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Residence time of carbon in paddy soils

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A R T I C L E I N F O

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A B S T R A C T

Mean residence time (MRT) of carbon (C) in soil is the most important parameter of C sequestration and stability and crucial for CO_2 removal from the atmosphere. Climate and soil properties controls of MRT of upland soils are well known, but the drivers of C stability in paddies were never summarized. Here, we estimated MRT of paddies across monsoon Asia using the stock-over-flux method, i.e., soil organic C (SOC) stock over organic matter input considering the net primary production (NPP), and determined the main factors affecting SOC turnover. The average MRT of paddy soils in monsoon Asia ranges between 19 and 50 yr, depending on straw management. These estimates are similar to recent estimates for the global average MRT across all soils, but longer than for upland croplands. Tropical regions have the shortest MRT for rice paddies (16–42 yr), while the MRT of C in soils of temperate and subtropical regions are longer (20–56 yr). Across a wide range of environmental factors, MRT was most strongly affected by temperature. We estimate that 2 °C warming decreases MRT by 7% on average, with the strongest decreases in the western Indonesian islands and north-east China. Because C stocks per area in paddy soils are larger and the MRT is longer than in corresponding upland cropland soils, paddies play a key role in the global C cycle. Our results emphasize the need for management practices that retain stable soil C input rates to reduce possible positive feedbacks for global warming.

1. Introduction

Soils serve as a massive C pool and affect global warming through C sequestration and CO_2 release to atmosphere (Lal, 2004; Smith et al., 2008). Soil organic carbon (SOC) stocks are determined by the balance between C input and decomposition (corresponding to turnover), which in turn depends on local environmental conditions, especially management and climate (Davidson and Janssens, 2006).

Mean residence time (MRT, years) of C in soil is widely used to characterize ecosystem C dynamics and stability at local, regional and global scales (Carvalhais et al., 2014; Chen et al., 2013; Yan et al., 2017). The residence time of SOC is an intrinsic parameter of the terrestrial C cycle with respect to C exchange with the atmosphere, determining the soils' capacity for C sequestration and C efflux (Luo et al., 2003). Knowing the MRT of C in terrestrial ecosystems would strongly improve predictions of future changes in SOC pools, the associated soil functions and the consequences for climate change (Lehmann and Kleber, 2015; Paustian et al., 2016; Schmidt et al., 2011).

The MRT can be estimated by the ratio of SOC stocks over fluxes based on a *steady state* assumption (Carvalhais et al., 2014; Chen et al., 2013; Kuzyakov, 2011). The fluxes represent either C inputs or outputs, which are equal under steady state. Because of ongoing environmental

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change (e.g. N deposition, rising levels of atmospheric CO_2, global warming), most SOC stocks are not at steady state in a strict sense. However, if environmental fluctuations are regular (e.g., cropland with repetitive management activities) or the environmental change occurs at slow rates compared to soil C turnover, soils could be considered to be in a quasi-steady state (Stockmann et al., 2013). Then, the MRT of soil C can be estimated through net annual C input to soil (i.e. annual net primary production, NPP) (Carvalhais et al., 2014; Yan et al., 2017).

The MRT differs strongly between ecosystem types and climatic zones (Chen et al., 2013; Yan et al., 2017). Moreover, external natural disturbances (e.g. fire and insect calamities) and ecosystem properties (e.g. plant age/type, soil properties and microbial community composition) influence both ecosystem C storage capacity and fluxes, thus affecting the MRT of soil C (Wang et al., 2018; Yan et al., 2017). Finally, C residence in terrestrial ecosystems is also affected by anthropogenic disturbances (e.g. agricultural activities, forest or orchard plantations, and land use change), especially in croplands (Carvalhais et al., 2014; Wu et al., 2020).

Previous studies on C residence time in agricultural soils mostly focused on upland systems (Bloom et al., 2016), whereas rice paddies were seldom considered. In comparison to other arable ecosystems, paddies have high soil C stocks and complex C dynamics as they are frequently flooded (Liu et al., 2019c, 2021). With two or even three croppings per year in the subtropics and tropics, C input into rice paddies is on average 60% higher than in upland croplands (Liu et al., 2019c). However, the key factors controlling paddy C residence time across large spatial scales remain largely unclear, making it difficult to compare C cycling in paddies with other soils.

Approximately 87% of the global rice harvested area and 90% of global rice production are concentrated in monsoon Asia (FAO, 2018). Rice paddies provide food for the regional population as they have for thousands of years (Liu et al., 2019a). Moreover, rice paddies in this area account for ~85% of global paddy soil C stocks and ~16% of global agricultural methane emissions (FAO, 2018; Liu et al., 2021). To predict future changes in global C storage and develop measures and policies to mitigate climate change, it is important to quantify the MRT in paddy soils. In this light, the relation between temperature and MRT is crucial. Future climate warming is anticipated to affect C dynamics of rice cropping systems, since temperature affects crop development and growth (Peng et al., 2004; Zhang et al., 2013) as well as decomposition rates (Tang et al., 2021). The net effect of these changes or MRT and soil C storage in rice paddies is not yet clear.

Previous studies estimated C fluxes from rice paddies (Frolking et al., 2004; G. Zhang et al., 2020) by determining net primary production (NPP) using remote sensing techniques across monsoon Asia. These studies revealed that the effects of climate on C fluxes in rice paddies are modulated by management (G. Zhang et al., 2020). However, because NPP data have not yet been assessed in relation to the spatial distribution of SOC stocks, the geographical distribution of MRT is still unknown. The objectives of this analysis were thus: i) to determine large-scale spatial patterns of MRT in rice paddies, ii) to assess how the MRT varies with environmental factors and management, and iii) to estimate temperature sensitivity of MRT of soil C to global warming.

2. Methods

2.1. Estimation of SOC residence time

Under steady state, soil C residence time can be estimated by the following equation (Carvalhais et al., 2014; Kuzyakov, 2011; Yan et al., 2017):

$$MRT = SOC/NPP \quad (1)$$

where MRT is the C residence time (years), SOC is the SOC stock (kg C m^{-2}), and NPP is annual net primary production (kg C m^{-2} $year^{-1}$).

The NPP of rice can be broken down in several elements (Xiong et al., 2014):

$$NPP_{rice} = NPP_{grain} + NPP_{straw} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposits} \quad (2)$$

In rice and other crop systems, all grain and substantial amounts of straw are removed at harvest. Depending on the country, rice straw is chopped and returned to the soil in 5–76% of the paddy area when the grain is harvested (ESCAP-CSAM, 2018). When grains are removed and straw is returned to paddy the MRT of paddy soil C can be estimated by the following equation:

$$MRT' = SOC_{paddy} / (NPP_{rice} - NPP_{grain}) \quad (3)$$

Data on paddy SOC stocks were taken from Liu et al. (2021). From this global dataset, we selected all data from rice-producing countries in monsoon Asia. In total, this subset consisted of soil C data from 529 paddy field experimental locations reported in 163 published papers (see Fig. 1a). Based on the Köppen-Geiger climate classification (Kottek et al., 2006) and the map of global terrestrial ecoregions (Olson et al., 2001), each paddy experimental location was categorized as either “tropics”, “subtropics” or “temperate” (see Fig. 1a). For each site, the dataset also contained information on location (i.e. longitude, latitude and altitude), mean annual temperature (MAT), mean annual precipitation (MAP), soil pH and clay content. Corresponding NPP data for each experimental site were extracted from MODIS 17A3 (https://lpdaac.usgs.gov/products/mod17a3hv006/) and averaged over the period of 2005–2014.

NPP of rice grains can be estimated by the following equation (Peng et al., 2004):

$$NPP_{grains} = NPP_{rice} \times R \times HI \quad (4)$$

R is the proportion of NPP allocated to aboveground productivity, and HI is the harvest index (that is, grain harvest as a fraction of aboveground biomass). Based on investigations at both regional and global scales, we assumed HI is 45% on average (Xiong et al., 2014), and R is 0.75 (Jeong et al., 2019; Singh and Benbi, 2020).

When both grain and straw are removed, paddy soil C turnover times (MRT ") can be estimated by the following equation:

$$MRT'' = SOC_{paddy} / (NPP_{rice} - NPP_{grain} - NPP_{straw}) \quad (5a)$$

NPP_{straw} was estimated based on the HI of 0.45 (Xiong et al., 2014).

2.2. Calculating paddy SOC turnover time in response to warming

Soil C residence time under global warming (MRT_w) can be estimated based on a model of soil C turnover(Varney et al., 2020):

$$MRT_w = MRT_0 \times \exp((-0.1 \times \log Q_{10}) \times \Delta T) \quad (5b)$$

where MRT_0 is the MRT before warming, ΔT is 2 °C, reflecting the Paris agreement goal to limit global warming to 2.0 °C above pre-industrial levels (Rogelj et al., 2016).

Q_{10} can be roughly estimated by the following equation (Zheng et al., 2009):

$$Q_{10} = 0.56 \times (0.13 \times SOC + 4.77) \times \exp(-0.018 \times MAT) \quad (6)$$

Where SOC and MAT are the SOC content (%) and mean annual temperature (°C) during the measurement periods.

The change in soil C residence time (ΔMRT) caused by a temperature increase of 2 °C can be calculated as follows:

$$\Delta MRT = MRT_0 - MRT_w \quad (7)$$

The rate of relative change in soil C residence time (R_{MRT}, %) with 2 °C warming can be calculated as follows:

$$R_{MRT} = (\Delta MRT / MRT_0) \times 100\% \quad (8)$$

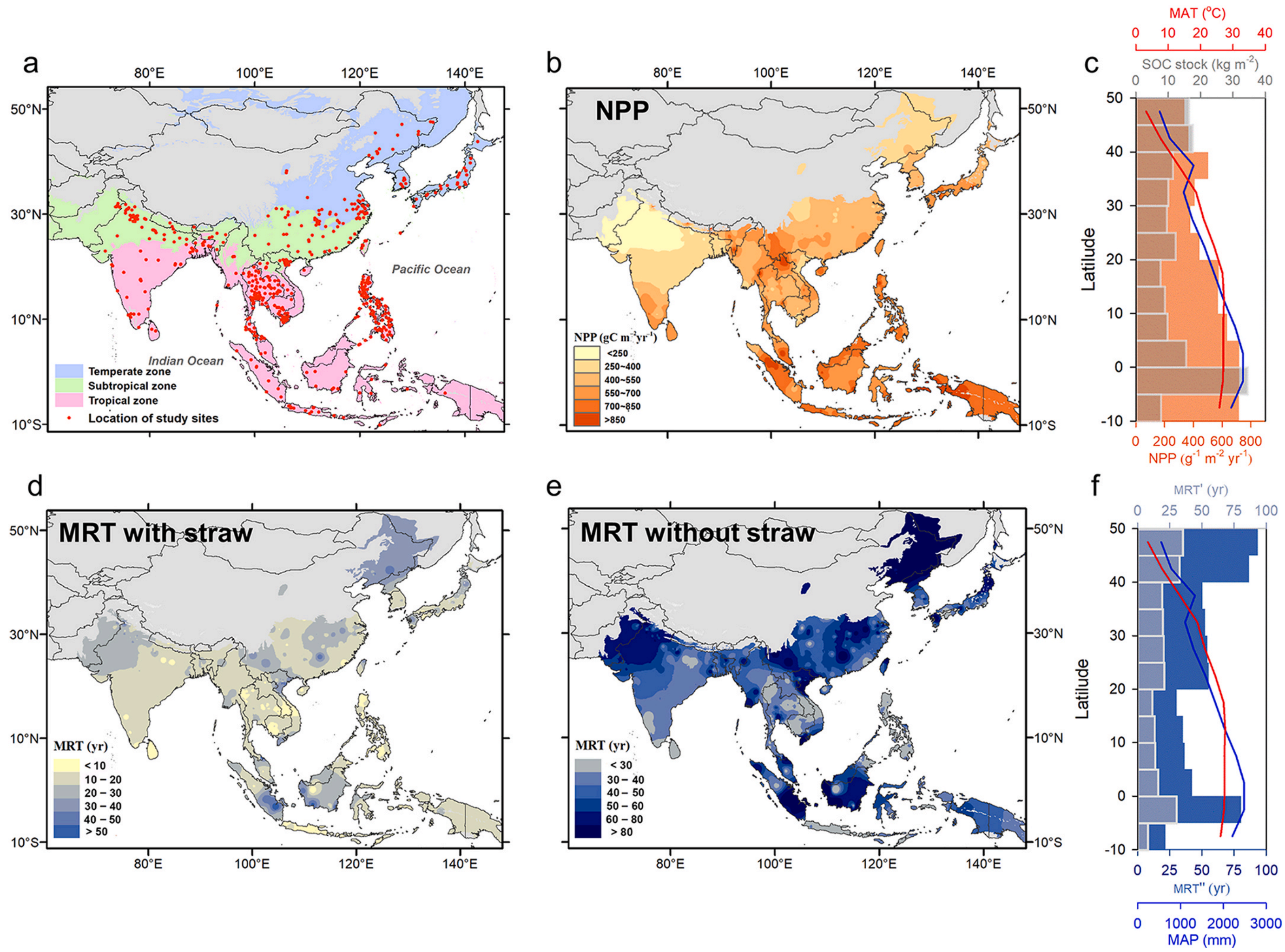

Fig. 1. Geographical distribution of mean residence times (MRT) of carbon (C) in paddy soils across monsoon Asia and latitudinal variation (per 5° latitude) depending on climate variables. a. Distribution of the study sites across monsoon Asia. All paddy locations were classified as three groups based on climate type: temperate paddy (Blue); wet subtropical paddy (Green) and tropical paddy (Pink). **b.** Distributions of net primary production (NPP) in monsoon Asia. **c.** Latitudinal trend in NPP (orange bars), soil organic carbon (SOC) stocks in the top 100 cm layer paddy soils (grey bins), mean annual temperature (MAT; red line) and mean annual precipitation (MAP; blue line) at every 5°. **d.** Distributions of estimated C turnover times with rice grain removal only in paddy soils. **e.** Distributions of estimated C turnover times with both grain and straw removal in paddy soils. **f.** Latitudinal trend in C turnover times with grain removal only (blue bars) and C turnover times with both grain and straw removal (grey bins) of paddy soils, mean annual temperature (MAT; red line) and mean annual precipitation (MAP; blue line) at every 5°. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.3. Data analysis

Inverse Distance Weighted (IDW) interpolation analyses of NPP and MRT were performed using ArcMap 10.3 (ESRI, Redlands, USA). Statistical analyses were performed using SPSS v20.0 (SPSS, Chicago, USA). After confirming the normal distribution of the data through the Shapiro-Wilk test, one-way ANOVA with Duncan's multiple-range tests were used to compare C residence times between climate zones, geographic sub-regions and main rice-producing countries. Structural Equation Modelling (SEM) was performed to analyse direct and indirect pathways determining C turnover times. In the SEM analysis, the data were fit to the model using the maximum likelihood estimation method. The chi-square (χ^2), associated p value, Goodness-of-Fit Index (GFI), and the Root-Mean-Square Error of Approximation (RMSEA) were used to evaluate the fitness of the model (Grace, 2006). The SEM analysis was implemented using Amos 21.0 (Amos Development Corporation, Chicago, USA). Four machine-learning models of partial least squares regression (PLSR), support vector regression (SVR), random forests (RF), and artificial neural networks (ANN) were examined to determine the relative importance of the environmental variables in predicting MRT (Supplementary Materials).

The plots were prepared using SigmaPlot software v12.5 (Systat Software, San Jose, USA) and R software v3.5.3 (R Development Core Team, 2019).

3. Results

3.1. Large-scale spatial patterns of mean residence time of soil carbon

The NPP increases more than tenfold from the north-east corner of Monsoon Asia to the south-west (120–1330 C g m^{-2} yr^{-1}) with a mean of 520 C g m^{-2} yr^{-1}. The highest NPP values are typically found in Southwest China and the Malay Peninsula, the lowest NPP rates are located mostly in Northern India (Fig. 1b). NPP in paddy fields near the equator (10° Ñ10° S, 715 C g^{-1} m^{-2} yr^{-1}) was on average 2 times larger than in high latitude paddy fields (40° Ñ50° N, 351 C g^{-1} m^{-2} yr^{-1}). Consistent with these findings, NPP decreased with latitude across monsoon Asia ($R^2 = 0.22$, $p < 0.001$, Fig. 1c, Fig. S1).

The overall MRT in paddy soils was 19 yr (range of 1.7–66 yr) under the assumption that the straw was retained, and 50 yr (range of 4.4–176 yr) under the assumption that straw was removed. The longest MRT are common in Northeast China, and the shortest on the Indochinese Peninsula (Fig. 1d and e). Accordingly, MRT decreased with latitude ($R^2 = 0.09$, $p < 0.001$, Fig. 1f) corresponding to the increasing MAT. Soil C turnover time is shortest in tropical paddies (16 yr), and increases from subtropical (20 yr) to temperate (21 yr) paddies with straw retention. When both grain and straw are removed, the MRT from tropical to temperate zone are 42, 52 and 56 years, respectively ($p < 0.05$; Fig. 3 and Table 1).

3.2. Factors controlling carbon turnover

Structural equation modelling (SEM) revealed that MRT values were strongly influenced by climatic factors, i.e., MAT and MAP. Both NPP and SOC decreased with soil pH, while high clay content increased SOC storage (Fig. 4a). Besides direct effects on SOC and NPP, climate indirectly affected C turnover by modifying soil pH and clay content. MAT had a direct and negative correlation with MRT ($p < 0.001$). After SOC and NPP, MAT explained most of the variation in MRT, followed by pH, MAP and clay content (Fig. 4b). The analysis results of machine learning also show that MAT is the most important factor for influencing paddy soil MRT. Although SVR's results showed MAP is important, its prediction accuracy was the worst (Fig. S2).

4. Discussion

4.1. Spatial pattern of MRT of C in paddies of monsoon Asia

Carbon residence time in paddy soils generally increased with latitude, being relatively short near the equator and longer at high latitudes (i.e. Northeast China, Fig. 1d and e). These results agree with previous assessments showing that the shortest C turnover are generally found in soils of the low-latitude zones and the longest turnover in the high-latitude zones (Bloom et al., 2016; Carvalhais et al., 2014). Nonetheless, several very long MRT (130–170 years) were close to the equator (Fig. 1f). Lu et al. (2018) reported similar patterns for latitudinal variation of global terrestrial C turnover times with an increase near the equator. This is mainly due to the high SOC stocks in the Western Malay Archipelago, which are comparable to or even higher than stocks at high latitudes (Liu et al., 2021). These results likely reflect the impact of former land use; the paddy fields in this area are often established on deforested land (Tsujino et al., 2016), and the C stocks under forest were much higher than that of paddy soil (Liu et al., 2021).

The MRT of soil C is largely determined by temperature and precipitation (Davidson and Janssens, 2006), as confirmed by modeling (Carvalhais et al., 2014; Wu et al., 2020), data synthesis studies (Wang et al., 2018), and studies estimating MRT from SOC stocks and heterotrophic respiration (Chen et al., 2013). Our assessments are largely consistent with these findings (Fig. 2). However, MAP is unlikely to affect MRT directly because rice paddies are often irrigated (Liu et al., 2021). Although MRT decreases with precipitation, this result likely reflects the covariance between temperature and precipitation ($p < 0.001$, Fig. 1c).

Benchmarking our results against previous observation-based estimates of global MRT of C in soils is important to understand how C turnover varies across regions, countries and ecosystems. The shortest MRT values for paddy soils are typically found in the tropics, while the turnover in temperate and wet subtropical regions is similar (Fig. 3 and Table 1). The MRT in forests and grasslands in temperate regions is 1.5–6 times longer than in the tropics (Table 1). Low temperatures, freezing over winter and freeze-thaw cycles in temperate zones reduce microbial activity and consequently, the decomposition of SOC (Sorensen et al., 2018). Similarly, low precipitation and temperature caused relatively small C fluxes (i.e., respiration and productivity) in terrestrial ecosystems in north-eastern China (Yu et al., 2013). In wet subtropics, on the other hand, higher MAT stimulates (bio)chemical weathering and the formation of secondary clays (Barshad, 1957) and sesquioxides. Consequently, SOC in this region is predominantly associated with the formed pedogenic minerals (Doetterl et al., 2015). Such organo-mineral stabilization protects SOC from microorganisms and exoenzymes, leading to large SOC stocks (Doetterl et al., 2015) and relatively high MRT values.

While MAT and MAP in tropics were close to that in subtropics, the MRT was much shorter (Fig. 3). This difference reflects both higher NPP values and lower SOC stocks in the tropics compared with the subtropics and temperate zones (Fig. S3). Higher temperatures in the tropics stimulate microbial activity and SOC turnover(Liu et al., 2021), whereas, the high optimum temperature of rice plant growth results in high NPP (Hatfield et al., 2011). Furthermore, average paddy soil pH in the tropics (pH = 5.6) was lower than in temperate (pH = 6.5) and subtropical zones (pH = 6.4, Fig. S3c), suggesting that more H^+ ions were available to act as electron acceptors during anaerobic fermentation (Stams, 1994). This also increase metabolic activity in anaerobic syntrophic methanogenesis (Stams and Plugge, 2009). Finally, Ca^{2+} becomes less prevalent at soil pH < 6.5, thereby reducing SOM stability through Ca^{2+} bridging or Ca-mediated aggregation (Kayler et al., 2011; Rowley et al., 2018, 2021).

Table 1
Soil C turnover times for the world's main terrestrial ecosystems.

Ecosystem type	Soil C stock ($kg\ m^{-2}$)	MRT_{soil} (yr)
Global terrestrial ecosystems	9.8 [l]	32[b r] ~50[s]
Woodland	6.9 [r]	14[b r]
Forest	18.9 [l]	17.7[y]
Cropland	7.9–8.9 [r]	17.7 [r] ~21[by]
Grassland	8.2[l]	34.4[y]
Shrubland	15.3[y]	36.2[y]
Deserts	5.8[r]	37[b r]
Tundra	20.4[r]	123[y]~490[b r]
Swamps and Marshes	72.3[r]	520[b r]
Tropical forests	–	8[y]
Temperate forests	13.4[r]	12[y]~29[b r]
Boreal forests	20.6[r]	91[b r] ~98[y]
Tropical grassland	4.2[r]	10[b r]
Temperate grassland	18.9[r]	61[b r]
Paddy in monsoon Asia	*10.6*	*35(19~50)*[c]
Tropical paddy in monsoon Asia	*9.6*	*29(16~42)*[c]
Subtropical paddy in monsoon Asia	*10.2*	*36(20~52)*[c]
Temperate paddy in monsoon Asia	*13.5*	*39(21~56)*[c]

[b] Turnover time is estimated based on the assumption that 30% of soil respiration is derived from root respiration.
[c] Our meta-analysis: The number before the tilde is the MRT of paddy with straw retention; the number after the tilde is the MRT of paddy with straw removal.
[l] Data reference from Liu et al. (2021).
[r] Data reference from Raich and Schlesinger (1992).
[y] Data reference from Yan et al. (2017).
[s] Data reference from Schmidt et al. (2011).

4.2. Comparison of MRT between ecosystems and countries

Estimates of the average global MRT of soil C range between 32–50 yr (Raich and Schlesinger, 1992; Schmidt et al., 2011; Yan et al., 2017). However, MRT differs strongly between ecosystems, spanning more than an order of magnitude from 8 yr in tropical forests to 123–520 yr in tundra, swamps and marshes (Table 1). We estimate the average MRT of C in paddy soils in monsoon Asia at 19 yr with straw retention and at 50 yr with straw removal. Both values are longer than MRT in woodland

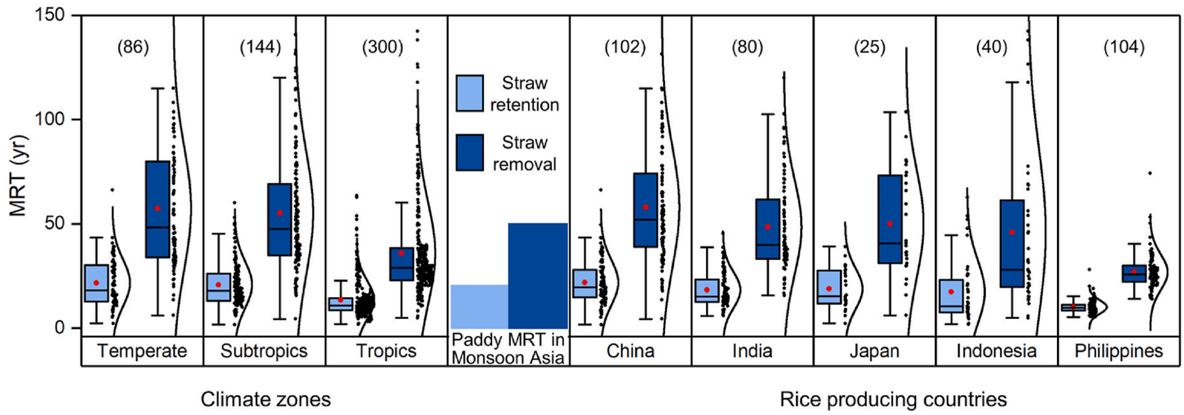

Fig. 2. Linear relationships between mean annual temperature (MAT) and mean residence time (MRT), mean annual precipitation (MAP) and mean residence time (MRT). Light blue triangles represent the relationships of soil C residence time with removal grains (MRT') between MAT and MAP; dark blue triangles represent the relationships of soil C residence time with removal grains and straw (MRT") between MAT and MAP. Statistical analysis was performed using ordinary least squares linear regressions; *p* values were indicated by asterisks: ***$p < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

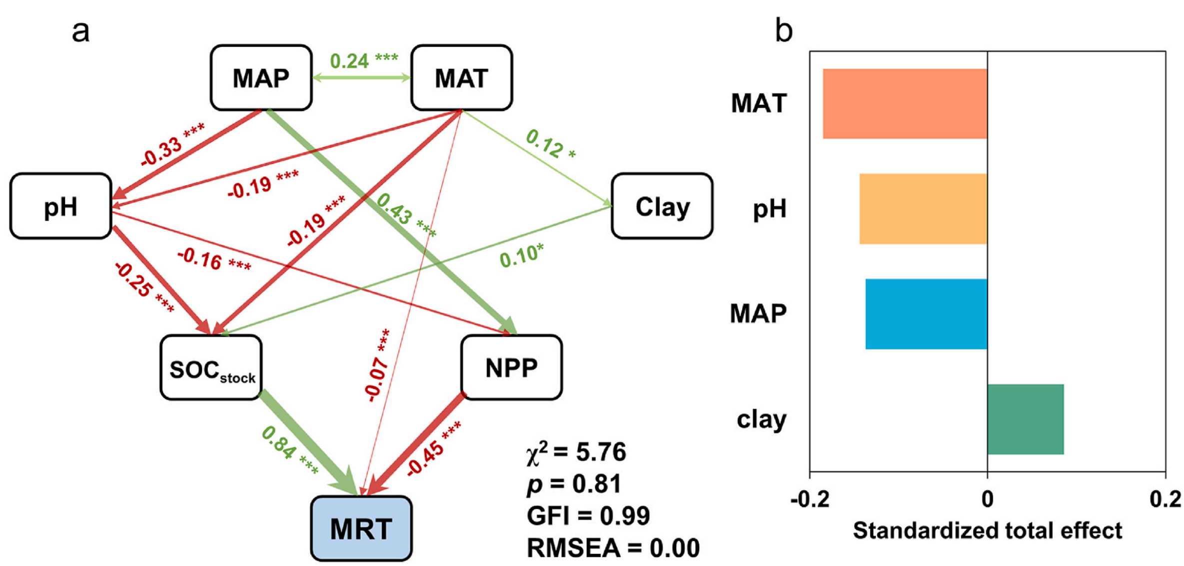

Fig. 3. Mean residence time (MRT) of carbon (C) in paddy soils depending on climate zones and main rice producing countries. Upper and lower bars: 95th and 5th percentiles of all observations, respectively; top and bottom of boxes: third and first quartiles; black horizontal solid lines in boxes: median values; red filled circle in boxes: mean values. The curves on the right side of the boxes represent the data distributions. The numbers in parentheses represent the number of samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and forest (Table 1). In woodland and forest, large diversity of plant residues provides highly available substrates for soil microorganisms, leading to fast rates of C turnover (Jing et al., 2021). Furthermore, ectomycorrhizal mycelium on tree roots contributes to SOM formation, but also for decomposition leading to fast turnover (Allen, 1991; Zhou et al., 2020). Paddy soils also contain 20% more SOC per unit area than upland agricultural soils, owing to slow decomposition under frequently flooded conditions (Liu et al., 2021). Compared to rice paddies, soil C residence is much longer in tundra, swamps and marshes, probably because the extreme environmental conditions in these ecosystems (i.e., drought, cold, and continuous flooding partly with saline water) reduce microbial activity.

Averaged across the globe, the MRT for grassland, shrubland and deserts fall in between the two mean MRTs for paddy soils with and without straw removal (Table 1). This is because the global average NPP of grassland and shrubland (<200 g^{-1} m^{-2} yr^{-1}) is lower than that of cropland (288 g^{-1} m^{-2} yr^{-1}) and paddy (>300 g^{-1} m^{-2} yr^{-1})(Raich and Potter, 1995; Zheng et al., 2003). Moreover, most grasslands and shrubs are in temperate and boreal zones (Quan et al., 2021) under a continental climate. Consequently, the low annual temperatures, long droughts in summer and frozen ground in winter strongly reduce SOC decomposition. In deserts, low SOC contents likely cause substrate limitation of soil microbes (Xu et al., 2018), but the main reasons for slow turnover are water and temperature limitations (Aanderud et al., 2010).

China and India harbor the largest total area of rice paddies, and together account for over 40% of the global paddy soil C stocks (Liu et al., 2021). According to our estimates, average paddy SOC stocks per unit area were almost 85% higher in China than in India, whereas NPP was only 45% higher. This leads to strong difference in C turnover times (*t*-test, $p = 0.03$), with China having longer MRT than India. We attribute this difference to the impact of specific edaphic, climatic and management conditions on C stocks and fluxes. Mean annual temperature in rice growing regions of India is higher than in China, leading to fast organic C mineralization (Ghimire et al., 2017). Furthermore, developed under tropical and humid climates, Vertisols with a very high smectite content

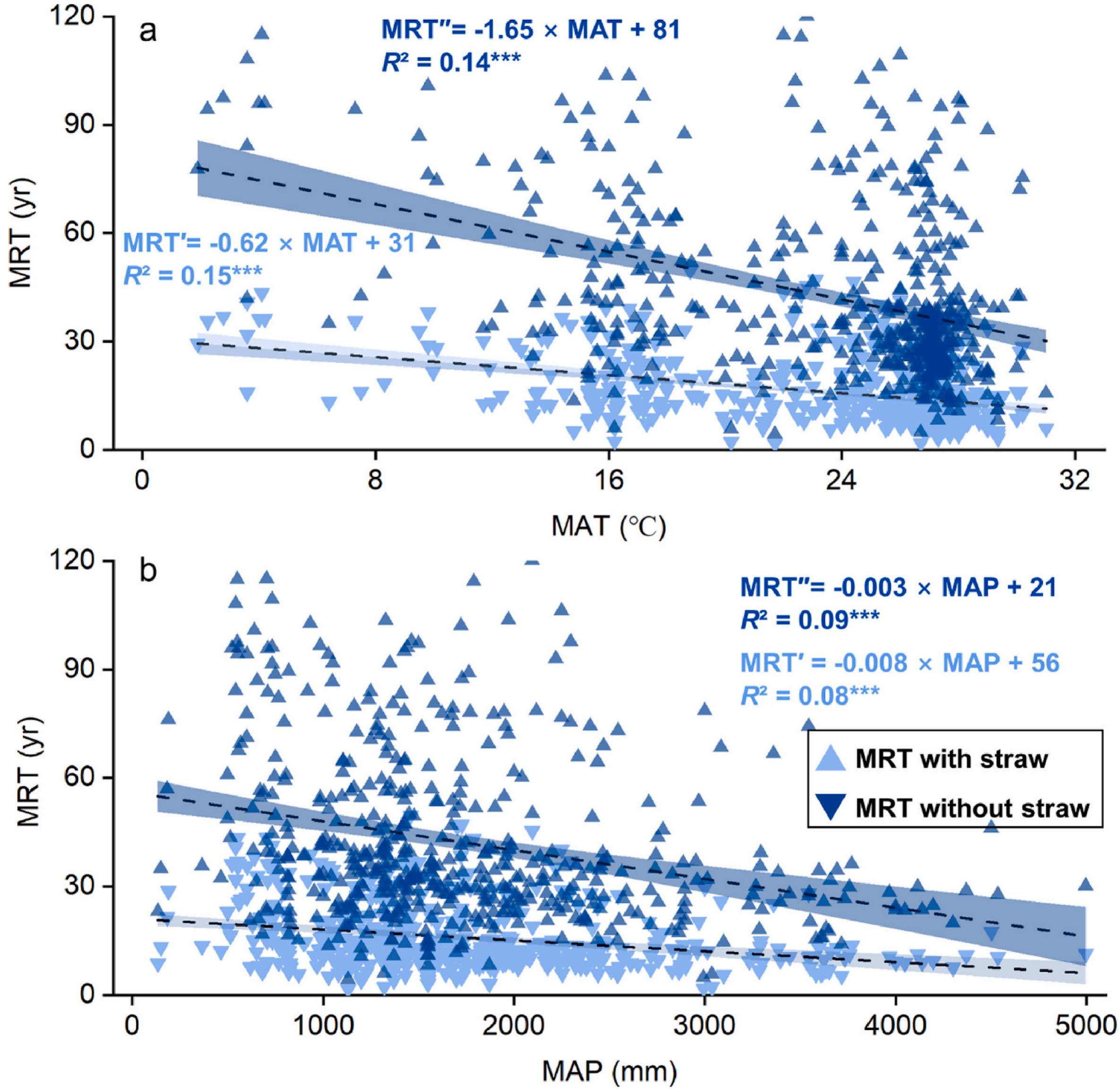

Fig. 4. Structural equation model (SEM) examining the effects of climatic and environmental factors on mean residence time of C in paddy soils. a. Evaluation of direct and indirect effects MRT of climatic and environmental variables on turnover time (MRT) of organic C in paddy soils (n = 480). Green and red lines indicate positive and negative relationships, respectively; line width represents the strength of the relationship. Numbers adjacent to arrows are standardized path coefficients, analogous to relative regression weights, and indicative of the effect size of the relationship. MAT, mean annual temperature; MAP, mean annual precipitation; SOC_{stock}, soil organic carbon stock; BD, bulk density. Goodness-of-fit statistics for the model are shown alongside the model. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. **b.** Standardized total effects (direct plus indirect effects) derived from SEM at the sub-continental scale in monsoon Asia. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

are widely distributed in India (Eswaran and Reich, 2005). Compared to other soil types, soil aggregates in Vertisols are more likely to break down under alternate wetting and drying in rice paddies, accelerating the turnover of soil C (Šimanský and Bajčan, 2014). Finally, management practices such as fertilizer application and straw return also affect C turnover. For example, under low-input farming in India, more crop nutrients are supplied through SOM decomposition, which suggesting higher rates of SOC turnover (Lal, 2004; Liu et al., 2021). The MRT of paddy soils in Japan is longer than in Indonesia and the Philippines (Fig. 3), partly because a colder climate limits plant productivity and microbial decomposition.

4.3. Controls on MRT of paddy soils

Our analysis provides new insights into the drivers controlling the MRT of C in paddy soils by identifying direct and indirect effects of environmental factors (Fig. 4). On the one hand, MAP and MAT affected NPP and SOC stock of paddy ecosystems directly through their impact on photosynthetic C fixation and microbial respiration. Climate factors also impacted NPP and SOC indirectly, however, likely by accelerating mineral weathering and clay formation and then changing pH (Barshad, 1957). While MAT had a greater predictive power for SOC at the global scale, MAP had a greater predictive power for NPP (Del Grosso et al., 2008; Li et al., 2020). MAP is not relevant for SOC in rice paddies, because rainfall will not affect soil-water content under regular flooding of paddy fields (Liu et al., 2021).

Due to the adaptability of japonica and indica rice varieties to temperate and tropical regions, respectively, MAT only has a limited impact on rice NPP, especially on large spatial scales. Nonetheless, MAT explains well the MRT variation than other environmental factors (Fig. 4b, Fig. S2). These results are consistent with previous studies indicating that MAT is the best predictor of the spatial distribution of C turnover globally (Carvalhais et al., 2014; Chen et al., 2013). Negative correlations between temperature and MRT can be linked to multiple mechanisms including stimulating microbial and enzyme activities (Bond-Lamberty and Thomson, 2010; Davidson and Janssens, 2006).

Human activities also play an important role in controlling the spatial pattern of SOC and NPP, which may explain the highly similar C turnover time under very different climate conditions (Fig. 1c and f). The impact of paddy management practices has been considered in C turnover models (e.g. DNDC, RothC) (Shibu et al., 2006). For instance, fertilization accelerates the turnover of rhizosphere C in rice paddies by 20–70% (Liu et al., 2019b). Rice straw return induces SOC mineralization and increases the CO_2 emissions from SOC by 75% under flooded conditions (Y. Zhang et al., 2020), but because of the positive balance, increase the C stocks by 13% (Liu et al., 2021). Tillage generally accelerates organic C decomposition by increasing the availability (aggregate destruction) and oxidation of SOC (Haddaway et al., 2017). Compared to conventional tillage in paddies, no-till and reduced tillage increases SOC stocks in the 0–30 cm layer by 8–10% (Liu et al., 2021).

4.4. Impact of warming on MRT in paddy soils

Our results suggest that a global average temperature increase of 2 °C will shorten the MRT of paddy soils across monsoon Asia by ~7% (Figs. 1 and 5). This acceleration is smaller than the average impact of warming on MRT across all upland soils (decreases by ~7% per 1 °C warming) (Davidson and Janssens, 2006), probably because the decomposition rate of organic matter is suppressed under anaerobic conditions (Liu et al., 2019c; Sahrawat, 2004). However, relatively small changes in soil C turnover in paddies could substantially alter future climate trajectories. Warming accelerates turnover of the labile SOM (Dorrepaal et al., 2009) and depolymerization of chemically complex organic matter (Lehmann and Kleber, 2015). In the long term, warming may also increase ligninase activity, thereby catalyzing the degradation of recalcitrant C (Chen et al., 2020). Warming not only affects the turnover of topsoil organic C, but may also accelerate C turnover in subsoils (Lin et al., 2018). This is because warming increases abundance of functional microorganisms that degrade recalcitrant organic matter in subsoil (Cheng et al., 2017). Warming also increases fine root turnover rate and activity in subsoil, thereby accelerating the decomposition of labile C (Lin et al., 2018).

Both with and without straw removal, the largest warming-induced reductions in the turnover time of soil C occurred in the western Indonesian islands and Northeast China (Fig. 5). This is possibly because paddy soils in these areas have high SOC stocks (Liu et al., 2021), and the effects of warming on C turnover increase with the size of the initial soil C stock (Zheng et al., 2009). Soils with high SOC usually have lower density and higher porosity, which in turn benefits soil aeration and the growth of roots and microorganisms. Consequently, the increase in microbial biomass and microbial activity with warming directly accelerate SOC decomposition (Tan et al., 2014). Soil C turnover in cold climates (high-latitude zones) is more sensitive to warming than in warm climates (low-latitude zones) (Chen et al., 2013; Koven et al., 2017), suggesting that considerable C amounts may be lost in high-latitude areas (Jin et al., 2000).

On the other hand, recent meta-analyses suggest that experimental warming has limited effects on soil C pools (Liu et al., 2020; Van Gestel et al., 2018), presumably because warming-induced increased plant-derived C input partly compensates for increased SOC decomposition. In that case, warming would increase MRT without net C loss. Several studies suggest this may also be true for rice paddies; experimental warming has been found to increase both C input (i.e. plant growth) and output (i.e. CO_2 emissions) in rice paddies, with limited changes to soil C stocks (Tokida et al., 2011; Xiong et al., 2014; Yue et al., 2017). Can plant growth keep up with increases in decomposition rates as temperatures continue to increase? The optimum temperature for SOC decomposition may be higher than for rice plant growth (Cao et al., 1995; Xiong et al., 2014), suggesting that additional warming would cause net soil C losses in warm climates. On the other hand, farmers can adapt management practices to rising temperatures, e.g. by changing rice cultivars and planting dates (Parry et al., 2007). Thus, while the impact of warming-induced increases in MRT on soil C storage in rice paddies is not yet clear, our results emphasize the need of management practices to maintain plant growth and soil C input in rice paddies. Rice paddies are projected to release 23% more CH_4 under ~1.5 °C warming and 40–50% more under 2 °C warming (Liu et al., 2020; Pereira et al., 2013; Tokida et al., 2010), mainly due to higher activity of methanogens, increased root exudation and decreased O_2 solubility in water (Fey and Conrad, 2000; Tokida et al., 2011). Thus, future warming will likely increase CH_4 release from paddies in monsoon Asia, especially in western Indonesian islands and Northeast China, where high SOC stocks may preclude substrate limitation of CH_4 production under global warming (Aben et al., 2017). Increases in CH_4 production, however, may partly be balanced by increased activity of methanotrophs and CH_4 oxidation in warmed soils (Fan et al., 2022) as well as nitrite-dependent anaerobic oxidation (Shi et al., 2022). Taken together, these results suggest that rising temperature will likely drive a positive land C–climate feedback that could accelerate climate change, but the exact amount of net C loss to the atmosphere needs further research.

In summary, we estimate that the average MRT for paddy soils across monsoon Asia ranges between 19–50 years. This estimate is close to the global average for soils in natural ecosystems (forests, grassland,

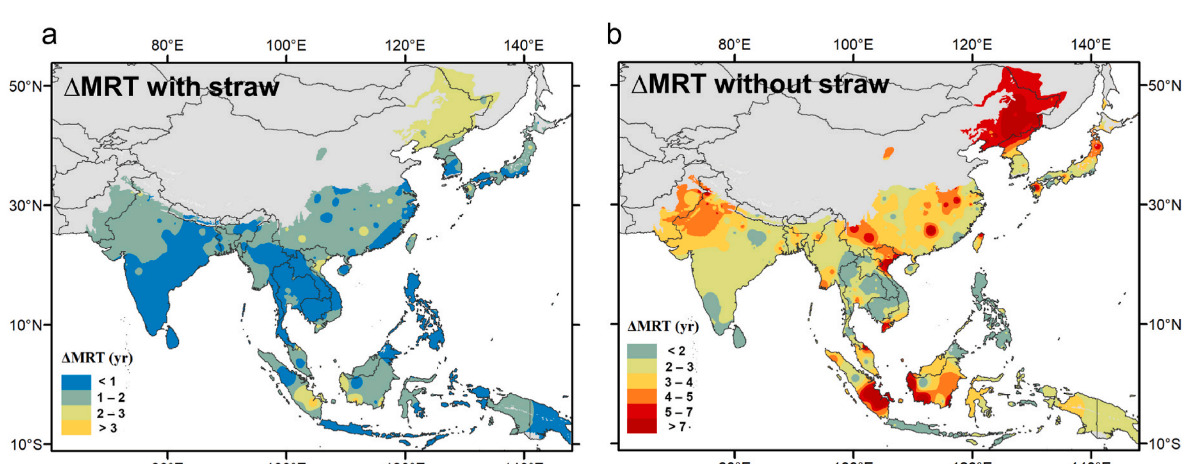

Fig. 5. Temperature sensitivity for MRT (ΔMRT) responses to 2 °C warming. A, rice grain removal only; b, both grain and straw removal.

shrubs), but longer than for upland croplands. MRT for rice paddies was shortest in tropical regions, while it was similar in temperate and wet subtropical climates. MAT influenced C turnover more than MAP, pH, or clay content. MRT on paddy soils across monsoon Asia are declining at an average rate of 7% to 2 °C warming. Our results revealed the spatial distribution of soil carbon turnover in paddy fields and its key influencing factors, and identified the areas, where future global warming will increase MRT most strongly. Protecting paddy soil C stocks in these sensitive areas may help reduce negative impacts on turnover rates and minimize positive feedbacks to global warming.

Author contributions

Liu, Y., Ge, T., van Groenigen K. J. and Kuzyakov, Y. conceived and designed this work; Liu, Y. and Wang, P. collected and organized data; Liu, Y., Ge, T., van Groenigen K. J., Xue, X., Chen, K., Zhu, Z., Wang, J., Guggenbergerm G., Chen, J., Luo, Y. and Kuzyakov, Y. took part in data discussion; Liu, Y. analyzed data and wrote the manuscript with contributions from all authors; Liu, Y., van Groenigen K. J. and Kuzyakov, Y. revised the manuscript with contributions from all authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136707.

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