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The spatial patterns of litter turnover time in Chinese terrestrial ecosystems

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Abstract

The feedback between plant, soil and climate is partly determined by plant litter turnover time, which is influenced by climate, litter quality and soil properties. However, the spatial patterns of litter turnover time and its interrelation with these variables are rarely quantified. With a database of 1,378 litter turnover times and key associated climate, litter quality and soil properties (total of 20 variables), this study investigated the driving factors and spatial patterns of litter turnover time across Chinese terrestrial ecosystems. The mean litter turnover time was the longest in forest ecosystems, followed by that in grassland and cropland ecosystems. The litter turnover time varied significantly depending on the litter quality and climate zone, and increased exponentially as latitude increased. Mean annual temperature (MAT) and mean annual precipitation (MAP) could accurately predict litter turnover time via negative exponential equations. Among these variables, MAT had the greatest influence on litter turnover time, which accounted for 37.4% of the variation, followed by litter quality (ecosystem types, litter types, C:N of litter and lignin content; 33.4%) and soil properties (sand content, soil pH and soil organic carbon (SOC); 29.2%) based on a boosted regression tree (BRT) model. Path analysis identified that MAT negatively affected litter turnover time both directly and indirectly through regulating soil properties and litter quality, which positively and directly affected litter turnover time. Finally, the spatial patterns of litter turnover time were obtained with a regional dataset of ecosystem types, MAT, sand content, soil pH and SOC as BRT model drivers. Overall, our results suggest that climate variables have contrasting effects on litter turnover time and could mediate the impact on litter turnover time by litter quality and soil properties. These results highlight important implications for climate-smart soil management and can be used to create reliable model predictions.

Highlights:

- We explored the driving factors and spatial patterns of litter turnover time in various ecosystems
- Accurate estimates of litter turnover time were obtained from dataset from 1,378 experimental sites
- Litter turnover time exponentially increased as latitude increased
- Climate-mediated litter quality and soil properties controlled the litter turnover time

KEYWORDS

climate, litter quality, litter turnover time, soil property, terrestrial ecosystems

1 | INTRODUCTION

Terrestrial ecosystems play a crucial role in global carbon (C) dynamics and the regulation of climate change. Terrestrial ecosystem C fluxes depend on C sequestration via photosynthesis and the release of C by plant litter and soil C decomposition via respiration (Luo, Keenan, & Smith, 2015). During these processes, litter acts as a bridge, linking atmospheric CO_2 and soil organic carbon (SOC) formation (Cotrufo, Wallenstein, Boot, Denef, & Paul, 2013). Litter dynamics is an important biogeochemical process that controls soil organic matter formation, nutrient release and energy cycling, affecting atmospheric CO_2 concentrations, plant growth and carbon sequestration. Consequently, understanding the litter turnover time is critical for quantifying the carbon footprints of the pedosphere, biosphere and atmosphere and for predicting global C dynamics (Wang et al., 2017). Moreover, litter turnover time is a critical parameter for ecosystem models (e.g., the CENTURY model, TECO model and Community Land Model) (Bonan, Hartman, Parton, & Wieder, 2013; Koven et al., 2013; Weng & Luo, 2008). However, the initial litter turnover time values in these models were estimated from laboratory experiments based on litter decay. The litter turnover time values will differ depending on the climate, litter quality and soil properties. Different litter turnover times could lead to great uncertainty in the predicted results because of the fixed default values in the models. Furthermore, litter turnover time has been less evaluated with field data over large spatial scales (Bonan et al., 2013; Koven et al., 2013). Therefore, the spatial pattern of litter turnover time is important and difficult to quantify, especially at large spatial scales.

Many factors have been proposed to explain the variation in litter turnover time over space and time (Bradford et al., 2014; Poll, Marhan, Ingwersen, & Kandeler, 2008; Portillo-Estrada et al., 2016). These factors can be categorized into four main groups: (a) climatic factors (temperature and precipitation); (b) litter characteristics, such as litter species (forest, grassland and cropland), litter tissues (i.e., root, stem, leaf and mixture) and the carbon-to-nitrogen ratio (C:N) of litter; (c) soil properties, including soil texture (sand, silt and clay content) and nutrient contents; and (d) biotic properties (i.e., microbial community structure and diversity). A combination of these factors regulates the litter turnover time in terrestrial ecosystems. Thus, the studies that aim to explore changes in litter turnover time based on a single factor elicit large uncertainties (Bradford et al., 2016). The incorporation of each factor is critical for predicting the terrestrial C cycle. However, the relative contributions of these factors in regulating litter turnover time over large spatial scales are still ambiguous.

Among the four main variables, climate is generally regarded as the dominant variable that drives the litter turnover time at regional and global scales (Portillo-Estrada et al., 2016). For example, mean annual temperature (MAT) and mean annual precipitation (MAP) explained 38% of the variance in litter decomposition for 11 litter species at different forest sites across Canada (Moore et al., 1999). Additionally, Gregorich et al. (2016)

reported that the time required for litter decomposition decreased by 1 and 2 years in the cool zone and warm zone, respectively. This relationship between climate and litter has been incorporated into ecosystem C cycle and terrestrial ecological models, and the litter turnover times of different litter tissues (leaves, stems and roots) are usually simulated using soil moisture and air temperature. Under certain climatic conditions, litter quality can become the dominant determinant of litter turnover time (Cornwell et al., 2008; Silver & Miya, 2001). Lignin is typically considered a recalcitrant material that is resistant to microbial decomposition; only specialized biota, predominantly fungi, are able to synthesize extracellular enzymes that breakdown these structures into biologically usable forms (Swift, Heal, & Anderson, 1979). Under homogeneous litter, belowground decomposition was found to be faster than aboveground decomposition, and the decomposition rate could be better predicted through the MAP (Bontti et al., 2009). Other than climate and litter quality, soil conditions, including geochemistry and physical structure, can also have considerable effects on litter turnover time. Frøseth and Bleken (2015) reported that litter turnover time was higher in sandy compared to clay soil. Gregorich et al. (2016) concluded that soil properties, such as soil nutrients, had little influence on litter turnover compared with soil moisture and temperature. It is clear that complex interconnections exist among these factors. Climate affects litter quality by impacting plant community and decomposer activity. Litter quality affects litter turnover time by regulating soil C pools through C input (Luo, Feng, Luo, Baldock, & Wang, 2017). Therefore, an enhanced understanding of how these variables directly and/or indirectly affect litter turnover time is urgently needed to accurately predict litter turnover time over large spatial scales.

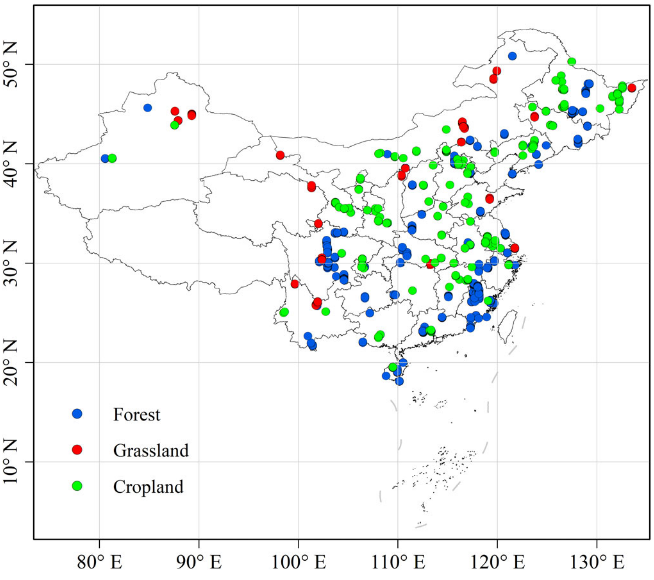

FIGURE 1 The locations of studies included in this analysis [Color figure can be viewed at wileyonlinelibrary.com]

We used a hypothesis-oriented path analysis on a regional database including the litter turnover time and external environmental variables. Through the combinations of path analysis and this database, we could determine the litter turnover time variation and quantify the potential effects of these variables on litter turnover time. Specifically, we aimed to answer three questions: (a) How does the litter turnover time vary under forest, grassland and cropland ecosystems? (b) What are the relative importance levels of climatic, litter quality and soil properties in controlling the variation in litter turnover time? (c) How do climate variables mediate the effects of key litter quality and soil properties on litter turnover time?

2 | MATERIALS AND METHODS

2.1 | Data sources

To investigate the spatial patterns and explore the driving factors of litter turnover time, a dataset of papers published until June 2017 was collected from the Web of Science (http://apps.webofknowledge.com) and the China Knowledge Resource Integrated Database (http://www.cnki.net/). The keywords included "litter mass loss", "litter decomposition" and "China". To standardize the dataset, five criteria were used: (a) data on litter dynamics from incubation studies that used surface litterbags were obtained, but data from laboratory experiments were excluded to ensure the comparability of environmental variables; (b) the data on litter dynamics were reported via figures, tables and text; (c) at least five values of litter mass loss with time were used to determine litter turnover time; (d) the experiments were not manipulated to influence litter decomposition, such as the addition of fertilizer; and (e) the litter decay rate was directly incorporated into our database from the presented equations. Meanwhile, if the published papers reported the litter turnover time, the value was directly recorded in our dataset.

For the actual litter mass (grams), we first normalized the values by converting the starting litter mass to 1 and then calculated litter turnover time using a first-order exponential decay function ($y = e^{-kx}$) according to Wider and Lang (1982) and Woodward et al. (2012), where y is remaining litter (%), x is the time at the beginning of litter decay (year) and k is the litter decay rate (year^{-1}). The mean turnover time under different decay stages (year) is $1\ k^{-1}$, which is the average time required for plant litter to be completely decomposed. Overall, our database

TABLE 1 Summary of site information and selected climate, litter quality and soil properties

Variables	Forest litter				Grassland litter				Cropland litter			
	No.	Mean ± SD	Range	Skewness	No.	Mean ± SD	Range	Skewness	No.	Mean ± SD	Range	Skewness
Latitude (°)	793	31.6 ± 7.4	18.2–50.8	0.6	153	39.0 ± 7.1	23.2–49.3	−0.5	432	36.45 ± 7.4	19.5–48.9	−0.3
Longitude (°)	793	115.0 ± 8.4	80.6–129.3	−0.3	153	109.9 ± 11.9	87.6–133.5	−0.2	432	116.2 ± 9.5	81.3–132.6	−0.8
Altitude (m)	793	743 ± 934	1–4,523	2.2	153	1,234 ± 1,200	13–3,570	1.0	432	432 ± 563	4–2,157	1.4
MAT (°C)	793	14.4 ± 6.5	−3.4 – 26.2	−0.5	153	8.0 ± 6.3	−2.0 – 23.1	1.0	432	11.6 ± 6.0	−2.1 – 24.3	0.1
MAP (mm)	793	1,137 ± 488	247–2,403	0.2	153	564 ± 497	144–2,176	1.8	432	872 ± 508	124–2,284	0.8
Lignin (%)	85	32.4 ± 9.8	13.8–56.5	0.5	23	20.2 ± 20.8	6.2–65.2	1.3	83	17.7 ± 7.5	10.4–130	0.5
C:N of litter	206	59 ± 20	10.1–115	1.1	41	52.7 ± 33.6	6.8–128.9	0.9	96	49 ± 28	6.5–29.1	0.0
Soil sand content (%)	793	43.5 ± 15.9	6.4–82.3	0.4	153	41.8 ± 15.8	13–73	−0.3	432	54.1 ± 15.7	14–86	0.1
SOC (mg kg^{-1})	215	26.2 ± 17.9	4.8–63.7	0.7	17	17.3 ± 12.7	4.9–49.8	1.3	292	12.1 ± 6.23	2.7–33.3	1.1
Soil N (mg kg^{-1})	221	1.7 ± 1.5	0.2–8.4	1.5	26	1.9 ± 1.4	0.4–4.6	0.8	167	1.2 ± 0.6	0.3–3.5	1.1

Abbreviations: C, carbon; MAP, mean annual precipitation; MAT, mean annual temperature; N, nitrogen; SOC, soil organic carbon.

included climatic conditions (MAT and MAP), soil properties (i.e., SOC, total soil N and soil texture) and litter quality (i.e., litter species, litter tissues, C:N of litter and ecosystem types), which is a total of 20 environmental variables. A total of 1,378 litter turnover times from 246 published studied were obtained. The spatial distribution of the study sites is shown in Figure 1. In our database, forest was the main vegetation type (57.5%), followed by crops (31.3%) and grass (11.2%). In cases where the referenced studies did not report MAT and MAP, the values were taken from nearby climatic stations via http://cma.gov.cn/. In cases where the referenced studies did not report soil texture, the data for soil texture were extracted from the Chinese second soil survey database. The main geographic locations, litter quality and soil properties were presented in Table 1.

2.2 | Statistical analysis

To explore the relationships between litter turnover time and the environmental variables, based on theoretical knowledge and the validity of our dataset, a total of 20 variables (MAT, MAP, soil texture (sand, silt and clay content), SOC, soil total and available N, soil total and available phosphorus, soil pH, ecosystem types, litter tissues and litter composition (carbon content, C:N of litter, protein, ash, hemicellulose, cellulose and lignin content) were first input into boosted regression tree (BRT) models to select the driving factors. Eight variables (MAT, ecosystem types (forest, grassland and cropland), litter types (root, stem and leaf), C:N of litter, lignin, sand content, soil pH and SOC) were retained according to their effects on predictive performance (deviance explained and area under the curve). Then, we clearly determined the importance of climate, litter quality and soil properties. Boosted trees were constructed using the recommended parameter values: learning rate (0.01), bag fraction (0.50), cross-validation (10) and tree-complexity (5) (Elith, Leathwick, & Hastie, 2008). Due to having categorical variables, the Bernoulli method was used for all BRT fittings. All BRT analyses were performed with the GBM package in R version 3.3.3 (Elith et al., 2008). Lin's concordance correlation coefficient (LCCC) is a measure of the deviation of the relationship between predicted and true values from the 45° angle (Lin, 1989). Therefore, LCCC was used to assess the quality of the relationship between observed and predicted litter turnover times.

Structural equation modelling (SEM) was used to determine the direct and/or indirect pathways and test whether climate affects litter turnover time via litter and soil properties. The following hypothetical paths were developed in the initial path models. First, six of the selected factors (MAT, C:N of litter, lignin, sand content, soil pH and SOC) had a direct effect on litter turnover time. Second, climate (MAT) indirectly affected litter turnover time via its effects on soil (sand content, soil pH and SOC) and litter (C:N of litter and lignin content) properties. Third, soil properties may indirectly affect litter turnover time through their effects on litter properties. Finally, all significant correlation paths were retained in the frame. The estimated means and intercepts (missing data of the selected variables) were set to assess the path parameter. Structural equation modelling is based on accepting the null hypothesis, which is true when $p > .05$. The root mean square error of approximation (RMSEA) is an index of the difference between the observed covariance matrix per degree of freedom and the hypothesized covariance matrix, which denotes the model. The RMSEA also takes the model complexity into account as it reflects the degree of freedom as well. Therefore, the model fit could be divided into four categories based on the RMSEA values: a good fit (RMSEA $\leq$ 0.05), an adequate fit (0.05 $\leq$ RMSEA $\leq$ 0.08), a mediocre fit (0.08 $\leq$ RMSEA $\leq$0.10) and a not acceptable fit (RMSEA > 0.10) (Grace & Keeley, 2006). Therefore, a good model fit was indicated by $.05 \leq p \leq 1.00$ and $0 \leq$ RMSEA ≤ 0.05 (Grace & Keeley, 2006). The SEM was carried out using the Amos 17.0 package for Windows 10.0.

Based on the result of BRT, five variables (ecosystem types, MAT, soil pH, soil sand content and SOC) were considered as a BRT model driving factors to accurately predict the spatial patterns of the litter turnover time. The MAT data were calculated by collecting meteorological data in China from 1970 to 2010 (http://cma.gov.cn/). The sand content, soil pH and SOC data were derived from the Second National Soil Survey of China. The resulting datasets have been made available for statistical calculations and mapping.

3 | RESULTS

3.1 | Mean litter turnover time

Litter turnover time varied among different ecosystems and litter tissues (Figure 2 and Figure S1). The mean litter turnover times of forest and grassland litter were 2.65 and 2.04 years, respectively, whereas the mean cropland litter turnover time (0.83 years) was shorter than that of forest and grassland. In the forest and grassland ecosystems, the mean litter turnover time was in the order of root (3.71 and 2.19 years) > stem (3.54 and 2.08 years) > leaf (2.77 and 1.48 years). The litter turnover times of the mixtures (different litter tissues) were 2.58 and 2.30 years for forest and grassland, respectively. For cropland straw tissues, the mean litter turnover time exhibited a similar order to the forest and grassland ecosystems, with values of 1.13 and 0.72 years for the root and stem pools, respectively (Figure S1). The order of the mean litter turnover time among the straw types differed from the order of the root and straw pools, with soybean (1.60 and 0.85 years) > rice (1.42 and 0.72 years) > maize (1.28 and 0.63 years) or wheat (1.16 and 0.69 years) > other species (0.88 and 0.53 years) (Figure S1). The mean manure litter turnover time was 0.94 years, with a range from 0.34 years (cake manure pool) to 1.29 years (farmyard pool) (Figure 2 and Figure S1).

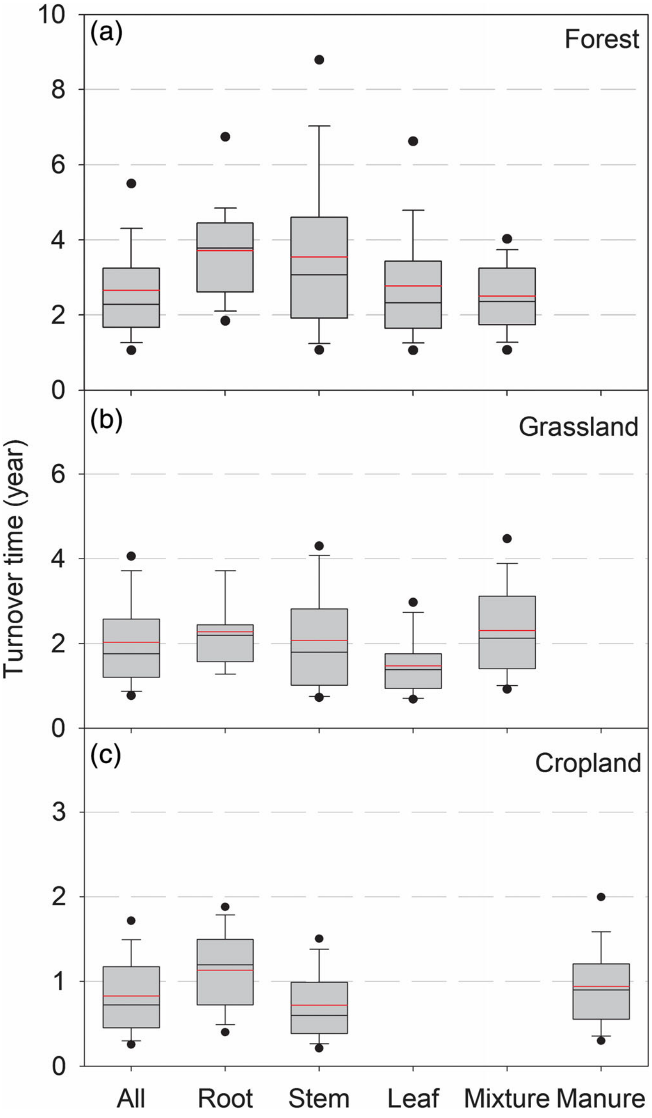

FIGURE 2 The turnover time for forest litter (a), grassland litter (b) and cropland litter (c) according to litter tissue types (root, stem, leaf, mixture and manure). The black and red lines within the boxes indicate the medians and means, respectively, the boxes represent the 25th and 75th percentiles, the whiskers indicate the lowest and highest values excluding outliers, and the circles represent outliers [Color figure can be viewed at wileyonlinelibrary.com]

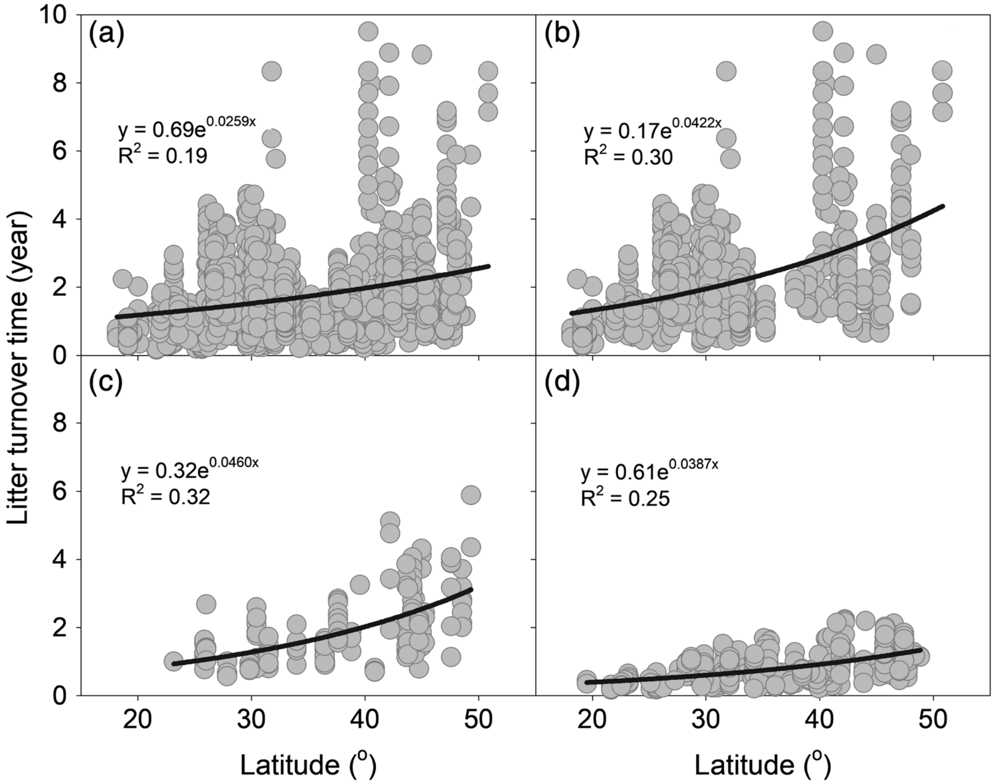

FIGURE 3 The relationship between litter turnover time (year) and latitude in all (a), forest (b), grassland (c) and cropland (d) terrestrial ecosystems

3.2 | Climate forcing

Litter turnover time was highly correlated spatially, albeit with high variance (Figure 3 and Figure S2). The litter turnover time increased exponentially as the latitude increased, in the order of middle-temperate > warm-temperate > subtropical > tropical zones (Figure S2). Latitude influenced the litter turnover time mainly via climate forcing, such as through differences in MAT and MAP. Therefore, litter turnover time decreased with the decrease in MAT, as described by the following exponential equations: litter turnover time = $4.64e^{-0.0582\mathrm{MAT}}$, $3.13e^{-0.0638\mathrm{MAT}}$ and $1.54e^{-0.0612\mathrm{MAT}}$ under forest, grassland and cropland ecosystems, respectively ($R^2 = 0.34$–0.42; Figure 4a,c,e). The temperature sensitivity of litter turnover time (Q_{10}) values in forest litter ($Q_{10} = 1.79$), grassland litter ($Q_{10} = 1.89$) and cropland litter ($Q_{10} = 1.84$) differed over large spatial scales. Similar relationships occurred between litter turnover time and MAP with an even smaller R^2 (litter turnover time = $4.10e^{-0.0006\mathrm{MAP}}$, $3.13e^{-0.0006\mathrm{MAP}}$ and $1.28e^{-0.0005\mathrm{MAP}}$ under forest, grassland and cropland ecosystems, respectively; Figure 4b,d,f).

3.3 | Driving factors and spatial patterns of litter turnover time variation

Climatic factors, litter quality and soil properties interactively regulate litter turnover time (Figures 5 and 6). The BRT results suggested that climate, litter quality and soil properties were responsible for 37.4%, 33.4% and 29.2% of the variations in litter turnover time across all (forest, grassland and cropland) ecosystems, respectively (Figure 5a). The MAT for forest and cropland and the MAP for grassland were the most influential variables on litter turnover time among the seven variables (Figure S3). Overall, the BRT model explained 92% of the variance in litter turnover time for Chinese terrestrial ecosystems (Figure 5a1). A simple BRT model was also performed by using widely available factors (MAT, ecosystem types, soil pH, SOC and sand content), which was used to predict the spatial patterns of litter turnover time (Figure 5b). If litter types, C:N of litter and lignin content were removed, the interpretation rate of the litter turnover time variations (LCCC = 0.89) did not decrease significantly compared with the model when all variables were used (LCCC = 0.92). The path analysis could explain 65% of the variance in litter turnover time ($R^2 = 0.65$; Figure 6). The MAT indirectly and negatively affected the litter turnover time through decreasing lignin (path coefficient: −0.34), C:N of litter (−0.18), soil pH (−0.33), sand content (−0.18) and SOC (−0.25). Moreover, MAT had a direct negative effect on litter turnover time (−0.28). Sand content, SOC, lignin content and C:N of litter had direct and positive influences on litter turnover time. Soil organic carbon was indirectly associated with litter turnover time due to positive associations with lignin content and C:N of litter. In contrast to other

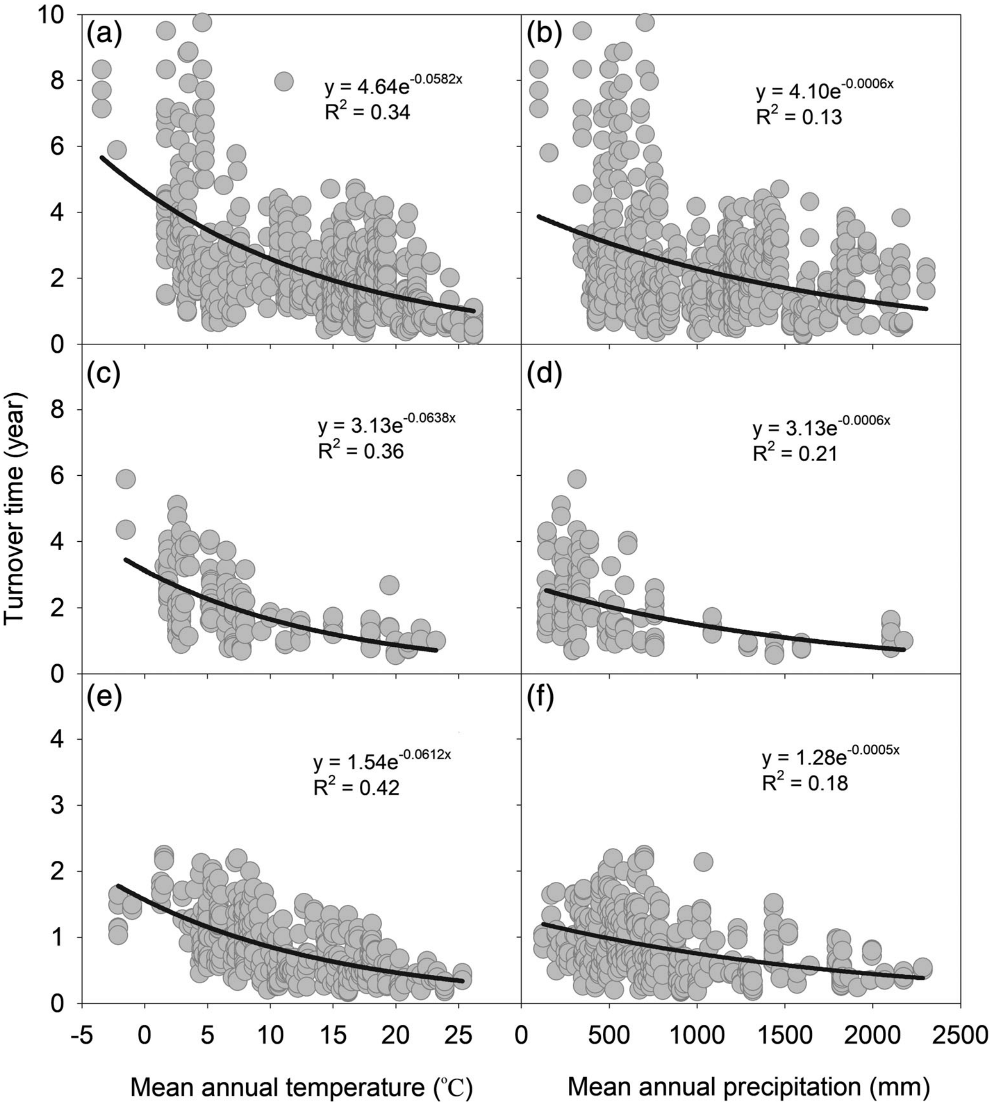

FIGURE 4 Forest, grassland and cropland litter turnover times in relation to mean annual temperature (a, c and e, respectively) and mean annual precipitation (b, d and f, respectively)

variables, soil pH did not directly affect litter turnover time. The highest path coefficient was observed between lignin content and litter turnover time (0.41), followed by SOC (0.37). Overall, climate affects litter turnover time by mediating soil properties and litter quality. Based on the BRT results, five widely available factors (MAT, ecosystem types, soil pH, SOC and sand content) were retained as model drivers to obtain the accurate spatial patterns of litter turnover time (Figure 7).

4 | DISCUSSION

4.1 | Spatial variations in litter turnover time

Litter turnover plays an important role in the global C budget and the formation of SOC in terrestrial ecosystems, but models are uncertain with respect to litter turnover time (Bonan et al., 2013; Koven et al., 2013). Data assimilation techniques have been used to infer litter turnover time and provide insight into the validity of litter turnover time estimations based on the dynamic data of litter decay (Shi et al., 2016). Another option is to obtain litter turnover time using experiments to determine the litter dynamics over larger spatial scales. In this study, we used data on litter dynamics to calculate the litter turnover time under different conditions and compared their differences across space. The mean litter turnover times were 2.65, 2.04 and 0.83 years for forest, grassland and cropland, respectively, and varied drastically for different litter tissues (leaves, stems and roots). The results of this study were significantly higher than the initial litter turnover time parameterizations used in the Community Land Model (20 hr to 71 days) and DAYCENT Model (46 to 183 days) (Koven et al., 2013). Bonan et al. (2013) found considerable discrepancies between the laboratory study used to parameterize the litter turnover time in the Community Land Model and their field study. Previous studies also indicated that

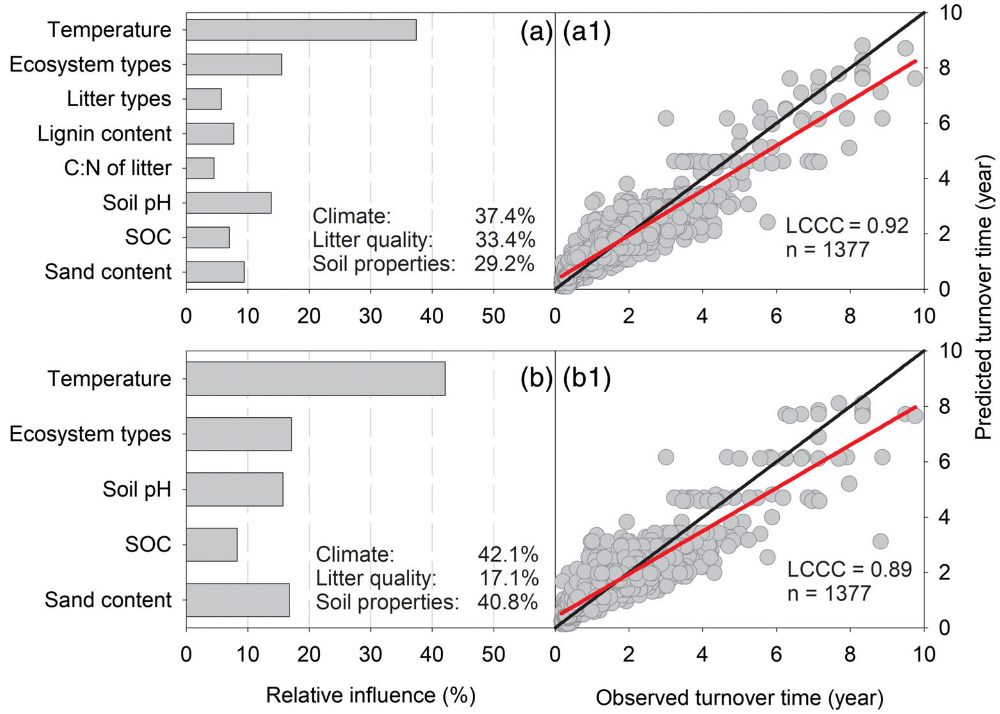

FIGURE 5 The relative influence (%) of predictor variables for the boosted regression tree model of turnover time for Chinese terrestrial ecosystems under all environmental variables ((a) climate, litter quality and soil properties) and widely available variables ((b) climate and soil properties). The observed turnover times and those predicted by the boosted regression tree model using various predictors are shown in Fig. 5a1 and b1. The black line indicates the 1:1 line. The climate is the mean annual temperature. Litter quality includes ecosystem types, litter types, carbon to nitrogen ratio (C:N) and lignin content. Soil properties are sand content, soil pH and soil organic carbon (SOC) [Color figure can be viewed at wileyonlinelibrary.com]

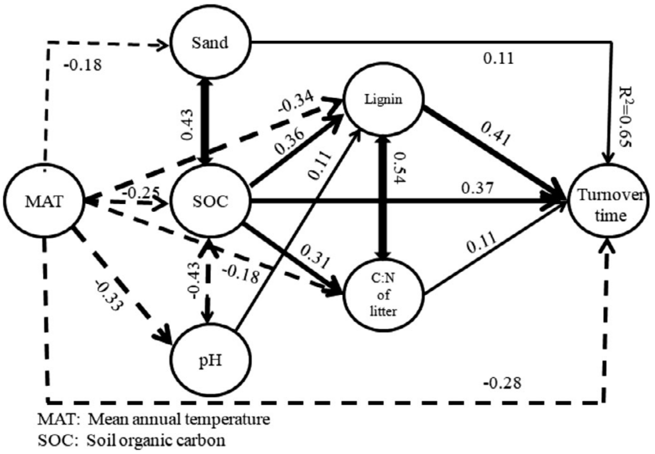

FIGURE 6 Path analysis results on the direct and indirect effects of climate (mean annual temperature), soil properties (sand content, soil pH and soil organic carbon) and litter quality (C:N of litter and lignin content) on litter turnover time across Chinese terrestrial ecosystems (chi/df = 0.37, $P = 0.33$; RMSEA = 0.04). The numbers indicate the path coefficients. The solid and dashed lines indicate significant positive and negative effects, respectively

plant community composition determined the litter chemical composition, which could affect the litter turnover time (Zhao, Huang, Ma, Li, & Tang, 2013). Dorrepaal, Cornelissen, Aerts, WalléN, and Van Logtestijn (2005) reported that plant growth form and litter chemistry accounted for 74% of litter turnover. Therefore, the order of litter turnover time was forest > grassland > cropland (Figure 2), which was also reported by Yan, Zhou, Jiang, and Luo (2017). Additionally, diverse ecosystems with different plant functional types may have diverse litter turnover times. For one ecosystem, different litter tissues could also lead to variations in litter turnover time (Dorrepaal et al., 2005; Zhao et al., 2013). The more recalcitrant compounds in roots relative to stems and leaves are considered the causes of slow turnover time. The spatial patterns of litter turnover time could be quantified by latitude with a positive exponential equation, and a similar result was shown by Silver and Miya (2001). The mean litter turnover time for subtropical and tropical zones was less than the mean litter turnover time for middle-temperate and warm-temperate zones. The higher temperature and humidity in subtropical zones, which promote biogeochemical nutrient cycling, may contribute to the short litter turnover time (Sanderman, Amundson, & Baldocchi, 2003). High variability in litter turnover time was noted at high latitudes because of the large variance in climate.

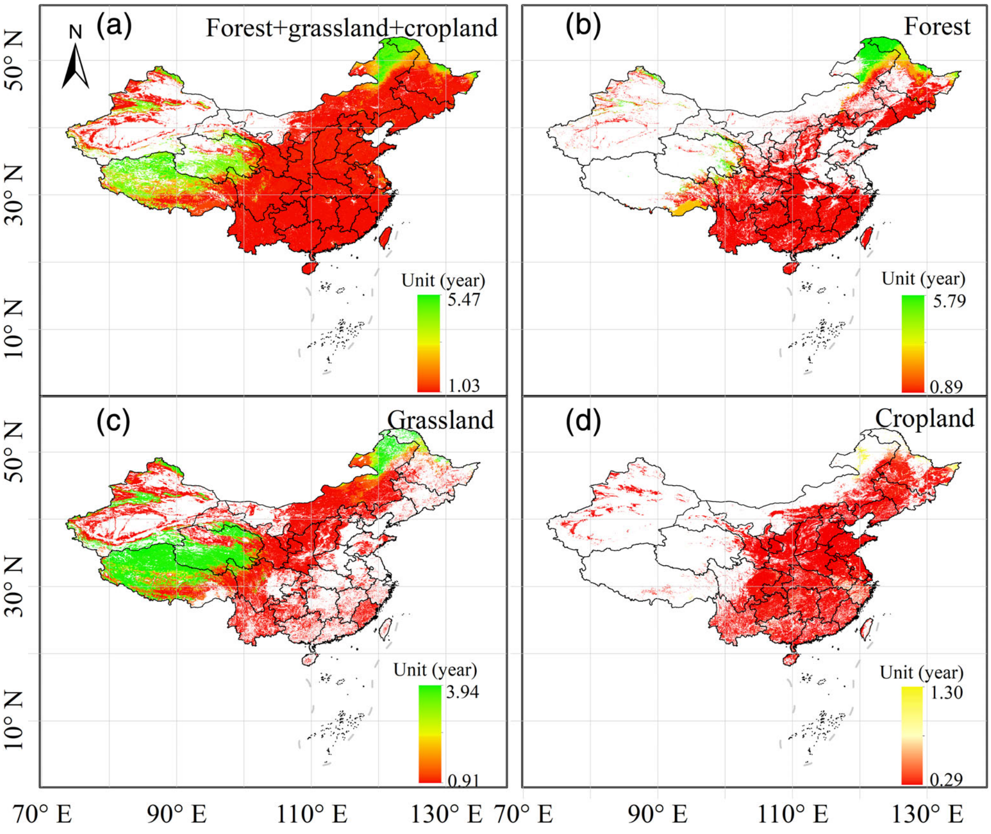

FIGURE 7 Accurate spatial patterns (model predictions) of litter turnover time across Chinese all (a), forest (b), grassland (c) and cropland (d) terrestrial ecosystems by using ecosystem types (a), climatic (mean annual temperature) and edaphic (sand content, soil pH and soil organic carbon) variables (a, b, c and d) as model drivers [Color figure can be viewed at wileyonlinelibrary.com]

4.2 | Contrasting effects of MAT and MAP on litter turnover time

In our study, litter turnover time was rapid at low latitudes because of the spatial patterns of temperature and precipitation. This result was consistent with the results of other studies on litter decomposition (Portillo-Estrada et al., 2016; Wang et al., 2017; Zhang, Hui, Luo, & Zhou, 2008). Consistent with previous observations, the litter turnover time significantly decreased with the increases in MAT and MAP because of the dependence of microbial activity and respiration rates on temperature, which impacts soil moisture (Lellei-Kovács et al., 2016). Additionally, temperature sensitivity of forest litter turnover time was lower than that of grassland and cropland because forest litter decomposes much faster than grassland and cropland litter (Portillo-Estrada et al., 2016). Using multivariate analyses, our results demonstrated that the most influential variable on litter turnover time was MAT for the forest and cropland ecosystems and MAP for the grassland ecosystems (Figure S3) (Piñeiro, Paruelo, Oesterheld, & Jobbágy, 2010). For grassland ecosystems, water content is a primary constraint on plant growth. Low water content can decrease the diffusion of substrates, nutrients and waste products and, thereby, inhibit soil microbial activity (Jing et al., 2015). Given the water limitations, MAP explained a higher proportion of the variability in decomposition than MAT. Wang et al. (2015) also found that precipitation was the foremost factor that controlled litter decomposition in the Inner Mongolia grassland ecosystem. Therefore, it is not surprising that precipitation is the principal factor that determines the grassland litter turnover time in a water-limited ecosystem.

4.3 | Mechanisms and spatial patterns of the variation in litter turnover time

Many studies have acknowledged that climatic, litter quality and soil factors control the litter turnover time under different conditions (Cai et al., 2018; Portillo-Estrada et al., 2016; Silver & Miya, 2001). The impacts of climate on litter quality, soil properties and, thus, litter turnover time are well documented but rarely quantified (Cai et al., 2018). The variation in litter turnover time is driven by the effects of climate and soil properties on microbial activity (Xiong et al., 2014). The MAT negatively affected litter turnover time both directly and indirectly by decreasing lignin (−0.34), C:N of litter (−0.18), soil pH (−0.33), sand content (−0.18) and SOC (−0.25). The negative effect of MAT on SOC has been reported by previous studies at both global and regional scales (Neil Adger, Arnell, & Tompkins, 2005), which is probably explained by increased SOC decomposition rates due to temperature changes. Temperature alters the litter chemistry of extant plants prior to senescence, thus indirectly affecting litter decomposition rates (Aerts, 2006). Shifts in vegetation composition also result in impacts on the litter quality and decomposability. Leaves fundamentally control the metabolic rates of plants and affect the litter quality. Wright et al. (2017) reported that large leaves predominated in hot and sunny environments, whereas small leaves commonly occurred in high latitudes and/or elevations across the globe. Therefore, MAT was found to negatively affect litter quality. The negative effects of MAT on litter turnover time occurred through decreases in the soil sand content, which positively and directly affected litter turnover time. Soil texture could drive the formation of microbial biomass (Creamer et al., 2016). Consequently, MAT was found to have a negative total effect on litter turnover time over large scales. The highest path coefficient was observed between lignin content and litter turnover time (0.41) (Figure 6). This observation indicates that lignin is generally more sensitive to climatic changes in litter turnover time than other variables. It is obvious that it is difficult to explain the spatial variation in litter turnover time using a single variable (Figures 3–5). For example, MAT, as a main driving factor, could account for only 37.4% of the spatial variation in litter turnover time. The interpretation rate reached 92% when litter quality (ecosystem types, litter types, C:N of litter and lignin content) and soil properties (pH, SOC and soil sand content) were taken into consideration. The studies that aim to explore the changes in litter turnover time based on a single factor result in large uncertainties (Bradford et al., 2016). Therefore, the widely available factors of MAT, ecosystem types, soil pH, SOC and sand content were used as model drivers to obtain accurate spatial patterns of litter turnover time. These results need to be tempered by the low model quality.

We recognize that there are uncertainties associated with our dataset and analytical methods, but these uncertainties are unlikely to change our results. First, microorganisms may introduce some uncertainty, and are actually more or equally relevant in explaining the spatial variation in litter turnover time (Bradford et al., 2014). However, we were unable to consider the effects of biotic variables on litter turnover time due to missing data on soil microorganisms. Second, the lack of data on soil sand content may cause uncertainty with regard to the paths between sand content and other variables in the boosted regression tree (BRT) and SEM; however, this uncertainly does not change the aggregate effects of climate on litter turnover time. Third, the SEM did not consider the potential interactions among variables, which could also be one of the reasons why the path model explained less of the variance in litter turnover time than BRT.

5 | CONCLUSIONS

Our meta-analysis of *in situ* data that were collected from diverse climates and ecosystems with varying litter and soil properties provided accurate litter turnover time estimates and quantitative evidence of the relative impacts of climate on litter turnover time through direct and indirect pathways. The mean litter turnover time was the longest in forest ecosystems, followed by grassland and cropland ecosystems, and varied significantly according to litter tissues and climate zones. Litter turnover time exhibited strongly spatial correlation. Climate accounted for 37.4% of the relative influence on litter turnover time, followed by litter quality (33.4%) and soil properties (29.2%) based on BRT. Path analysis identified that MAT negatively affected litter turnover time both directly and indirectly by regulating the litter quality and soil properties. The effect of litter lignin on litter turnover time is generally more sensitive to climatic changes than other variables. The widely available factors of MAT, ecosystem types, soil pH, SOC and sand content were used as BRT model drivers to obtain accurate spatial patterns of litter turnover time. These findings have important implications for ecosystem models and the global C cycle forecasts.

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DATA AVAILABILITY STATEMENT

All data related to this publication are available from the Dryad Digital Repository: https://doi.org/10.6084/m9.figshare.6289121 (Cai, 2018).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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