Distribution and altitudinal patterns of carbon and nitrogen storage in various forest ecosystems in the central Yunnan Plateau, China

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The carbon (C) pool in forest ecosystems plays a long-term and sustained role in mitigating the impacts of global warming, and the sequestration of C is closely linked to the nitrogen (N) cycle. Accurate estimates of C and N storage (SC, SN) of forest can improve our understanding of C and N cycles and help develop sustainable forest management policies in the context of climate change. In this study, the SC and SN of various forest ecosystems dominated respectively by Castanopsis carlesii and Lithocarpus mairei (EB), Pinus yunnanensis (PY), Pinus armandii (PA), Keteleeria evelyniana (KE), and Quercus semecarpifolia (QS) in the central Yunnan Plateau of China, were estimated on the basis of a field inventory to determine the distribution and altitudinal patterns of SC and SN among various forest ecosystems. The results showed that (1) the forest SC ranged from 179.58 ± 20.57 t hm⁻¹ in QS to 365.89 ± 35.03 t hm⁻¹ in EB. Soil, living biomass and litter contributed an average of 64.73%, 31.72% and 2.86% to forest SC, respectively; (2) the forest SN ranged from 4.47 ± 0.94 t ha⁻¹ in PY to 8.91 ± 1.83 t ha⁻¹ in PA. Soil, plants and litter contributed an average of 86.88%, 10.27% and 2.85% to forest SN, respectively; (3) the forest SC and SN decreased apparently with increasing altitude. The result demonstrates that changes in forest types can strongly affect the forest SC and SN. This study provides baseline information for forestland managers regarding forest resource utilization and C management.

C and N are major constituents of plant and soil organic matter and play a fundamental role in nutrient cycling, plant growth, and ecological functions. Forest SC is the most important part of the global C pool across various terrestrial ecosystems and plays a long-term and continuous role in mitigating the effects of global warming. N is a vital and limiting nutrient in forest ecosystems, and C storage is closely linked to the N cycle. Furthermore, N deposition alters SC and SN. Consequently, accurate identification of the spatial patterns of forest SC and SN is important for accessing the global C and N pool.

Forest SC is estimated to account for approximately 45% of terrestrial ecosystem SC. In forest ecosystems, C is stored in living biomass, litter and soils. Living biomass has a great capacity to sequester atmospheric C and the aboveground living biomass has been considered as a major C pool. Soil is another indispensable component of forest ecosystems and acts as an important C pool in terrestrial ecosystems. The amount of C stored in soil is approximately double the amount in the atmosphere. Consequently, exploring the distribution patterns of SC in forest ecosystems is essential for understanding the C cycle. Many studies have explored the spatial distribution of SC in forest ecosystems at a landscape scale using remote sensing and statistical methods; however, these estimates are not reliable in hilly terrain, because the mountainous and hilly conditions can increase errors of forest vertical structure measured using remote sensors. Hence, to accurately quantify forest SC at a large scale, it is essential to develop estimates based on ground measurements. Forest inventory data are recognized as one of the most reliable sources of data for global C cycle research.

The amount of C stored in forest vegetation and soil is considered to be the result of a long-term balance between C absorption and release. The magnitude of SC and SN in forests depends on stand age, species composition, climate variability, geographical circumstances, management strategy and natural disturbances. The School of Ecology and Environment, Southwest Forestry University, Kunming 650224, China. Email: JQ-Lee83125@hotmail.com
| Forest type | Mean tree age/yr | Mean diameter at breast height/cm | Mean height/m | Wood density/ha | Main species composition |
|-------------|------------------|-----------------------------------|---------------|----------------|--------------------------|
| PY          | 35               | 15.2                              | 10.2          | 1887           | *Pinus yunnanensis*, *Quercus aliena* Blume, Schima superba Gardn. et Champ., *Pyrus pseudopashia* Yu |
|             |                   |                                   |               |                | *Rhododendron* spiciferum Franch., *Quercus variabilis* Blume, Vaccinium bracteatum Thunb |
| PA          | 30               | 12.0                              | 10.6          | 2029           | *Pinus armandii* Franch., Eurya obliquifolia Hemsl., Ternstroemia gymnanthera (Wight et Arn.) Beddome |
|             |                   |                                   |               |                | *Vaccinium dauluxii* (Levl.) Hand.-Mazz., Cyclobalanopsis glauca (Thunberg) Oersted, Ternstroemia gymnanthera (Wight et Arn.) Beddome |
| QS          | 40               | 5.9                               | 3.3           | 3586           | *Quercus semecarpifolia* Smith., *Quercus fabri Hance*, Ternstroemia gymnanthera (Wight et Arn.) Beddome, *Elymus ovalifolius* (Wall.) Drude |
|             |                   |                                   |               |                | *Vaccinium bracteatum* Thunb., *Rhododendron moulainnense* Hook. f., *Gaultheria fragrantissima* Wall |
| KE          | 50               | 21.2                              | 7.6           | 1475           | *Keteleeria evelyniana* Mast., *Quercus acutissima* Carr., *Rhododendron delavayi* Franch., *Rhododendron miniatiflorum* Franch., *Quercus aliena* Blume |
|             |                   |                                   |               |                | *Jasminum grandiflorum* L., *Myrica esculenta* Buch.-Ham., *Rhododendron miniatiflorum* Hu |
| EB          | 60               | 9.7                               | 11.1          | 3085           | *Castanopsis carlesii* (Hemsl.) Hayata., *Lithocarpus macrophylos* (Schottky) Rehder., *Camellia mairei* (Levl.) Melch., *Dichotomanthes floribunda* Kurok., *Rhododendron delavayi* Franch., *Vaccinium bracteatum* Thunb., *Betula utilis* D. Don |
|             |                   |                                   |               |                | *Camellia mairei* (Levl.) Melch., *Lithocarpus macrophylos* (Schottky) Rehder., *Vaccinium bracteatum* Thunb., *Rhododendron spiciferum* Franch., Eurya yunnanensis Hu, *Symplocos anomala* Brand, *Ternstroemia gymnanthera* (Wight et Arn.) Beddome |

Table 1. Stand information of various study forests in Mopan Mountain in the central Yunnan Plateau.

distribution patterns of *S_C* and *S_N* also differ among spatial landscape patterns, plant species and plant organs. Mopan Mountain in the central Yunnan Plateau is located in the Yunnan–Guizhou Plateau and the southern margin of the Qinghai–Tibet Plateau. The area belongs to a subtropical mountain climate region, and vegetation patterns shift vertically due to changes in altitude. The main forest vegetation types are subtropical evergreen broad-leaved forest, subtropical mixed coniferous and broad-leaved forests, coniferous forest and alpine forest. In this region, forests cover more than 72.6% of the land area, and they represent the most important forest resources in the central Yunnan Plateau and in Yunnan Province. The main objectives of this study are to (1) assess the spatial variation in forest biomass based on a field inventory; (2) characterize the spatial variation in *C* and *N* density and storage in forest ecosystems; and (3) explore the impact of altitude on biomass and *S_C* and *S_N* in Mopan Mountain. This study will provide baseline information for forestland managers regarding forest resource utilization and *C* and *N* management.

Materials and methods

Study area. This study was conducted in Mopan Mountain National Forest Park (23°46′18″N–23°54′34″N, 101°16′06″E–101°16′12″E) in the central Yunnan Plateau of Yunnan province, southwestern China. The total area of the forest is about 7348.5 ha with an altitude from 1260 to 2614 m a.s.l.

The area belongs to a subtropical mountain climate region. The temperature ranges from ~2.2 to 33 °C with a mean annual temperature 15 °C, and the annual rainfall is approximately 1050 mm. Precipitation shows strong seasonal variation with approximately 85% occurring in the rainy season from May to October and the left 15% occurring in the dry season from November to the next April.

The study sites were occupied by subtropical evergreen broad-leaved forest, coniferous forest and alpine forest dominated respectively by *C. carlesii* and *Lithocarpus macrophylos* (EB), *Pinus yunnanensis* (PY), *Pinus armandii* (PA), *Keteleeria evelyniana* (mixed with the *Quercus* species, KE) and *Quercus semecarpifolia* (QS). The characteristics of these forests are listed in Table 1.

Study design and sampling. Study design. To test the variation in *S_C* and *S_N* among various forests, 16 sample plots in each forest were chosen for analysis. These 16 sample plots contained one 100 m × 100 m and fifteen 30 m × 30 m tree plots, and each tree plot had three shrub and three herb plots. The sizes of the shrub and herb plots were 5 m × 5 m and 1 m × 1 m, respectively. The sample plots were distributed across the altitude range as follows: for QS, from 2467 to 2611 m; for PY, from 2012 to 2151 m; for PA, from 2035 to 2381 m; for KE, from 1865 to 2265 m; and for EB, from 1450 to 2436 m.
Plant census and sampling. In each tree plot, census of plant individuals which diameter at breast height was more than 1 cm was performed. In addition, in each shrub and herb plot, the species name and abundance were recorded. All plant individuals in each plot were collected with different parts for C and N testing, i.e., trees with roots, trunks, leaves, branches and bark; shrubs with roots, stems and leaves; and herbs with above- and belowground part.

Litter sampling. Triplicate plots with a size of 1 m × 1 m were established in the tree plots for ground litter sampling. For each of these samples, horizons L, F and H were separated and carefully placed in plastic bags for determining of the dry weight and C and N contents. The L horizon was composed of fresh or slightly discoloured material that was not weak or friable; the F horizon was composed of medium to strongly fragmented material with many mycelia and thin roots; and the H horizon consisted of humified amorphous material.

Mineral soil sampling. Mineral soil samples were collected from each tree plot, with three replicates. Most of the slope gradients of these soil profiles were less than 15°. After removal of the forest floor mass, soil samples were collected from three layers: 0–20 cm, 20–40 cm and 40–60 cm, and the corresponding soil bulk density (BD) of each layer was measured using the cutting-ring method. The soil samples were placed in sacks and air dried for soil C and N testing.

Laboratory analysis. Shrub, herb and ground litter samples were dried to a constant weight at 105 °C and then weighed for biomass estimation. Plant and soil total N concentrations were determined by a continuous flow analytical system (Analytical AA3, SEAL, Germany) with sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) digestion. The total C concentration was determined by an elemental analyser (Vario TOC cube, Elementar, Germany).

The estimation of biomass, SC and SN. The estimation of forest vegetation biomass. Tree biomass (roots, trunks, leaves, branches and bark biomass) was estimated using allometric equations based on long-term practical measurements of forest vegetation in southwestern China. The shrub and herb biomass was directly expressed as their dry weights. For each forest plot, the total biomass was the sum of the biomass of each vegetation type in the plot.

The estimation of plant, litter and soil SC and SN. The SC (t ha⁻¹) and SN (t ha⁻¹) of trees, shrubs, and herbs were obtained by multiplying the forest vegetation biomass (t ha⁻¹) by the corresponding C and N content coefficient.

The litter SC and SN were the sum of the SC and SN of horizons L, F and H. The litter SC and SN storage was calculated by the following formula:

\[ \text{Litter } S_C = \sum_{i=1}^{n} L_{Bi} \times T_{Ci}; \quad \text{Litter } S_N = \sum_{i=1}^{n} L_{Bi} \times T_{Ni} \]  

where \( L_{Ci} \) and \( T_{Ni} \) are the respective litter C and N storage; \( T_{Ci} \) and \( T_{Ni} \) are the C and N (g kg⁻¹) contents of horizons L, F and H, respectively; and \( L_{Bi} \) is the litter biomass (dry litter weight) of horizons L, F and H.

The soil SC and SN were calculated as the sum of the SC and SN of the 0–20 cm, 20–40 cm and 40–60 cm soil layers. The soil SC and SN were calculated using the following formula:

\[ \text{Soil } S_C = \sum_{i=1}^{n} B_{Di} \times T_{Ci} \times D_{i}; \quad \text{Soil } S_N = \sum_{i=1}^{n} B_{Di} \times T_{Ni} \times D_{i} \]  

where \( B_{Di} \) is the soil BD (g cm⁻³), \( T_{Ci} \) and \( T_{Ni} \) are the soil total C and N contents (g kg⁻¹), respectively, and \( D_{i} \) is the soil layer thickness (cm).

Statistical analysis. Statistical analyses were carried out using the software Statistical Package for the Social Sciences 19 (SPSS 19) and Microsoft Office Excel (version 2013). One-way ANOVA was used to test whether the variations in SC and SN were significantly different among the plant, litter and soil type components. Duncan’s shortest range test was used to examine the difference among different forest types at P < 0.05. The relationships between altitude and biomass, SC and SN were examined by linear regression.

Results

Biomass in forest ecosystems. The biomass of the forest ecosystems in the central Yunnan Plateau ranged from 142.36 ± 18.36 to 271.77 ± 34.71 t ha⁻¹. The biomass of the forest ecosystems was significantly different among the various forests (Table 2). Plant biomass made a significant contribution to ecosystem biomass and accounted for a much higher proportion (more than 90%) than forest litter. Tree biomass was significantly higher than that of shrubs and herbs in PY, PA, KE and EB and accounted for 99.64%, 94.46%, 95.33% and 95.88% of the total plant biomass, respectively. The tree and shrub biomass in QS accounted for a nearly equal proportion of plant biomass at 46.72% and 51.01%, respectively. The biomass of each component of plants and litter is presented in Fig. 1.
The C and N concentrations in plants, shrubs and herbs varied significantly among forests and their components (Fig. 2 A-B). Generally, the N concentration was classified into three levels by the lines in the figure. The N concentration was highest in the leaves of trees and shrubs and the aboveground parts of herbs, and it ranged from 6.64 ± 2.01 to 21.99 ± 6.66 g·kg⁻¹. The N concentration in tree branches, shrub stems and the L, F and H litter horizons ranged from 3.86 ± 0.90 to 8.78 ± 1.73 g·kg⁻¹, and these values were higher than those in the roots and trunks of trees, shrub roots and soil, which had N concentrations lower than 4.89 ± 1.31 g·kg⁻¹. Significant differences were not observed in the C concentrations in the plant and litter components among different forests, which ranged from 323.21 ± 63.58 to 503.00 ± 97.56 g·kg⁻¹, and the mean C concentration of the forest vegetation and litter was 425.80 ± 100.34 g·kg⁻¹. However, the soil C concentrations were significantly lower than those in the plants and litter, i.e., less than 81.08 ± 13.62 g·kg⁻¹, with a mean of 29.74 ± 12.20 g·kg⁻¹.

Table 2. Biomass (t ha⁻¹) and proportion (%) of plant components and the litter layer in various forests in the central Yunnan Plateau. Mean values ± standard deviations are illustrated; Different lowercase letters in each row indicate significant differences (P < 0.05) among the plant components and litter layer, and different capital letters in each line indicate significant differences (P < 0.05) among forests.

|       | QS   | PY   | PA   | KE   | EB   |
|-------|------|------|------|------|------|
| Plant | 146.56 ± 24.97 D | 158.99 ± 2013 C | 142.36 ± 18.36 D | 215.30 ± 27.95 B | 271.77 ± 34.71 A |
| Tree  | 68.47 ± 8.52 Da | 155.24 ± 19.32 Ca | 134.47 ± 16.73 Ca | 205.25 ± 25.54 Ba | 260.57 ± 32.42 Aa |
| Shrub | 74.76 ± 15.23 Aa | 3.45 ± 0.70 Db | 7.75 ± 1.58 Cb | 7.81 ± 1.59 Cb | 11.19 ± 2.28 Bb |
| Herb  | 3.33 ± 1.22 Ab | 0.30 ± 0.11 Cc | 0.14 ± 0.05 Cc | 2.24 ± 0.82 Bc | 0.01 ± 0.00 Dc |
| L layer | 2.92 ± 0.78 Ba | 6.92 ± 1.85 Aab | 5.73 ± 1.53 Ac | 7.01 ± 1.87 Ac | 2.91 ± 0.78 Bb |
| Ecosystem | 158.47 ± 27.37 D | 188.80 ± 26.09 B | 167.50 ± 23.38 C | 245.58 ± 34.02 A | 283.68 ± 37.14 A |

Figure 1. Biomass (t ha⁻¹) allocation among plants and litter layer in various forests in the central Yunnan Plateau. Error bars mean standard deviation.
The ecosystem $S_C$ was calculated as the sum of the plant $S_C$, litter $S_C$ and soil $S_C$. The ecosystem $S_C$ was significantly different among the forests (Table 3 and Fig. 3 A). The ecosystem $S_C$ ranged from a high of $365.89 \pm 35.03$ t hm$^{-1}$ in EB to a low of $179.58 \pm 20.57$ t hm$^{-1}$ in QS. The levels of ecosystem $S_C$ in PY, PA and KE were $258.38 \pm 24.92$, $203.01 \pm 19.79$ and $326.89 \pm 31.71$ t hm$^{-1}$, respectively. The soil $S_C$ contributed $62.40–67.06\%$ to the ecosystem $S_C$ in various forests and was higher than the contributions of plants and litter. Plant $S_C$ accounted for $29.50–34.91\%$, and litter $S_C$ accounted for only $1.35–5.15\%$ of ecosystem $S_C$.

The plant $S_C$ of different forests varied significantly from $62.70 \pm 11.33$ t hm$^{-1}$ in QS to $120.35 \pm 13.01$ t·hm$^{-1}$ in EB, although the difference between QS and PA was not significant. Tree $S_C$ contributed more than $94\%$ to the plant $S_C$ in PY, PA, KE and EB; however, the tree $S_C$ of QS contributed only $47.11\%$ to the plant $S_C$. The shrub $S_C$ of QS accounted for a high proportion of $50.78\%$ of the plant $S_C$, whereas the shrub and herb $S_C$ in the other four forests contributed less than $1\%$ to the plant $S_C$. The litter $S_C$ varied from a high concentration of $13.20 \pm 2.12$ t·hm$^{-1}$ in PY to a low concentration of $4.82 \pm 0.77$ t·hm$^{-1}$ in QS. Generally, the $S_C$ of different layers among the forests decreased in the order of H > F > L, while the litter $S_C$ in EB decreased in the order of H > L > F. The highest soil $S_C$ was in EB at $240.59 \pm 32.90$ t hm$^{-1}$. The soil $S_C$ in KE was $219.21 \pm 29.98$ t·hm$^{-1}$, which was significantly lower than that in EB but significantly higher than that in PY and PA, which were $164.42 \pm 22.90$ t·hm$^{-1}$ and $129.20 \pm 17.67$ t·hm$^{-1}$, respectively. The lowest soil $S_C$ was in QS at $112.06 \pm 15.32$ t·hm$^{-1}$. In KE, the $S_C$ at 20–40 cm was higher than that at 0–20 cm and the soil $S_C$ decreased with increasing soil depth.

The forest ecosystems varied significantly among the forests, although significant differences were not found between PY and PA (Table 3 and Fig. 3 B). The Ecosystem $S_N$ ranged from $8.91 \pm 1.83$ t·ha$^{-1}$ in EB to $120.35 \pm 13.01$ t·ha$^{-1}$ in PA, with the highest $S_N$ in KE, QS and PY was $7.13 \pm 1.52$ t·ha$^{-1}$, $6.36 \pm 1.19$ t·ha$^{-1}$ and $5.14 \pm 1.10$ t·ha$^{-1}$, respectively. Soil was the most important contributor to total $S_N$ in the forest ecosystems and accounted for

Figure 2. C (g kg$^{-1}$) and N (g kg$^{-1}$) concentrations in the plant components, litter layer and soil in various forests in the central Yunnan Plateau. Error bars mean standard deviation.
84.12 t·ha$^{-1}$, which is much higher than the average values of vegetation C storage in Chinese forest ecosystems and previous results indicate that the soil is the most important component for SC and SN in forest ecosystems$^{42,43}$. 

A significant correlation ($P < 0.001$) with increasing altitude. Whether calculated within the same forest or across all forests, significant correlations were found between the altitude and biomass at the 0.005 level (Table 4). The $S_C$ of QS, PA, KE and EB was also significantly ($P < 0.005$) correlated with altitude, but for PY, the correlation between $S_C$ and altitude was significant at the 0.05 level. In all forests, $S_C$ decreased significantly ($P < 0.001$) with increasing altitude. A significant correlation ($P < 0.005$) was observed between $S_C$ and altitude in QS, PA, KE and EB, and a less significant correlation was observed between $S_N$ and altitude ($P < 0.01$) in PY. However, for all forests, the variation in $S_N$ was not significant ($P = 0.400$) with respect to altitude.

**Discussion**

Different forest ecosystems have different C sequestration capacities. The total $S_C$ values of the forest ecosystems of KE and EB in Mopan Mountain in the central Yunnan Plateau are apparently higher than the average values of forest ecosystems (258.83 t C·ha$^{-1}$) across China$^{4,6}$, whereas the total $S_C$ values of the forest ecosystems of QS PA and PY are lower. The results of the present research show that changes in forest types can strongly affect $S_C$ and $S_E$ values. Generally, broad-leaved species can store more C and N than conifers$^{40,41}$. Although the alpine forest (QS) had the lowest $S_C$, its $S_N$ was higher than that in PY and PA. The $S_E$ and $S_N$ of forests in Mopan Mountain in the central Yunnan Plateau averaged 266.75 ± 26.40 t ha$^{-1}$ and 6.40 ± 1.32 t ha$^{-1}$, respectively. With respect to $S_E$, the living biomass, litter layer and soil accounted for 31.72, 3.55% and 64.73% of the total C storage, respectively. The corresponding $S_N$ accounted for 10.27%, 2.85% and 86.88% of the total N storage, respectively. The current and previous results indicate that the soil is the most important component for $S_C$ and $S_N$ in forest ecosystems$^{42,43}$. The living biomass of forests is one of the major C and N pools. Quantification of stored C in the living biomass of a forest is necessary for future management$^{44}$. The estimated mean living biomass $S_C$ in this study was 84.12 t ha$^{-1}$, which is much higher than the average values of vegetation C storage in Chinese forest ecosystems (57.07 t ha$^{-1}$)$^{45,46}$. This finding is mainly because of the high tree density and low anthropogenic disturbance at the location of Mopan Mountain National Forest Park. The tree growth rate and biomass allocation to different tree parts and varying rates of C sequestration in ecosystem components can affect the rate of C sequestration and longevity of C storage$^{2,41}$. The present study showed that the $S_C$ in plants ranged from 62.70 ± 11.33 t ha$^{-1}$ in QS to 120.35 ± 13.01 t ha$^{-1}$ in EB, which accounted for 31.72% of the total C storage. Among all forests, QS had the lowest $S_C$ in living biomass, which was caused by its lower biomass and lower C concentration in living biomass.
However, the higher biomass in EB resulted in higher SC of living biomass compared with the other groups in Mopan Mountain in the central Yunnan Plateau. The SN in living biomass varied from a high of 1.11 ± 0.33 t·ha−1 in EB to a low of 0.39 ± 0.17 t·ha−1 in PA, with a mean contribution of 10.27% to total SN. Tree SC and SN accounted for a large proportion of living biomass SC and SN in PY, PA, KE and EB, whereas shrubs contributed more C and N than trees to living biomass SC and SN in QS. The SC and SN of vegetation are mainly determined by the biomass of live vegetation components and C and N contents. Consequently, the interspecific differences in tree biomass caused by inherent variation in growth rates47–49 were the main reasons for the variations in SC and SN allocation among forests. Furthermore, the effect of forest species on the growth and diversity of understorey plant biomass2,30,50 also resulted in the variation in SC and SN allocation in forest vegetation.

Forest litter and its decomposition rate are key factors in nutrient cycling in forest ecosystems51, and the current litter SC in the world's forests is estimated at 43 ± 3 Pg·C (5% of total forest C)52. In the present study, the estimated mean litter SC and SN in the forests were 8.93 ± 1.44 t·ha−1 and 0.17 ± 0.01 t·ha−1, which accounted for 3.55% and 2.85% of the total SC and SN, respectively. The mean litter SC in this study is slightly higher than the mean litter SC in China (8.21 t·ha−1)53. The study also found that conifer litter stored more C and N than broadleaf litter, and a similar result was found in previous studies41,53. The above results occurred mainly because conifer litter is more difficult to decompose than broadleaf litter, resulting in a higher rate of litter accumulation on the forest floor.

The estimated mean soil SC and SN of different forests in this study were 173.70 ± 23.75 t·ha−1 and 5.56 ± 1.08 t·ha−1, which accounted for 64.73% and 86.88%, respectively, of the total SC and SN. The results showed that soil is the largest C pool in forest ecosystems, similar to a previous study conducted in China30.42. The mean reported value of soil SC was 193.55 t·ha−1 in Chinese forest ecosystems45,46, and the soil SC was 6.27 t·ha−1 in subtropical forests of China54. The SC and SN of KE and EB was higher and that of the other forests in this study was lower.

Figure 3. SC (t·ha−1) and SN (t·ha−1) storage allocation among the plant components, litter and soil layers in various forest types in the central Yunnan Plateau. Error bars mean standard deviation.
than the mean soil SN in China and soil SN in subtropical forests in China. The C stored in soil is significantly influenced by the C inputs (e.g., litter decomposition) and soil organic matter decomposition. Therefore, SC is determined by the balance between the input or output patterns and controlled mainly by tree species under similar environmental conditions. There were significant differences in the soil SC and SN at depths of 0–20 cm, 20–40 cm and 40–60 cm among the forests. The topsoil (0–20 cm) in the forests stored 43.38% of the C and 45.48% of the N from 0 to 60 cm. The soil C and N were mainly stored in the topsoil, which is probably because of the variation in the soil bulk density and concentrations of C and N in soil layers, which are two important determining factors of SC and SN at fixed soil depths. Although the soil bulk density decreased with increasing soil depth, the topsoil contained more C and N.

The forest ecosystem biomass (158.47 ± 27.37 to 283.68 ± 37.14 t·ha−1, with an average of 208.81 ± 29.60 t·ha−1), SC (179.58 ± 20.57 to 365.89 ± 35.03 t·ha−1, with an average of 266.75 ± 26.40 t·ha−1) and SN (4.47 ± 0.94 to 8.91 ± 1.83 t·ha−1 with an average of 6.40 ± 1.32 t·ha−1) in the five forests in Mopan Mountain decreased with increasing altitude.

Figure 4. Altitudinal patterns of biomass, SC and SN of different forests in the central Yunnan Plateau.
increasing altitude, although the SC of PY and the SN of all forest ecosystems in this study were not highly significantly correlated with altitude. Previous reports indicated that the soil SC in forest ecosystems increases with altitude\textsuperscript{58,59} and the living biomass and total SC of forest ecosystems decreased significantly with increasing latitude in different regions\textsuperscript{60,61} because increasing altitude changed the climate factors (i.e., temperature and precipitation) and resulted in the shifting of vegetation types and a decline in net primary production and litterfall\textsuperscript{58,62,63}. The vegetation patterns in the study area shifted vertically due to changes in altitude. With increasing altitude, the forest vegetation types in this area shifted from subtropical evergreen broad-leaved forest, subtropical mixed coniferous and broad-leaved forest, and coniferous forest to alpine forest, and the living biomass of the forests declined significantly. Therefore, the total SC and SN of forest ecosystems exhibited decreasing trends with increasing altitude.

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|          | C     | a     | R²    | P      |
|----------|-------|-------|-------|--------|
| AL and Biomass |       |       |       |        |
| QS       | 423.917 | −0.105 | 0.558 | 0.001  |
| PY       | 316.777 | −0.065 | 0.767 | 0.000  |
| PA       | 283.243 | −0.049 | 0.566 | 0.001  |
| KE       | 342.446 | −0.045 | 0.733 | 0.000  |
| EB       | 336.079 | −0.024 | 0.569 | 0.001  |
| All      | 468.772 | −0.118 | 0.362 | 0.000  |

|          | C     | a     | R²    | P      |
|----------|-------|-------|-------|--------|
| AL and SC |       |       |       |        |
| QS       | 513.472 | −0.131 | 0.558 | 0.001  |
| PY       | 411.679 | −0.078 | 0.356 | 0.019  |
| PA       | 336.246 | −0.060 | 0.474 | 0.003  |
| KE       | 545.976 | −0.103 | 0.547 | 0.002  |
| EB       | 505.896 | −0.067 | 0.786 | 0.000  |
| All      | 713.268 | −0.204 | 0.481 | 0.000  |

|          | C     | a     | R²    | P      |
|----------|-------|-------|-------|--------|
| AL and SN |       |       |       |        |
| QS       | 8.945  | −0.0010 | 0.605 | 0.001  |
| PY       | 5.767  | −0.0003 | 0.421 | 0.009  |
| PA       | 4.959  | −0.0002 | 0.681 | 0.000  |
| KE       | 7.783  | −0.0003 | 0.557 | 0.010  |
| EB       | 9.478  | −0.0003 | 0.718 | 0.000  |
| All      | 9.565  | −0.0014 | 0.057 | 0.400  |

Table 4. The results of the generalized linear model analyses of the effects of altitude on biomass, SC and SN. Three linear models were built: model I: Biomass (t ha$^{-1}$) = C + a × AL (altitude, m); model II: SC (t ha$^{-1}$) = C + a × AL (altitude, m); and model III: SN (t ha$^{-1}$) = C + a × AL (altitude, m), where C is the regression constant and a is the regression coefficient of the given variable.
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**Author contributions**
J.L. and Q.C. contributed to the conception of the study. J.L., Q.C., Z.L., B.X., J.Z., X.X., B.Z., and D.S. performed the investigation and experimental test. J.L. performed data analysis and wrote the paper.

**Competing interests**
The authors declare no competing interests.

**Additional information**

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