Supplementary material

1. Calculation of aggregate turnover(modified Peng et al., 2017):

The mass transfer and turnover rate for each aggregate fraction were modified following the method in Peng et al. (2017). This study tracked the mass flow out of the A, B, and C fractions following three potential breakdown pathways (a-c; Fig. 1) and mass flow into the A, B, and C fractions following three potential formation pathways (d-f; Fig. 1). The mass of soil transfers along each pathway from time t_1 to t_2 can be described with a discrete transfer matrix $K_{(t_2-t_1)}$ (Peng et al., 2017):

$$K_{(t_2-t_1)} = \begin{bmatrix} 1-a-b & d & f \\ a & 1-c-d & e \\ b & c & 1-e-f \end{bmatrix} \quad \text{(S1)}$$

where a to l are the changes of proportions of REE oxidess relating the specific pathways in Fig. 1 from time t_1 to t_2, which is equivalent to the changes of proportions of aggregates relating the specific pathways.

First, we gain the REO concentrations of different aggregate fractions at time t_1 as follows:

$$\mathrm{REO}_{\mathrm{con.}(t)} = \begin{bmatrix} [La_A] & [Nd_A] & [Sm_A] \\ [La_B] & [Nd_B] & [Sm_B] \\ [La_C] & [Nd_C] & [Sm_C] \end{bmatrix} \quad \text{(S2)}$$

where, e.g., Gd_A is the concentration of Gd in large macroaggregate (A,2.00-5.00 mm) fraction. The amount of aggregates at time steps t can be described by vectors S(t) :

$$S(t) = \begin{bmatrix} A(t) \\ B(t) \\ C(t) \end{bmatrix} \quad \text{(S3)}$$

where the A, B, C and D represent the amounts of large macroaggregates (2-5 mm), small macroaggregates (0.25-2 mm), microaggregates (0.053-0.25 mm), and silt and clay sized aggregates(<0.053 mm), respectively.

The absolute REO amounts in the four aggregate fractions are:

$$\mathrm{REO}_{amo.(t)} = \begin{bmatrix} A(t)[\mathrm{La}_A] & A(t)[\mathrm{N}d_A] & A(t)[\mathrm{S}m_A] \\ B(t)[\mathrm{La}_B] & B(t)[\mathrm{N}d_B] & B(t)[\mathrm{S}m_B] \\ C(t)[\mathrm{La}_C] & C(t)[\mathrm{N}d_C] & C(t)[\mathrm{S}m_C] \end{bmatrix} \quad \text{(S4)}$$

When the absolute tracer amounts in aggregates is assumed during transfer between time steps t_1 and t_2, their relationship can then be described as follows:

$$\mathrm{REO}_{amo.(t2)} = K(t_2 - t_1)\mathrm{REO}_{amo.(t1)} \tag{S5}$$

Consequently, the transformation matrix $\mathrm{K}_{(t_2\text{-}t_1)}$ can be calculated:

$$K(t_2 - t_1) = \mathrm{REO}_{amo.(t1)}{}^{-1}\mathrm{REO}_{amo.(t2)} \tag{S6}$$

Finally, the predicted aggregates fractions were calculated as:

$$\mathrm{A}_{t2} = (1 - a - b)\mathrm{A}(t_1) + d\mathrm{B}(t_1) + fC(t_1) \tag{S7}$$

$$\mathrm{B}_{t2} = aA(t_1) + (1 - c - d)\mathrm{B}(t_1) + eC(t_1) \tag{S8}$$

$$\mathrm{C}_{t2} = bA(t_1) + cB(t_1) + (1 - e - f)C(t_1) \tag{S9}$$