{\partial}{\partial t} X_{mic} = F_{mic}^{growth} - \eta_{mic \to dom} \frac{X_{mic}}{\tau_{mic}} + \Phi_{immobilisation} - \frac{\partial}{\partial c} (D_b \frac{\partial X_{mic}}{\partial c}) - \frac{\partial(\omega \cdot X_{mic})}{\partial c}$$
(S1e)

$$-\frac{\partial}{\partial z} \left( D_b \frac{\partial A_{mic}}{\partial z} \right) - \frac{\partial \left( \omega \cdot A_{mic} \right)}{\partial z}$$
(S1e)
$$X_{res} = n_{mis} \sum_{mic} \frac{X_{mic}}{z} - F^{depoly} - F^{sorp} = n_{mis} - \sigma_{maxids}$$

$$\frac{\partial}{\partial t} X_{res} = \eta_{mic \to res} \frac{X_{mic}}{\tau_{mic}} - F_{res \to dom}^{depoly} - F_{res \to aRes}^{sorp} - \sigma_{recycle} - \frac{\partial}{\partial z} (D_b \frac{\partial X_{res}}{\partial z}) - \frac{\partial (\omega \cdot X_{res})}{\partial z}$$
(S1f)

$$\frac{\partial}{\partial t}X_{aDom} = F_{res \to aRes}^{sorp} - \frac{\partial}{\partial z}(D_b \frac{\partial X_{aDom}}{\partial z}) - \frac{\partial(\omega \cdot X_{aDom})}{\partial z}$$
(S1g)

$$\frac{\partial}{\partial t} X_{aRes} = F_{dom \to aDom}^{sorp} - \frac{\partial}{\partial z} \left( D_b \frac{\partial X_{aRes}}{\partial z} \right) - \frac{\partial (\omega \cdot X_{aRes})}{\partial z}$$
(S1h)

where F<sub>Lvp</sub> is the litterfall of the various plant tissue types, f<sub>vp→i</sub> are the coefficients determining the partitioning of this
20 litterfall to the litter pools (see Section S1.1), τ<sub>i</sub> are temperature and moisture adjusted turnover times of the respective pools (X; i = sol, wl, mic), η<sub>i→j</sub> are the fractions of mass transfer from pool i to j (see Section S1.2), F<sub>i→j</sub><sup>Y</sup> is the the flux rates of processes Y (depoly: depolymerisation; upt: microbial uptake of DOM; sorp: sorption to mineral surface) from pool i to j (see Section S1.4, S1.3 and S1.5), F<sup>growth</sup><sub>mic</sub> the microbial growth rate, σ<sub>recycle</sub> is the additional nutrients recycled to DOM when microbes decay, Φ<sub>immobilisation</sub> is the immobilisation terms for N and P, required to balance the microbial C:N:P stoichiometry
25 (are Section S1.5).

25 (see Sect. S1.5). The  $D_b$  is a prescribed diffusion constant for transfer of soil organic matter through bioturbation, and  $\omega$  is the flux rate representing the advective transport of soil organic matter due to SOM accumulation/diminishing, where the aboveground woody litter is not subjective to this transport (see Section S3), and  $\frac{\partial v_{dom} dom}{\partial z}$  is the percolation loss term given by the *dom* concentration and water mass flow between soil layers.

#### S1.1 Partitioning of litterfall to litter pools

Non-woody litterfall is partitioned to the soluable and polymeric litter according to the CENTURY approach (Parton et al., 1993). Litter from labile and reserve pools is assumed to enter the soluable pools, litter from sap- and heartwood enters the woody pool. The soluable fraction of litterfall from each vegetation pool ( $_{vp}$ , i.e. leaves, fine and coarse roots, fruits and seed-bed) is determined as:

$$f_{vp \to sol,C} = f_{sol,max,C} - k_{sol,C} \cdot LC_{vp} \frac{C_{vp}}{N_{vp}}$$
(S2)

where  $f_{vp \to sol,C}$  is constrained to positive solutions,  $f_{sol,max,C}$  is the maximum fraction allocated to the soluable pool,  $k_{sol,C}$  a factor relating the soluable litter fraction to the lignin to nitrogen ratio,  $LC_{vp}$  the tissue-specific fraction of the lignin content of that tissue type, and  $\frac{C_{vp}}{N_{vp}}$  the C:N ratio of litterfall from that tissue. The lignin content is assumed constant for all but the leaf tissues. For the latter, an empirical dependency between lignin content and specific leaf-area (*sla*) is used (White

10 but the leaf tissues. For the latter, an empirical dependency between lignin content and specific leaf-area (sla) is used (White et al., 2000).

$$LC_{leaf} = LC_{leaf,max} + k_{leaf2sla} \cdot sla \tag{S3}$$

The remainder of litterfall is allocated to the polymeric pool. For N and P, the partitioning assumes that the relative proportions of C:N and N:P are preserved in the partitioning according to:

$$15 \quad f_{vp \to sol,X} = \frac{1}{1 + \frac{1 - f_{vp \to sol,C}}{k_{sol,vp,X} \cdot f_{vp \to sol,C}}}$$
(S4)

#### S1.2 Litter turnover

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Woody decomposition is assumed to be a two-stage process. The first step implies physical destabilisation and a first level of biochemical processing, which releases a constant fraction of carbon  $(1 - \eta_{C,wl \rightarrow poly})$  to heterotrophic respiration. The remainder is assumed to enter the polymeric litter that further depolymerises into DOM. soluable litter decomposes with a similar two-stage process, where during the first step a fraction of carbon  $(1 - \eta_{C,sol \rightarrow dom})$  is respired but the remainder

directly enters the DOM pool, which is taken up by microbes.

The turnover times  $(\tau_i^{base})$  of the woody and soluable litter respond to soil temperature  $(T_{soil})$  and soil water content  $(\Theta)$  as follows:

$$\tau_i^* = \tau_i^{base} f(T_{soil}) g(\Theta_{soil}), where$$
(S5a)

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$$f(T_{soil}) = e^{-\frac{E_{a,depoly}}{R}(\frac{1}{T_{soil}} - \frac{1}{T_{ref}^{\tau}})}$$
 (S5b)

$$g(\Theta) = \frac{afps^{k1_{afps}}}{k_{afrac} + afps^{k1_{afps}}}, where$$
(S5c)

$$afps = \frac{\Theta_{fc} - \Theta_{soil}}{\Theta_{fc}}$$
(S5d)

where  $E_{a,depoly}$  is the activation energy of depolymerisation,  $T_{ref}^{\tau}$  is the reference temperature of the turnover rate,  $k1_{afps}$ and  $k_{afps}$  are parameters, afps is the air filled pore space, and  $\Theta_{soil}$  and  $\Theta_{fc}$  are the absolute soil water content and soil water field capacity, respectively.

#### S1.3 Depolymerisation

The depolymerisation from polymeric litter or microbial residue to DOM (*dom*) are assumed to be enzyme-limited and described with "reverse Michaelis-Menten" kinetics ((Ahrens et al., 2015), (Schimel and Weintraub, 2003)).

$$F_{poly \to dom}^{depoly} = v_{max,depoly}^{poly}(T_{soil},\Theta) \frac{X_{mic}Enz_{frac}^{poly}}{K_{m,depoly}(T_{soil},\Theta) + X_{mic}Enz_{frac}^{poly}} X_{poly}$$
(S6a)

$$F_{res \to dom}^{depoly} = v_{max,depoly}^{res}(T_{soil},\Theta) \frac{X_{mic}Enz_{frac}^{res}}{K_{m,depoly}(T_{soil},\Theta) + X_{mic}Enz_{frac}^{res}} X_{res}, where$$
(S6b)

$$K_{m,depoly}(T_{soil},\Theta) = K_{m,depoly}e^{-\frac{Ea,hsc}{R}(\frac{1}{T_{soil}} - \frac{1}{T_{ref}^{\tau}})} \cdot (\frac{\Theta}{\Theta_{fc}})^{k_{hsc}}$$
(S6c)

where  $v_{max,depoly}^X$  is the maximum depolymerisation rate of pool X (poly or res) and its temperature and moisture responses are the same as those of litter turnover (Eq.S5),  $Enz_{frac}^X$  is the fraction of enzyme (see Sect.S1.5.2) which targets to depolymerise pool X, and  $K_{m,depoly}(T_{soil},\Theta)$  is the temperature and moisture corrected, microbial biomass scaled, half-saturation

enzyme concentration of depolymerisation.

#### S1.4 SOC sorption stabilisation

The sorption of DOM and microbial residue to mineral soil surface is represented with dynamic Langmuir isotherm, modified from the COMISSION model (Ahrens et al., 2015).

$$F_{dom \to aDom}^{sorp} = k_{dom}^{ads} X_{dom} f(T_{soil}, \Theta) Q_{avail}^{org} + k_{dom}^{des} f(T_{soil}, \Theta) X_{aDom}$$
(S7a)

$$F_{res \to aRes}^{sorp} = k_{res}^{ads} X_{res} f(T_{soil}, \Theta) Q_{avail}^{org} + k_{res}^{ads} f(T_{soil}, \Theta) X_{aRes}, where$$
(S7b)

$$f(T_{soil},\Theta) = e^{-\frac{Ea,sorption}{R}\left(\frac{1}{T_{soil}} - \frac{1}{T_{ref}}\right)} \cdot \frac{\Theta}{dz}$$
(S7c)

$$Q_{avail}^{org} = Q_{max}^{org} - X_{aDom} - X_{aRes}$$
(S7d)

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$$Q_{max}^{org} = q_{max,mineral}^{org} \cdot (Silt + Clay)\rho_{soil}V_{mineral}^{frac}$$
(S7e)

where  $k_X^{ads}$  and  $k_X^{des}$  are the adsorption rate and desorption rate between X (dom or res) and its mineral-associated form (aDom or aRes), respectively, dz is the soil depth, and Silt and Clay are the silt and clay content in weight fraction. It is assumed that the two substrates share the same sorption sites, which is represented by the maximum sorption capacity of organic matter  $Q_{avail}^{org}$  and it is calculated based on the weight and sorption capacity of fine soil,  $q_{max,mineral}^{org}$ , following COMISSION (Ahrens et al., In prep.).

#### S1.5 Microbial growth and decay

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In JSM, the growth of microbial biomass  $(F_{mic}^{growth})$  depends on three factors: i) the uptake rate of DOM  $(F_{dom \to mic}^{upt})$ , ii) the microbial carbon use efficiency (CUE),  $mic_{cue}^{mavg}$ , and iii) nutrient (N and P) limitation,  $scal_{C,N,P}$  limit.

$$F_{mic}^{growth} = mic_{cue}^{mavg} F_{dom \to mic}^{upt}$$
(S8a)

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$$F_{dom \to mic}^{upt} = MIN(F_{dom \to mic}^{upt^*}, scal_{C,N,P \ limit} \cdot C_{dom})$$
 (S8b)

The potential uptake of DOM,  $F_{dom \to mic}^{upt^*}$ , is constrained by the DOM concentration, meaning at high DOM concentration the uptake is limited by ability of microbes to assimilate DOM (Ahrens et al., 2015). It is described with "Michaelis-Menten" kinetics,

$$F_{dom \to mic}^{upt^*} = v_{max,upt}^{dom}(T_{soil},\Theta)C_{mic}\frac{C_{dom}}{K_{m,upt}(T_{soil},\Theta) + C_{dom}}$$
(S9a)

$$K_{m,upt}(T_{soil},\Theta) = K_{m,upt}e^{-\frac{Ea,hsc}{R}(\frac{1}{T_{soil}} - \frac{1}{T_{ref}^{+}})} \cdot (\frac{\Theta}{\Theta_{fc}})^{k_{hsc}}$$
(S9b)

where  $v_{max,upt}^{dom}$  is the maximum DOM uptake rate and has the same temperature and mositure responses as those of litter turnover (Eq.S5),  $K_{m,upt}(T_{soil}, \Theta)$  is the temperature and moisture corrected half-saturation coefficient for DOM uptake.

5 Microbes response to the instantaneous conditions and associated fluxes to adapt their CUE. It is assumed in JSM that all the microbial adaptation has a process-specific lag time. Therefore, the microbial growth is calculated using the time-averaging microbial CUE,  $mic_{cue}^{mavg}$ , which is a moving average of the current effective microbial CUE ( $mic_{cue}^{eff}$ ) over a certain lag time.

$$mic_{cue}^{mavg,new} = mic_{cue}^{mavg,old} \cdot (1 - \frac{dt}{\tau_{mavg}^{mic}}) + mic_{cue}^{eff} \cdot \frac{dt}{\tau_{mavg}^{mic}}$$
(S10a)

$$mic_{cue}^{eff} = MAX(mic_{cue}^{min}, \frac{F_{mic}^{growth^*}}{F_{upt^*}^{dom \to mic}})$$
(S10b)

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$$F_{mic}^{growth^*} = MIN(F_{mic}^{growth,C^*}, F_{mic}^{growth,N^*}, F_{mic}^{growth,P^*}), where$$
(S10c)

$$F_{mic}^{growth,C^*} = mic_{cue}^{max} F_{dom \to mic}^{upt^*}$$
(S10d)

$$F_{mic}^{growth,N^*} = (mic_{nue} \frac{F_{dom \to mic}^{upt}}{\chi_{com}^{C:N}} + U_{NO_3,mic}^* + U_{NH_4,mic}^*)\chi_{mic}^{C:N}$$
(S10e)

$$F_{mic}^{growth,P^*} = (mic_{pue} \frac{F_{dom \to mic}^{upt^*}}{\chi_{dom}^{C:P}} + U_{PO_4,mic}^*)\chi_{mic}^{C:P}$$
(S10f)

where τ<sup>mic</sup><sub>mavg</sub> is the time span of the microbial CUE acclimation, mic<sup>min</sup><sub>cue</sub> is the theoretical minimal microbial CUE,
15 F<sup>growth,X\*</sup><sub>mic</sub> is the maximum potential microbial growth rate only considering the availability of element X, which takes account of the microbial nitrogen and phosphorus use efficiencies, mic<sub>nue</sub> and mic<sub>pue</sub><sup>1</sup>, and the potential microbial uptake rate of nutrient, U<sup>\*</sup><sub>X,mic</sub> (X=NO<sub>3</sub>, NH<sub>4</sub>, PO<sub>4</sub>, see Sect.S2.2). The smallest growth potential determines the current effective CUE.

Given the time-averaging microbial CUE, the potential microbial growth only considering C is recalculated as  $F_{mic}^{growth,C^{**}}$ . 20 The uptake rate of DOM will be reduced if  $F_{mic}^{growth,C^{**}}$  is bigger than  $F_{mic}^{growth,X^{*}}$ , and the scaling factor  $scal_{C,N,P \ limit}$  is

calculated as,

$$scal_{C,N,P\ limit} = \begin{cases} MIN\left(\frac{F_{dom \to mic}^{upt^{*}}}{C_{dom}}, \frac{(U_{NO_{3},mic}^{*}+U_{NH_{4},mic}^{*})\chi_{mic}^{C,N}}{mic_{cue}^{mavg}C_{dom}-mic_{nue}N_{dom}\chi_{mic}^{C,N}}\right), \ if\ F_{mic}^{growth,N^{*}} < F_{mic}^{growth,C^{**}}\&F_{mic}^{growth,P^{*}}\\ MIN\left(\frac{F_{dom \to mic}^{upt^{*}}}{C_{dom}}, \frac{U_{PO_{4},mic}^{*}\chi_{mic}^{C,P}}{mic_{cue}^{mavg}C_{dom}-mic_{pue}P_{dom}\chi_{mic}^{C,P}}\right), \ if\ F_{mic}^{growth,P^{*}} < F_{mic}^{growth,C^{**}}\&F_{mic}^{growth,N^{*}}\end{cases}$$
(S11a)

where, 
$$F_{mic}^{growth,C^{**}} = mic_{cue}^{mavg}F_{dom \to mic}^{upt^*}$$
 (S11b)

<sup>1</sup>In Eq.S10f and all the following cases, the microbial  $\chi_{mic}^{C:P} = \chi_{mic}^{C:N} \cdot \chi_{mic}^{N:P}$ 

#### S1.5.1 Microbial nutrient uptake, mineralisation, and microbial recycle

Given the microbial growth and the C:N:P stoichiometry, the uptake of inorganic N and P,  $U_{X,mic}$ , is calculated as,

$$U_{NH_4,mic} = U_{NH_4,mic}^* scal_N \tag{S12a}$$

$$U_{NO_3,mic} = U_{NO_3,mic}^* scal_N \tag{S12b}$$

$$U_{PO_4,mic} = U_{PO_4,mic}^* scal_P, where$$
(S12c)

$$scal_{N} = \frac{MAX(\frac{F_{mic}^{griden,C}}{\chi_{mic}^{C:N}} - mic_{nue}F_{mic}^{upt,N}, 0.0)}{U_{NO_{3},mic}^{*} + U_{NH_{4},mic}^{*}},$$

If 
$$F_{mic}^{growth,C} \leq F_{mic}^{growth,N^{**}}$$

$$MAX(\frac{F_{mic,C}^{growth,C}}{Max^{(r_{mic,C})}} - mic_{me}F_{mic}^{upt,P}, 0.0)$$

$$scal_P = \frac{U_{Mic}^{*} + U_{mic}^{*} + U_{mic}^{*}}{U_{PO_4,mic}^{*}}$$

If 
$$F_{mic}^{growth,C} \le F_{mic}^{growth,P^{**}}$$
 (S12e)

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$$F_{mic}^{upt,N} = mic_{cue}^{mavg} \frac{F_{dom \to mic}^{upt}}{\chi_{dom}^{C:N}}$$
(S12f)

$$F_{mic}^{upt,P} = mic_{cue}^{mavg} \frac{F_{dom \to mic}^{upt}}{\chi_{dom}^{C:P}}$$
(S12g)

$$F_{mic}^{growth,N^{**}} = (F_{mic}^{upt,N} + U_{NO_3,mic}^* + U_{NH_4,mic}^*)\chi_{mic}^{C:N}$$
(S12h)

$$F_{mic}^{growth,P^{**}} = (F_{mic}^{upt,P} + U_{PO_4,mic}^*)\chi_{mic}^{C:P}$$
(S12i)

where  $F_{mic}^{growth,N^{**}}$  and  $F_{mic}^{growth,P^{**}}$  are the potential microbial growth only considering N or P availability given the time-15 averaging CUE.

The effective microbial nutrient use efficiency ( $mic_{nue}^{eff}$  and  $mic_{pue}^{eff}$ ) and the net mineralisation of N and P ( $\Phi_{NorP}^{net}$ ) are thus calculated as,

$$mic_{nue}^{eff} = MIN(mic_{nue}, \frac{\frac{F_{mic}^{growth,C}}{\chi_{mic}^{C:N}} - U_{NH_4,mic} - U_{NO_3,mic}}{F_{mic}^{upt,N}})$$
(S13a)

$$mic_{pue}^{eff} = MIN(mic_{pue}, \frac{\frac{F_{mic}^{growth,C}}{\chi_{mic}^{CP}} - U_{PO_4,mic}}{F_{mic}^{upt,P}})$$
(S13b)

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$$\Phi_{NH_4}^{net} = (1 - mic_{nue}^{eff}) F_{mic}^{upt,N} - U_{NH_4,mic}$$
(S13c)

$$\Phi_{NO_3}^{net} = -U_{NO_3,mic} \tag{S13d}$$

$$\Phi_{PO_4}^{net} = (1 - mic_{pue}^{eff})F_{mic}^{upt,P} - U_{PO_4,mic}$$
(S13e)

When microbes decay in JSM, there is a faction of the dead microbes  $(\eta_{mic \rightarrow dom})$  which directly recycles into the DOM pool and the rest  $(\eta_{mic \rightarrow res})$  become microbial residues. Due to the fact that microbial cell wall has a lower nutrient content than plasma, it is assumed in JSM that N and P are more prone to be recycled into DOM when microbes decay, which is

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represented by  $\sigma_{recycle}$  in Eq.S1.

$$\sigma_{recycle}^{X} = \eta_{mic \to res} \frac{X_{mic}}{\tau_{mic}} \eta_{res \to dom}^{X}$$
(S14a)

where X represents N or P, and  $\eta_{res \to dom}^X$  is the fraction of X that is recycled from newly formed *res* to *dom* during microbial decay.

## S1.5.2 Enzyme allocation in depolymerisation

The enzyme allocation to polymeric litter and microbial residue is presented with the steady state of the Revenue strategy in the SEAM model (Wutzler et al., 2017), assuming that the microbial community adapts in a way that the fraction of enzyme allocation is proportional to its revenue (return-investment rate) of the limiting elements (C, N, or P).

$$\alpha_{poly}^{X} = \frac{Rev_{poly}^{X}}{Rev_{poly}^{X} + Rev_{res}^{X}}$$
(S15a)

$$\alpha_{res}^{X} = \frac{Rev_{res}^{X}}{Rev_{poly}^{X} + Rev_{res}^{X}}, where$$
(S15b)

$$Rev_{poly}^{X} = \frac{return}{investment} = \frac{v_{max,depoly}^{poly} \cdot \frac{\alpha_{poly}^{X}C_{mic}}{K_{m,depoly} + \alpha_{poly}^{X}C_{mic}} \cdot X_{poly}}{\alpha_{poly}^{X}C_{mic}}$$

$$= \frac{v_{max,depoly}^{poly}}{X_{poly}} X_{poly} = X_{poly}$$

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$$Rev_{res}^{X} = \frac{v_{max,depoly}}{K_{m,depoly} + \alpha_{res}^{X}C_{mic}} X_{res}, and$$
(S15d)

$$\alpha_{poly}^X + \alpha_{res}^X = 1 \tag{S15e}$$

where  $\alpha_Y^X$  is the potential enzyme allocation fraction to Y (poly or res) based on the revenues of element X (C, N, or P), and  $Rev_y^X$  is the revenue of element X from source y and is defined as the production of X divided by the potential allocation of enzyme. In JSM the enzyme levels are not explicitly represented, thus a steady state assumption is made: the production and turnover of the enzyme is in equilibrium therefore the enzyme is always linear with the microbial biomass. we could get the analytical solution of the potential enzyme allocation fractions by rearranging Eq.S15,

$$\frac{\alpha_{poly}^X}{\alpha_{res}^X} = \frac{Rev_{poly}^X}{Rev_{res}^X} \Longrightarrow$$
(S16a)

$$\frac{v_{max,depoly}^{poly} X_{poly}}{v_{max,depoly}^{res} X_{res}} = \frac{\alpha_{poly}^X}{1 - \alpha_{poly}^X} \frac{K_{m,depoly} + \alpha_{poly}^X C_{mic}}{K_{m,depoly} + (1 - \alpha_{poly}^X) C_{mic}} \Longrightarrow$$
(S16b)

$$\alpha_{poly}^{X} = \frac{d_{poly}K_{m,depoly} + 2d_{poly}C_{mic} + d_{res}K_{m,depoly} - \sqrt{D}}{2C_{mic}(d_{poly} - d_{res})}, where$$
(S16c)

$$d_{poly} = v_{max,depoly}^{poly} X_{poly}$$
(S16d)

$$d_{res} = v_{max,depoly}^{res} X_{res} \tag{S16e}$$

$$D = 4d_{poly}d_{res}C_{mic}^2 + 8d_{poly}d_{res}C_{mic}K_{m,depoly} + K_{m,depoly}^2d_{poly}^2 + 2d_{poly}d_{res}K_{m,depoly}^2 + K_{m,depoly}^2d_{res}^2$$
(S16f)

25 It is assumed that the microbial community would acclimate gradually to allocate the enzyme to optimize the utilisation of the most limiting element of depolymerisation, which is determined similarly as that in microbial growth (Eq.S10) except that the uptake of inorganic nutrients are not considered.

$$Enz_{frac}^{poly,new} = Enz_{frac}^{poly,old} \cdot \left(1 - \frac{dt}{\tau_{mavg}^{enzyme}}\right) + \alpha_{poly,mavg}^{X,new} \cdot \frac{dt}{\tau_{mavg}^{enzyme}}, where$$
(S17a)

$$\alpha_{poly,mavg}^{X,new} = \alpha_{poly,mavg}^{X,old} \cdot \left(1 - \frac{dt}{\tau_{mavg}^{enzyme}}\right) + \alpha_{poly}^X \cdot \frac{dt}{\tau_{mavg}^{enzyme}}$$
(S17b)

and the most limiting element X is determined as

$$MIN\left((F_{poly \to dom}^{depoly} + F_{res \to dom}^{depoly}) \cdot mic_{cue}^{mavg}, \\ \left(\frac{F_{poly \to dom}^{depoly}}{\chi_{poly}^{C:N}} + \frac{F_{res \to dom}^{depoly}}{\chi_{res}^{C:N}}\right) \cdot mic_{nue}^{mavg}\chi_{mic}^{C:N}, \\ \left(\frac{F_{poly \to dom}^{depoly}}{\chi_{poly}^{C:P}} + \frac{F_{res \to dom}^{depoly}}{\chi_{res}^{C:P}}\right) \cdot mic_{pue}^{mavg}\chi_{mic}^{C:P}\right)$$
(S17d)

(S17c)

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where  $\tau_{mavg}^{enzyme}$  is the time span of enzyme allocation acclimation, and  $mic_{nue}^{mavg}$  and  $mic_{pue}^{mavg}$  are the time averaging microbial N and P use efficiency, which is calculated similarly as  $mic_{cue}^{mavg}$  in Eq.S10.

#### S2 Inorganic nutrient cycles

In JSM, the net mineralisation and plant uptake of  $NH_4$  and  $NO_3$  are represented next to transport process. The dynamics of 10 inorganic nitrogen are described as:

$$\begin{split} \frac{\partial}{\partial t} NH_4 &= F_{dep,NH_4} - U_{NH_4,plant} + \Phi_{NH_4}^{net} \\ &\quad - \frac{\partial}{\partial z} (D_b \frac{\partial NH_4}{\partial z}) - \frac{\partial (\omega \cdot NH_4)}{\partial z} - \frac{\partial v_{NH_4} NH_4}{\partial z} \end{split} \tag{S18a} \\ \frac{\partial}{\partial t} NO_3 &= F_{dep,NO_3} - U_{NO_3,plant} + \Phi_{NO_3}^{net} \\ &\quad - \frac{\partial}{\partial z} (D_b \frac{\partial NO_3}{\partial z}) - \frac{\partial (\omega \cdot NO_3)}{\partial z} - \frac{\partial v_{NO_3} NO_3}{\partial z} \end{aligned} \tag{S18b}$$

15 where U are the uptake rates of plants and microbes (see Section S2.2); the  $F_{dep,X}$  are the atmospheric deposition fluxes;  $\frac{\partial v_x X}{\partial z}, \frac{\partial}{\partial z} (D_b \frac{\partial X}{\partial z})$ , and  $\frac{\partial (\omega \cdot X)}{\partial z}$  are vertical transport terms due to percolation loss, bioturbation, and SOM accumulation/diminishing, respectively (see Sect.S3). The inorganic phosphorus cycle is mostly based on that of the QUINCY model (Thum et al., 2019) with modifications due to microbial interactions. The dynamics of inorganic phosphorus are described as:

$$\frac{\partial}{\partial t}PO_4 = F_{dep,PO_4} + F_{weath,PO_4} + F_{biomin,PO_4}$$

$$-U_{plant,PO_4} - F_{adsorp,PO_4} + \Phi_{PO_4}^{net} - \frac{\partial}{\partial z} (D_b \frac{\partial PO_4}{\partial z}) - \frac{\partial (\omega \cdot PO_4)}{\partial z} - \frac{\partial v_{PO_4} PO_4}{\partial z}$$
(S19a)

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$$\frac{\partial}{\partial t}P_{lab} = F_{adsorp,PO_4} - F_{absorb,PO_4} - \frac{\partial(\omega \cdot P_{lab})}{\partial z}$$

$$\frac{\partial}{\partial (\omega \cdot P_{sorb})}$$
(S19b)
(S19b)

$$\frac{\partial}{\partial t}P_{sorb} = F_{absorb,PO_4} - F_{occlusion,PO_4} - \frac{\partial(\omega + I_{sorb})}{\partial z}$$
(S19c)

$$\frac{\partial}{\partial t}P_{ocl} = F_{occlusion,PO_4} - \frac{\partial(\omega \cdot P_{ocl})}{\partial z}$$
(S19d)

$$\frac{\partial}{\partial t}P_{primary} = -F_{weath,PO_4} - \frac{\partial(\omega \cdot P_{primary})}{\partial z}$$
(S19e)

where P<sub>lab</sub>, P<sub>sorb</sub>, P<sub>ocl</sub>, and P<sub>primary</sub> are adsorbed, absorbed, occluded, and primary P, respectively; the F<sub>dep,PO4</sub>, F<sub>weath,PO4</sub>,
10 F<sub>biomin,PO4</sub>, F<sub>adsorp,PO4</sub>, and F<sub>absorb,PO4</sub> are the atmospheric deposition, weathering, fast adsorption, and absorption fluxes, respectively (see Section S2.1).

## S2.1 Phosphorus weathering, biomineralisation and absorption

Weathering is assumed to be driven by root and microbial exudation, and modified from Wang et al. (2010) as:

$$F_{weath,PO_4} = f(T_{soil},\Theta) \frac{C_{exu}}{K_{m,weath} + C_{enz}} k_{weath} \rho_{soil}^{cor}, where$$
(S20a)

$$f(T_{soil},\Theta) = e^{-\frac{Ea,hsc}{R} \cdot \left(\frac{1}{T_{soil}} - \frac{1}{T_{ref}^{\dagger}}\right)} \cdot \left(\frac{\Theta}{\Theta_{fc}}\right)^3,$$
(S20b)

$$C_{exu} = C_{fine\_root}k_{enz,root} + C_{mic}k_{enz,mic}$$
(S20c)

where  $k_{weath}$  is the rate constant for weathering,  $\rho_{soil}^{cor}$  is the soil bulk density corrected by SOM content,  $C_{exu}$  represents an implicit general assemble of all exudation, analogous to the enzymatic abundance of fine roots and microbes ( $k_{enz,root}$  and  $k_{enz,mic}$ ), and  $K_{m,weath}$  is the half-saturation coefficient for weathering. The weathering rate decreases with soil depth as the fine root C and microbial biomass decreases and is modified by soil temperature and moisture.

The biomineralisation of  $PO_4$  is determined as an additional enzyme-catalysed cleavage of the P contained in the solid SOM pools (X = *res*, *aRes*, *aDom*), modified by temperature and moisture modifiers, affected by the concentration of  $PO_4$  and enzyme abundance, and constrained by the C:P ratio of the organic pools:

$$F_{biomin,PO_4} = v_{max,biomin} f(T_{soil},\Theta) f(C_{enz} f(PO_4) f(\chi_X^{C:P}), where$$
(S21a)

$$f(C_{enz}) = \frac{C_{enz}}{K_{m,biomin}^{exu} + C_{enz}}$$
(S21b)

$$f(PO_4) = \frac{K_{m,biomin}^{PO_4}}{K_{m,biomin}^{PO_4} + PO_4}$$
(S21c)

$$f(\chi_X^{C:P}) = \frac{1}{1 + \chi_X^{C:P} K_{m,biomin}^{CP}}$$
(S21d)

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where  $K_{m,biomin}$ ,  $K_{m,biomin}^{PO_4}$  and  $K_{m,P:C}$  are constants constraining the biomineralisation rate under low enzyme, high PO<sub>4</sub> concentration, and high SOM C:P ratio, respectively,  $\chi_X^{C:P}$  is the C:P ratio of the organic pools, and the temperature and moisture responses are calculated as those in Eq. S5.

 $PO_4$  absorption and occlusion are modelled as:

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$$F_{occlusion, PO_4} = k_{ocl} P_{sorb}$$
 (S22a)

$$F_{desorp,PO_4} = f(T_{soil}, E_{a,abs})k_{abs}P_{lab} - f(T_{soil}, E_{a,des})k_{s,des}P_{sorb}, where$$
(S22b)

$$f(T_{soil,E_a}) = e^{-\frac{E_a}{R} \cdot \left(\frac{1}{T_{soil}} - \frac{1}{T_{ref}}\right)}$$
(S22c)

where  $k_{ocl}$ ,  $k_{abs}$  and  $k_{s,des}$  are the rate constants of occlusion, absorption and slow desorption, and  $E_{a,abs}$  and  $E_{a,des}$  are the respective activation energies which equal to that of OM sorption (Eq.S7).

#### 10 S2.2 Nutrient acquisition

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It is assumed in the JSM model that the soluble forms of inorganic  $NH_4$ ,  $NO_3$ , and  $PO_4$  are the only bio-available nutrients for plants and microbes, and specifically for  $PO_4$ , the soluble inorganic form is assumed to be the only form that could be adsorbed by the mineral surfaces. The uptake of plants and microbes as well as the  $PO_4$  adsorption are all represented by the formations of consumer-substrate network using their full equilibrium chemistry approximations (ECA), following Tang and Riley (2013):

$$U_{X,y_1}^* = f(T_{soil},\Theta)_{y_1} v_{max,y_1}^X \frac{[X]}{K_{m,y_1}^X + [X] + Enz_{y_1}^X + K_{m,y_1}^X \frac{Enz_{y_2}^X}{K_{m,y_2}^X} + K_{m,y_1}^X \frac{Enz_{y_3}^X}{K_{m,y_3}^X}}, where$$
(S23a)

$$Enz_{plant}^{\chi} = C_{fine\_root} k_{enz,root}^{\chi}$$
(S23b)

$$Enz_{mic}^{X} = C_{mic}k_{enz,mic}^{X}$$
(S23c)

(S23d)

Specificlly, for  $PO_4$  adsorption flux we assumed

$$20 \quad Enz_{adsorp}^{PO_4} = S_{max}^{PO_4} - P_{lab} \tag{S23e}$$

$$v_{max,adsorp}^{PO_4} = k_{ads} \cdot En z_{adsorp}^{PO_4} \cdot PO_4 \tag{S23f}$$

$$k_{ads} = \frac{\kappa_{des,f}}{K_S} \tag{S23g}$$

$$[PO_4] = P_{lab} + PO_4 \tag{S23h}$$

where U<sup>\*</sup><sub>X,y</sub> is the potential acquisition rate of substrate X (NH<sub>4</sub>, NO<sub>3</sub>, and PO<sub>4</sub>) through process y (plant: plant uptake,
mic: microbial uptake, or adsorp: adsorption). The maximum uptake rates (v<sup>X</sup><sub>max,y</sub>) of plant and microbes are adopted from literature (see Table S1), while the maximum PO<sub>4</sub> adsorption rate is calculated following Van der Zee et al. (1989); Enz<sup>X</sup><sub>y</sub> represents the enzymatic capacity of y to consume the substrate X and it is assumed to be linear with the root biomass of plant, microbial biomass for microbe, and equals with the available sorption sites for mineral soil, and k<sup>X</sup><sub>enz,y</sub> is the coefficient representing the transporters' abundance and capacity; the [X] represents the total substrate concentration for all the relevant acquisition processes, and it equals the soluble inorganic concentration for NH<sub>4</sub> and NO<sub>3</sub>, while for PO<sub>4</sub> it is the sum of soluble and labile inorganic P. The uptake rate of plants and microbes are influenced by temperature and moisture as that in

Eq.S6.

The potential acquisition rate will be down scaled if the sum of them exceed the size of the substrate pool. The actual microbial uptake rate also depends on the uptake demand of microbes (see Sect.S1.5). The actual adsorption rate are further calculated based on the assumption that the soluble inorganic P tend to equilibrate with the adsorbed P (see Sect.S2.2.1).

$$U_{X,y_1}^* = U_{X,y_1}^* \cdot \frac{X}{\sum(U_{X,y}^*)} \text{ when } X < \sum(U_{X,y}^*)$$
(S24a)

## 5 S2.2.1 PO<sub>4</sub> adsorption equilibrium

The adsorption  $(F_{adsorp,PO_4})$  flux from soil solution to the soil adsorption sites is calculated assuming constant Langmuir equilibrium (Barrow, 1978) between soluble and adsorbed P:

$$P_{lab} = \frac{S_{max}^{PO_4} \cdot PO_4}{K_S + PO_4}, where$$
(S25a)

$$S_{max}^{PO_4} = \Theta_{soil} \cdot \left(S_{max,om}^{PO_4} V_{om}^{frac} \rho_{bulk}^{org} + S_{max,mineral}^{PO_4} V_{mineral}^{frac} \rho_{soil}\right)$$
(S25b)

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$$K_S = K_{S,om} V_{om}^{frac} \rho_{bulk}^{org} + K_{S,mineral} V_{mineral}^{frac} \rho_{soil}$$
(S25c)

where  $S_{max}^{PO_4}$  and  $K_S$  are the maximum sorption capacity, and the half-saturation concentration coefficient of the soil, and are both modified by soil moisture and SOM content;  $V_{om}^{frac}$  and  $V_{mineral}^{frac}$  are volumetric fractions of organic matter and fine soil minerals, respectively.  $S_{max,om}^{PO_4}$  and  $S_{max,mineral}^{PO_4}$  are the maximum PO<sub>4</sub> sorption capacity of pure organic matter and pure fine soil, respectively.  $K_{S,om}$  and  $K_{S,mineral}$  are the half-saturation concentration coefficient of pure organic matter and pure fine soil, respectively.  $K_{S,om}$  and  $K_{S,mineral}$  are the half-saturation concentration coefficient of pure organic matter and pure fine soil, respectively.

The Eq.S25 is solved analytically since  $S_{max}^{PO_4}$  and  $K_S$  are also changing with time.

$$P_{lab}^{'} = \frac{[PO_4]^{'} + S_{max}^{PO_4} + K_S - \sqrt{([PO_4]^{'} + S_{max}^{PO_4} + K_S)^2 - 4 \cdot [PO_4]^{'} S_{max}^{PO_4}}{2}$$
(S26a)

$$PO_{4}^{'} = [PO_{4}]^{'} - P_{lab}, where$$
 (S26b)

$$[PO_4]' = P_{lab} + PO_4 + \frac{\partial(P_{lab} + PO_4)}{\partial t}$$
(S26c)

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$$\frac{\partial(P_{lab} + PO_4)}{\partial t} = F_{dep,PO_4} + F_{weath,PO_4} + F_{biomin,PO_4} 
- U_{plant,PO_4} - U_{mic,PO_4} + \Phi_{PO_4}^{net} 
- \frac{\partial}{\partial z} (D_b \frac{\partial PO_4}{\partial z}) - \frac{\partial(\omega \cdot PO_4)}{\partial z} - \frac{\partial v_{PO_4} PO_4}{\partial z} 
- F_{absorb,PO_4} - \frac{\partial(\omega \cdot P_{lab})}{\partial z}$$
(S26d)

where the pools with apostrophe as superscript denote the size at the end of time step.

## S3 Transport and bulk density correction

In JSM the soil profile always starts from the top of the organic layer, therefore changes of SOM content would affect the layering of the soil profile, which is represented by an advective transport rate  $\omega$ , following COMISSION model Ahrens et al. (2015)

$$\omega_{sl=n} = \frac{\sum\limits_{sl=n}^{1} \Delta W_{OM_{sl}} \cdot dz_{sl}}{\rho_{bulk}^{org}}, where$$
(S27a)

$$\Delta W_{OM_{sl}} = \sum \left( C_{X_{sl}}^{'} - C_{X_{sl}} \right) \frac{Mol_C}{1000 \cdot frac_{OM}^C}$$
(S27b)

where subscript sl denotes the soil layer, dz the layer depth,  $\rho_{bulk}^{org}$  the bulk density of organic material;  $\Delta W_{OM}$  is the change of total SOM weight which includes all the organic pools (NOTE: for the first layer woody litter is excluded), and is calculated based on the change of C content  $(C'_{X_{sl}} - C_{X_{sl}})$ , carbon molecular weight  $(Mol_C)$  and weight fraction of C in OM  $(frac_{OM}^C)$ .

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based on the change of C content  $(C'_{X_{sl}} - C_{X_{sl}})$ , carbon molecular weight  $(Mol_C)$  and weight fraction of C in OM  $(frac_{OM}^C)$ . Not only all the organic pools and inorganic pools shift with the advective transport rate  $\omega$  in JSM, but also the physical soil properties, such as soil texture, mineral soil density  $(\rho_{soil})$  and mineral soil volumetric fraction  $(V_{mineral}^{frac})$ , shift with  $\omega$  to ensure that the soil bulk density is properly corrected by the SOM content.

$$\rho_{soil}^{cor} = V_{mineral}^{frac} \rho_{soil} + (1 - V_{mineral}^{frac}) \rho_{bulk}^{org}$$
(S28a)

Table	<b>S1</b> .	JSM	parameters
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Symbol	Description	Value	Unit	Equation	Citation
Litter partitioning and turnover					
$f_{sol,max,C}$	maximum fraction of soluble litter formation	0.85	-	S2	Parton et al. (1993)
$k_{sol,C}$	slope of soluble fraction with lignin to N ratio	0.018	-	S2	Parton et al. (1993)
$LC_{fine\_root}$	lignin content of fine root	0.2565592	$mol^{-1}$	S2	White et al. (2000)
$LC_{coarse\_root}$	lignin content of coarse roots	0.8163248	$mol^{-1}$	S2	Thum et al. (2019)
$LC_{woody\_litter}$	lignin content of woody litter	0.8163248	$mol^{-1}$	S2	White et al. (2000)
$LC_{fruit}$	lignin content of seed bed	0.2565592	$mol^{-1}$	S2	Thum et al. (2019)
$LC_{seed\_bed}$	lignin content of fine root	0.2565592	$mol^{-1}$	S2	Thum et al. (2019)
$LC_{leaf,max}$	maximum lignin content of leaves	0.3440226	$mol^{-1}$	<b>S</b> 3	White et al. (2000)
$k_{leaf2sla}$	slope of lignin to <i>sla</i> relationship	-0.4328854	$m^{-2}$	<b>S</b> 3	Parton et al. (1993)
$k_{sol,vp,N}$	proportionality factor controlling C:N of soluble vs.	5.0	-	S4	Parton et al. (1993)
	polymeric pool				
$k_{sol,vp,P}$	proportionality factor controlling C:P of soluble vs.	5.0	-	S4	Parton et al. (1993)
	polymeric pool				
$\eta_{C,wl \to poly}$	fraction of woody litter C transformed into poly-	0.3	-	Sect.S1.2	This study
	meric litter				
$\eta_{C,sol \to dom}$	fraction of soluble litter C transformed into DOM	0.7	-	Sect.S1.2	This study
$ au_{sol}^{base}$	turnover time of soluble litter	0.033	years	S5	Parton et al. (1993)
$ au_{wl}^{base}$	turnover time of woody litter	2.5	years	S5	Thum et al. (2019)
$T_{ref}^{\tau}$	reference temperature for depolymerisation	293.15	K	S5	Wang et al. (2012)
$E_{a,depoly}$	activation energy for depolymerisation	53000.0	$Jmol^{-1}$	S5	Ahrens et al. (In prep.)
$k1_{afps}$	parameter for moisture response of litter turnover	1.33	-	S5	This study
$k_{afps}$	parameter for moisture response of litter turnover	0.001	-	S5	This study

Table S1.	JSM	parameters	(ctnd.)
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Symbol	Description	Value	Unit	Equation	Citation
Depolymerisation, sorption, transport, and bulk density correction					
$v_{max,depoly}^{poly}$	maximum depolymerisation rate of polymeric litter	0.1849	$yr^{-1}$	S6	This study
$v_{max,depoly}^{res}$	maximum depolymerisation rate of microbial residue	0.2317	$yr^{-1}$	S6	This study
$K_{m,depoly}$	half-saturation microbial biomass for depolymerisa-	3.70	$\frac{mol}{m^3}$	S6	This study
	tion				
$E_{a,hsc}$	activation energy of half-saturation point	30000.0	$\frac{J}{mol}$	<b>S</b> 6	Wang et al. (2013)
$k_{hsc}$	scaling factor for the sensitivity of half-saturation	0.001	-	<b>S</b> 6	Davidson et al. (2012)
	constant to moisture limitation		_		
$k_{dom}^{ads}$	adsorption rate of DOM	0.720	$\frac{m^3}{mol\ yr}$	<b>S</b> 7	This study
$k_{dom}^{des}$	desorption rate of mineral-associated DOM	0.508	$yr^{-1}$	<b>S</b> 7	This study
$k_{res}^{ads}$	adsorption rate of microbial residue	0.00372	$\frac{m^3}{mol\ ur}$	<b>S</b> 7	This study
$k_{res}^{des}$	desorption rate of mineral-associated residue	0.154	$yr^{-1}$	<b>S</b> 7	This study
$E_{a,sorption}$	activation energy for sorption	5000.0	$Jmol^{-1}$	<b>S</b> 7	Ahrens et al. (In prep.)
$\rho_{soil}$	bulk density of mineral soil	1000 - 1600	$\frac{kg}{m^3}$	<b>S</b> 7	Lang et al. (2017)
$ ho_{bulk}^{org}$	bulk density of organic material	248.84	$\frac{\frac{h}{kg}}{m^3}$	S28	Lang et al. (2017)
$D_b$	diffusion velocity due to bioturbation	0.15	$\frac{m^2 kg}{m^3 ur}$	<b>S</b> 1	Koven et al. (2013)
Microbial gro	owth and decay				
$v_{max,upt}^{dom}$	maximum microbial uptake rate of DOM	95.76	$day^{-1}$	<b>S</b> 8	This study
$K_{m,upt}$	half-saturation DOM density for microbial DOM up-	85.34	$\frac{mol C}{m^3}$	S9	This study
	take				
$mic_{cue}^{min}$	minimal microbial CUE	0.3	-	S10	Manzoni et al. (2008)
$mic_{cue}^{max}$	maximum microbial CUE	0.6	-	S10	Manzoni et al. (2008)
$mic_{nue}$	microbial nitrogen use efficiency	0.8	-	S10	Sinsabaugh et al. (2016)
$mic_{pue}$	microbial phosphorus use efficiency	0.89	-	S10	Sinsabaugh et al. (2016)
$\chi^{C:N}_{mic}$	microbial CN ratio	13	$\frac{mol}{mol}$	S10	Lang et al. (2017)
$\chi^{N:P}_{mic}$	microbial NP ratio	0.8	$\frac{mol}{mol}$	S10	Lang et al. (2017)
$ au_{mic}$	microbial turnover time	154.7	days	S14	Ahrens et al. (2015)
$\eta_{mic \rightarrow res}$	fraction of microbial biomass that become residue	0.828	-	S14	Ahrens et al. (2015)
	during decay				
$\eta^N_{res \to dom}$	fraction of N recycled from res to dom during mi-	0.4	-	S14	This study
	crobial decay				
$\eta^P_{res \to dom}$	fraction of P recycled from $res$ to $dom$ during micro-	0.8	-	S14	This study
	bial decay				
$ au_{mavg}^{mic}$	memory time scale for microbial CUE	30	days	S10	This study
$ au_{mavg}^{enzyme}$	memory time scale for microbial enzyme allocation	7	days	S17	This study

Table S1.	JSM	parameters	(ctnd.)
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Symbol	Description	Value	Unit	Equation	Citation
Nutrient acquisition					
$v_{max\ mic}^{nh_4}$	maximum microbial uptake rate of $NH_4$	1278.7	$\frac{\mu mol \ N}{mol \ C \ h}$	S23	Kuzyakov and Xu (2013)
$v_{max,mic}^{no_3}$	maximum microbial uptake rate of $NO_3$	1039.0	$\frac{\mu mol \ N}{mol \ C \ h}$	S23	Kuzyakov and Xu (2013)
$K^{nh_4}_{mmin}$	Half-saturation concentration for microbial $NH_4$	0.0129	$\frac{mol C}{M}$	S23	Kuzyakov and Xu (2013)
m,mic	uptake		m°		
$K_{m\ mic}^{no_3}$	half+saturation concentration for microbial $NO_3$	0.0293	$\frac{mol N}{m^3}$	S23	Kuzyakov and Xu (2013)
	uptake		111		-
$k_{enz.mic}^{N}$	coefficient of microbial transporter for N uptake	0.00005	$\frac{mol \ N}{mol \ C}$	S23	Zhu et al. (2016)
$v_{max.plant}^{nh_4}$	maximum plant uptake rate of $NH_4$	1305.4	$\frac{\mu mol N}{mol C h}$	S23	Kuzyakov and Xu (2013)
$v_{max.plant}^{no_3}$	maximum plant uptake rate of $NO_3$	218.4	$\frac{\mu mol \ N}{mol \ C \ h}$	S23	Kuzyakov and Xu (2013)
$K_{m\ nlant}^{nh_4}$	Half-saturation concentration for microbial $NH_4$	0.0857	$\frac{mol \ N}{m^3}$	S23	Kuzyakov and Xu (2013)
m,ptant	uptake		m.•		-
$K_{m,plant}^{no_3}$	half+saturation concentration for microbial NO <sub>3</sub>	0.129	$\frac{mol N}{m^3}$	S23	Kuzyakov and Xu (2013)
,.	uptake				
$k_{enz,root}^N$	coefficient of root transporter for N uptake	0.000125	$\frac{mol \ N}{mol \ C}$	S23	Zhu et al. (2016)
$v_{max,mic}^{po_4}$	maximum microbial uptake rate of $PO_4$	188.6	$\frac{\mu mol P}{mol C h}$	S23	Zhu et al. (2016)
$K_{m,mic}^{po_4}$	Half-saturation concentration for microbial $PO_4$	0.000645	$\frac{mol P}{m^3}$	S23	Zhu et al. (2016)
	uptake				
$v_{max,plant}^{po_4}$	maximum microbial uptake rate of $PO_4$	15.84	$\frac{\mu mol P}{mol C h}$	S23	Kavka and Polle (2016)
$K_{m,plant}^{po_4}$	half-saturation concentration for root $PO_4$ uptake	0.00216	$\frac{mol P}{m^3}$	S23	Kavka and Polle (2016)
$k_{enz,mic}^P$	coefficient of microbial transporter for P uptake	0.0005	$\frac{mol P}{mol C}$	S23	This study
$k_{enz,plant}^P$	coefficient of root transporter to take up P	0.000125	$\frac{mol P}{mol C}$	S23	This study
Soil Pi fluxes					
$k_{weath}$	Weathering rate constant of mineral soil	8.16208	$10^{-14} \frac{molP}{m^3 s}$	S20	Wang et al. (2010)
$K_{m,weath}$	half-saturation C exudation level for PO <sub>4</sub> weath-	0.083	$\frac{molC}{m^3}$	S20	This study
	ering				
$v_{max,biomin}$	maximum biomineralisation rate of $PO_4$	0.005	$\frac{mol P}{mol C}d^{-1}$	S21	Bünemann et al. (2016)
$K_{m,biomin}^{exu}$	half-saturation C exudation level for $PO_4$ biomin-	0.417	$\frac{mol C}{m^3}$	S21	This study
<b>P</b> O :	eralization				
$K_{m,biomin}^{IO_4}$	half-saturation solute P concentration for $PO_4$	0.001	$\frac{morr}{m^3}$	S21	This study
TTCP	biomineralization		molP		
$K_{m,biomin}^{O1}$	half-saturation substrate P:C ratio for $PO_4$	0.0002	$\frac{mot \ I}{mol \ C}$	\$21	This study
7	biomineralization	2.96	10-13 -1	600	V (1(2014)
$\kappa_{ocl}$	Occlusion coefficient of sorbed $PO_4$	3.80 0.014	$10 \ s$ $h^{-1}$	S22	Van der Zee et al. (1080)
$\kappa_{des,f}$	$PO_4$ last desorption rate from $P_{lab}$ to $PO_4$	0.014	Π μmol	525 522	Van der Zee et al. $(1989)$
$\kappa_{abs}$	$PO_4$ (ab)sorption rate from $P_{lab}$ to $P_{sorb}$	0.000722	kg soil s mol	522 522	$\begin{array}{l} \text{rang et al. (2014)} \\ \text{Varue at al. (2014)} \end{array}$
$\kappa_{des}$	$PO_4$ desorption rate from $P_{sorb}$ to $P_{lab}$	0.000733	kg soil s mmol P	522 525	rang et al. $(2014)$
$S_{om}$	$PO_4$ sorption capacity of organic matter	0.4	kg OM mol P	825 825	Thum et al. $(2019)$
$S_{mineral}$	$PO_4$ sorption capacity of mineral soil	0.0387	kg soil	\$25	Thum et al. (2019)
$K_{S,om}$	half-saturation concentration for $PO_4$ adsorption	0.045	kgOM	S25	Thum et al. (2019)
V	to UM	0.00005	mmolP	605	$T_{\rm hom} = 1.(2010)$
$\kappa_{S,mineral}$	nair-saturation concentration for $PO_4$ adsorption	0.00225	kg soil	525	1 num et al. (2019)
	to son mineral				

Parameter	Processes			
All the values vary between $80\%$ and $120\%$ of the default values in Table S				
$k_{dom}^{ads}$	OM sorption			
$k_{dom}^{des}$	OM sorption			
$k_{res}^{ads}$	OM sorption			
$k_{res}^{des}$	OM sorption			
$k_{des,f}$	Nutrient acquisition			
$\chi^{C:N}_{mic}$	Microbial growth and decay			
$\chi^{N:P}_{mic}$	Microbial growth and decay			
$mic_{nue}$	Microbial growth and decay			
$mic_{pue}$	Microbial growth and decay			
$mic_{cue}^{min}$	Microbial growth and decay			
$\eta_{C,wl \to poly}$	Litter partitioning and turnover			
$\eta_{C,sol \to dom}$	Litter partitioning and turnover			
$ au_{mic}$	Microbial growth and decay			
$v_{max,upt}^{dom}$	Microbial growth and decay			
$v_{max\ depoly}^{poly}$	Depolymerisation			
$v_{max,depoly}^{res}$	Depolymerisation			
$\eta^P_{res \to dom}$	Microbial growth and decay			
$\eta^N_{res \to dom}$	Microbial growth and decay			
$v_{max\ mic}^{nh_4}$	Nutrient acquisition			
$v_{max,mic}^{no_3}$	Nutrient acquisition			
$v_{max,mic}^{po_4}$	Nutrient acquisition			
$k_{enz\ mic}^N$	Nutrient acquisition			
$k_{enz,mic}^{P}$	Nutrient acquisition			
$k_{enz,root}^{N}$	Nutrient acquisition			
$k_{enz,root}^{P}$	Nutrient acquisition			
$k_{weath}$	Soil Pi cycle			
$k_{ocl}$	Soil Pi cycle			
$v_{max,biomin}$	Soil Pi cycle			

Table S2. Parameters for sensitivity analysis

## References

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**Figure S1.** Simulated and observed (a) SOC content, (b) C:N ratio in SOM, (c) C:P ratio in SOM, (d) organic P to inorganic P ratio in soil, (e)  ${}^{14}C$  content, (f) soil bulk density, (g) microbial C content, (h) microbial N content and (i) microbial P content at the study site at 1-m soil depth. Black lines and dots: observations; Coloured lines and shades: simulated mean values and ranges of standard deviation by base scenario, the global microbial stoichiometry scenario (Glob. Mic. Stoi), and the extended base scenarios with simulation length of 1000 years (Base\_1000) and 5000 years (Base\_5000). The microbial C, N, and P were only measured in the top 30 cm of soil. Simulated means and standard deviations were calculated using data from the last 10 years of model experiments.



**Figure S2.** Simulated and observed (a) SOC content, (b) C:N ratio in SOM, (c) C:P ratio in SOM, (d) organic P to inorganic P ratio in soil, (e)  ${}^{14}C$  content, (f) soil bulk density, (g) microbial C content, (h) microbial N content and (i) microbial P content at the study site at 1-m soil depth. Black lines and dots: observations; Coloured lines and shades: simulated mean values and ranges of standard deviation by different initial SOM contents, ranging from 50 % to 200 % of the default values. All runs were simulated for 1000 years using base scenario parameterisation. The microbial C, N and P were only measured in top 30cm soil. Simulated means and standard deviations were calculated using data from the last 10 years of model experiments.



**Figure S3.** Simulated seasonal and vertical distribution of (a) respiration, (b) net N mineralisation, (c) biochemical P mineralisation, (d) net P mineralisation, (e) microbial inorganic P uptake, (f) plant P uptake, (g) microbial inorganic N uptake, and (h) plant N uptake at the study site at 1-m soil depth. Points represent the mean values and error bars represent the standard deviations, both calculated using data from the last 10 years of model experiments.



**Figure S4.** Simulated SOC fractions (upper panels) and their respective radiocarbon profiles (bottom panels) at 1-m soil depth. Column (a): mineral-associated C (MOC), including adsorbed DOM and adsorbed microbial residue; Column (b): litter, including woody, polymeric and soluble litter; Column (c): live and dead microbes. Data points were derived from the last 10 years of model experiments.



**Figure S5.** Simulated yearly budget of (A) N and (B) P in soil solution. In panel A, sourcing fluxes of N are presented in the order of gross mineralisation of NH<sub>4</sub> and NO<sub>3</sub>, N deposition (In the bar plot: from right to the zero point; in the legend: from the top to the separation line); sinking fluxes of N are presented in the order of plant and microbial uptakes of NH<sub>4</sub>, plant and microbial uptakes of NO<sub>3</sub>, N leaching (both inorganic and organic) and changes in soluble N content ( $delta\_sol\_N$ ) (In the bar plot: from left to the zero point; in the legend: from the separation line to the bottom). In panel B, sourcing fluxes of P include weathering, gross mineralisation of PO<sub>4</sub>, biochemical mineralisation of PO<sub>4</sub> and P deposition; sinking fluxes of P include adsorption (*Exchange\_fast*), microbial and plant uptake, P leaching (both inorganic and organic) and changes in soluble P content ( $delta\_sol\_P$ ) (The order of presented processes follows the same rule as N). The budget were calculated using data from the full simulation of model experiments.



**Figure S6.** QUINCY simulated and observed (a) SOC content, (b) C:N ratio in SOM, (c) C:P ratio in SOM and (d) organic P-to-inorganic P ratio in soil at the study site up to 1 m soil depth. Black lines and dots: observations; Orange lines and shades: simulated mean values and ranges of standard deviation using QUINCY model(Thum et al., 2019). Simulated means and standard deviations were calculated using data from the last 10 years of model experiments.