

## Postprint: Carbon and Nitrogen Storage and Allocation Patterns in Different Subalpine Forest Ecosystems in Western Sichuan

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### Abstract

Forest harvesting and restoration are important factors affecting forest carbon and nitrogen storage. Using primary *Abies faxoniana* forest, *Picea asperata*-broadleaf forest, natural secondary forest, and *Picea asperata* plantation in the subalpine region of western Sichuan as study objects, we investigated the carbon and nitrogen storage and their allocation characteristics in various components of different forest ecosystems through plot survey and biomass measurement methods. The results indicated that ecosystem carbon storage in primary *Abies faxoniana* forest, *Picea asperata*-broadleaf forest, natural secondary forest, and *Picea asperata* plantation were 611.18, 252.31, 363.07, and 239.06 t C/hm<sup>2</sup>, respectively; nitrogen storage were 16.44, 12.11, 15.48, and 8.92 t N/hm<sup>2</sup>, respectively. The soil-vegetation allocation pattern of carbon storage differed between restored stands and primary forest, whereas nitrogen storage remained unchanged. Primary *Abies faxoniana* forest was dominated by vegetation carbon storage, while restored stands were dominated by soil, with nitrogen storage being soil-dominated across all forest types. Carbon storage in the tree layer accounted for 56.65%, 17.63%, 13.57%, and 22.05% of total ecosystem storage, respectively, while the soil layer (0-80 cm) accounted for 32.03%, 69.87%, 76.20%, and 72.12%, respectively; nitrogen storage in the soil layer comprised 76.80%-92.58% of total ecosystem storage. Carbon and nitrogen storage in plant residues accounted for 4.40%-9.83% and 2.94%-7.08% of total ecosystem storage, respectively, with understory vegetation representing the smallest proportion. In terms of spatial patterns, the vegetation component of primary *Abies faxoniana* forest exhibited high carbon storage and should be conserved. The three restored stand types demonstrated high carbon sequestration potential, with low aboveground/belowground carbon storage ratios, indicating that their carbon sequestration potential is particularly expressed in aboveground components. Natural secondary forest facilitated soil organic carbon accumulation, while plantation forest exhibited higher carbon storage in the tree layer.

## Full Text

# Carbon and Nitrogen Storage and Distribution in Different Forest Ecosystems in the Subalpine Region of Western Sichuan

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## Abstract

Carbon (C) and nitrogen (N) are major constituents of plant tissues and soil organic matter, playing fundamental roles in nutrient cycling, plant growth, and ecological function. The biogeochemical cycling of C and N has attracted considerable attention because oxide emissions from ecosystems are important drivers of global warming, and N availability limits plant productivity. Forests represent the main C pool in terrestrial ecosystems and substantially influence the global C cycle and atmospheric CO<sub>2</sub> concentrations. However, C and N storage in forests varies greatly due to differences in forest type, age, regional climate, and soil conditions. Forest harvesting and restoration lead to different forest types and structures, which are critical factors affecting C and N stocks.

The subalpine forest in western Sichuan is important for water resource conservation and serves as an ecological barrier in the upper reaches of the Yangtze River. Historically, large areas of fir forest were cut down and subsequently restored through three different pathways (plantation, natural secondary forest, and mixed forest under combined artificial and natural influences), resulting in varying species compositions including spruce. The changes in C and N stores following these disturbances remain poorly understood. More studies are needed to calculate C and N pools in this region due to its varying topography, community diversity, and complex ecosystems.

This study quantified C and N storage in different forest ecosystems in the subalpine region of western Sichuan, including *Abies faxoniana* primary forest (AF), *Picea asperata*-broadleaf mixed forest (PB), natural secondary forest (NS), and *Picea asperata* plantation (PA). Using plot surveys and biomass measurements, we investigated C and N storage and distribution patterns across ecosystem

components. Results showed that ecosystem organic carbon storage in AF, PB, NS, and PA was 611.18, 252.31, 363.07, and 239.06 tC/hm<sup>2</sup>, respectively, while nitrogen storage was 16.44, 12.11, 15.48, and 8.92 tN/hm<sup>2</sup>, respectively. Distribution patterns of carbon storage between soil and vegetation changed between primary and restored forests, whereas nitrogen storage patterns did not. Carbon storage in primary forest was dominated by vegetation, while restored forests were soil-dominated; nitrogen storage was soil-dominated across all forest types. The tree layer accounted for 56.65%, 17.63%, 13.57%, and 22.05% of total ecosystem carbon storage, while the soil layer (0–80 cm) contributed 32.03%, 69.87%, 76.20%, and 72.12% of carbon storage and 76.80%–92.58% of nitrogen storage. Woody debris and litter carbon and nitrogen storage represented 4.40%–9.83% and 2.94%–7.08% of ecosystem totals, respectively, both higher than understory vegetation contributions. The primary forest exhibited high carbon storage, particularly in aboveground vegetation, and should be protected. Restored forests showed high carbon sequestration potential, especially aboveground, with natural secondary forest benefiting soil organic carbon accumulation and plantation forest showing higher tree layer carbon storage but lower belowground carbon storage.

**Keywords:** carbon and nitrogen storage; distribution; primary forest; restored forest; subalpine region of western Sichuan

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## 1. Study Area Overview

The study site is located in Bipenggou Nature Reserve, Li County, Aba Tibetan and Qiang Autonomous Prefecture, Sichuan Province (102°53'–102°57' E, 31°14'–31°19' N), within the transition zone between the Qinghai-Tibet Plateau and Sichuan Basin. The elevation ranges from 2,458 to 4,619 m. The area has a mean annual temperature of 2.7°C and mean annual precipitation of 850 mm, concentrated in the growing season. The primary vegetation is subalpine dark coniferous forest dominated by *Abies faxoniana*. Extensive logging of primary dark coniferous forests was historically followed by artificial regeneration with spruce (*Picea asperata*) in some areas and natural regeneration with broadleaf pioneer species such as birch in others. Since the implementation of the Natural Forest Protection Project, logging has been prohibited, resulting in a mosaic distribution of plantations, natural secondary forests, and mixed forests formed through combined artificial and natural processes.

Dominant tree species include *Abies faxoniana*, *Picea asperata*, and *Betula albo-sinensis*. Major shrubs are *Salix paraplesia*, *Fargesia spathacea*, *Rhododendron delavayi*, and *Berberis julianae*. Primary herbs include *Carex tristachya*, *Cacalia auriculata*, and *Cystopteris montana*. Soils are mountain brown earth with high gravel content.

## 2. Methods

**2.1 Plot Establishment** Four forest types were selected: *Abies faxoniana* primary forest (AF), *Picea asperata*-broadleaf mixed forest (PB), natural secondary forest (NS), and *Picea asperata* plantation (PA). Details of each forest type are provided in . Primary forest and plantation plots were established randomly. Due to block planting of *Picea asperata* after harvesting, PB and NS are alternately distributed; we selected these alternating patches for plot establishment. Each forest type had three replicate plots (20 m × 20 m). Within each plot, 2 m × 2 m subplots were established along diagonal lines for shrub biomass surveys, and 1 m × 1 m subplots were established for herb, moss, and litter biomass measurements.

Characteristics of different forest types

**2.2 Biomass and Litter Measurement** All trees in sample plots were measured for species, diameter at breast height (DBH), and height. Biomass prediction models from Shen et al. [30] and Jiang et al. [31] were used to estimate biomass by organ. Fresh weights of shrubs, herbs, mosses, and woody residues were measured in subplots. Woody residues included coarse woody debris (diameter > 10 cm, comprising stumps and large branches) and fine woody debris (1 cm < diameter < 10 cm) [32]. Coarse woody debris measurement followed Zhang [33], while fine woody debris was measured using line intersect sampling.

**2.3 Sample Collection and Analysis** Litter layer was divided into fresh litter layer (LL), fragmented litter layer (FL), and humified litter layer (HL). Samples from all components were collected, oven-dried, and weighed to calculate biomass. Soil profiles were excavated in each plot following a plum-blossom pattern. Soil samples were collected from depths of 0-10, 10-20, 20-40, 40-60, and 60-80 cm using a cutting ring. Samples from the same layer across a plot were mixed proportionally by mass. Soil bulk density was determined by oven-drying at 105°C. Soil organic carbon and nitrogen contents were determined using the potassium dichromate oxidation method and Kjeldahl method, respectively [34].

**2.4 Carbon and Nitrogen Storage Calculation** Carbon and nitrogen storage in vegetation, woody residues, and litter layers were calculated as the product of carbon/nitrogen concentration and biomass. Soil carbon and nitrogen storage were obtained by summing across soil layers using the formula [35]:

$$TX = \sum_{i=1}^n X_i \times L_i \times BD_i \times 0.1$$

where  $X_i$  is organic carbon or nitrogen content in layer  $i$  (g/kg),  $L_i$  is thickness of layer  $i$  (cm),  $BD_i$  is bulk density of layer  $i$  (g/cm<sup>3</sup>), and 0.1 is a unit conversion coefficient.

**2.5 Data Analysis** One-way ANOVA was used to test differences in carbon and nitrogen storage among forest types, followed by least significant difference (LSD) tests for multiple comparisons. Statistical analyses and graphing were performed using SPSS 17.0 and Origin 8.0 ( $n = 3$ ).

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### 3. Results and Analysis

#### 3.1 Vegetation Layer Carbon and Nitrogen Storage

**3.1.1 Tree Layer** Tree layer carbon and nitrogen storage constituted the major portion of vegetation layer storage, accounting for 57.00%–83.34% of vegetation carbon and 43.35%–63.47% of vegetation nitrogen. Tree layer carbon and nitrogen storage in AF (346.24 tC/hm<sup>2</sup> and 2.42 tN/hm<sup>2</sup>) were significantly higher than in PB, NS, and PA ( $F = 1168.76$ ,  $p < 0.05$  for carbon;  $F = 290.36$ ,  $p < 0.05$  for nitrogen). Carbon storage in PB, NS, and PA tree layers was only 12.85%, 14.22%, and 15.22% of AF values, respectively, while nitrogen storage was 25.13%, 20.79%, and 34.30% of AF values, respectively. Carbon storage was primarily distributed in tree stems, accounting for 43.30%–56.66% of tree layer carbon, with allocation patterns varying among forest types.

**3.1.2 Plant Residue Layer** Plant residue layer (woody debris and litter) was the second largest component of vegetation layer carbon and nitrogen storage. Carbon storage ranged from 10.53 to 60.06 tC/hm<sup>2</sup> (14.46%–33.97% of vegetation carbon), and nitrogen storage ranged from 0.37 to 1.16 tN/hm<sup>2</sup> (30.52%–39.64% of vegetation nitrogen). Both carbon and nitrogen storage differed significantly among forest types ( $p < 0.05$ ). AF had the highest plant residue carbon storage (60.06 tC/hm<sup>2</sup>), followed by NS (29.36 tC/hm<sup>2</sup>), PB (17.27 tC/hm<sup>2</sup>), and PA (10.53 tC/hm<sup>2</sup>). AF nitrogen storage (1.16 tN/hm<sup>2</sup>) was significantly greater than other forest types. Woody debris contributed more to plant residue carbon in PB and NS (71.31% and 63.23%, respectively) than in PA (22.52%). In contrast, litter nitrogen contributed 68%–93.17% of plant residue nitrogen across all forest types.

**3.1.3 Understory Vegetation Layer** Understory vegetation carbon and nitrogen storage accounted for 2.20%–18.76% and 6.01%–26.01% of vegetation layer totals, respectively. Shrub layer carbon and nitrogen storage were highest in PB, followed by PA and NS. Moss layer carbon storage was highest in AF (2.75 tC/hm<sup>2</sup>) and lowest in NS (1.09 tC/hm<sup>2</sup>). Herb layer carbon and nitrogen storage followed the trend: AF > PA > NS > PB. Detailed values are provided in .

Vegetation C and N storage in different forest types

#### 3.2 Soil Carbon and Nitrogen

**3.2.1 Soil Carbon and Nitrogen Content** Forest type and soil depth significantly affected soil carbon and nitrogen content ( $F = 3.405$ ,  $p = 0.014$  for carbon;  $F = 5.372$ ,  $p = 0.008$  for nitrogen). Mean carbon and nitrogen contents were highest in NS (55.33 and 2.87 g/kg), followed by AF (39.15 and 2.53 g/kg), PB (35.26 and 2.14 g/kg), and PA (34.48 and 1.59 g/kg). Soil carbon and nitrogen content decreased with depth across all forest types.

**3.2.2 Soil Carbon and Nitrogen Storage** Soil carbon and nitrogen storage differed significantly among forest types ( $p < 0.05$ ). NS had significantly higher soil carbon storage (276.67 tC/hm<sup>2</sup>) than other forest types. Soil carbon storage values were 195.75, 176.29, and 172.40 tC/hm<sup>2</sup> for PB, NS, and PA, respectively. Soil nitrogen storage values were 14.33, 12.63, 10.71, and 7.96 tN/hm<sup>2</sup> for NS, AF, PB, and PA, respectively. The 0–20 cm layer contained 50.47%–62.97% of soil carbon and 50.85%–58.61% of soil nitrogen, showing no pronounced surface enrichment effect.

Soil C and N storage in different forest types

[Figure 1: see original paper] Soil C, N content and bulk density in different forest types

**3.3 Ecosystem Carbon and Nitrogen Storage and Distribution** Ecosystem carbon and nitrogen storage followed the same trend across forest types: AF (611.18, 16.44 t/hm<sup>2</sup>) > NS (363.07, 15.48 t/hm<sup>2</sup>) > PB (252.31, 12.11 t/hm<sup>2</sup>) > PA (239.06, 8.92 t/hm<sup>2</sup>). Carbon storage distribution differed between primary and restored forests: AF was dominated by the tree layer (56.65%), while restored forests were soil-dominated (69.87%–76.20%). Soil nitrogen storage accounted for 76.80%–92.58% of ecosystem nitrogen across all forest types.

[Figure 2: see original paper] Distribution pattern of carbon and nitrogen storage in different forest ecosystems

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## 4. Discussion and Conclusion

Land use change is an important factor affecting carbon and nitrogen storage [36–37]. The AF ecosystem carbon storage in this study (611.18 tC/hm<sup>2</sup>) is higher than primary forests in northern Thailand (269.57 tC/hm<sup>2</sup>) [38], mountain evergreen forests in China (357.62 tC/hm<sup>2</sup>) [39], and tropical mountain rainforests in Jianfengling (340.47 tC/hm<sup>2</sup>) [41], but lower than temperate moist *Eucalyptus regnans* forests (618.86 tC/hm<sup>2</sup>) [40]. The differences mainly reflect variations in environmental conditions, rainfall, radiation, topography, stand age, and natural disturbance.

Among restoration methods, NS showed higher ecosystem carbon storage (363.07 tC/hm<sup>2</sup>) than the national forest average (258.83 tC/hm<sup>2</sup>) [42], while PB and PA were lower. The difference primarily reflects soil carbon

accumulation, possibly because artificial planting of *P. asperata* disturbed soil carbon accumulation [44], whereas natural restoration enhanced soil carbon sequestration. Soil carbon and nitrogen pools are major ecosystem components. Previous studies show varying trends in soil carbon after afforestation: decline, initial decline followed by long-term accumulation, or redistribution within soil profiles [45]. Natural recovery can restore soil carbon stocks after disturbance [41, 46]. Our results show that after nearly 30 years, NS soil carbon and nitrogen storage approached AF levels.

Soil carbon and nitrogen storage were concentrated in the 0–40 cm layer (50.47%–62.97% of total soil storage), but without strong surface enrichment, consistent with studies in the Liupan Mountains [50]. High gravel content and leaching may reduce depth-related differences. The 0–20 cm layer in PB showed higher carbon and nitrogen proportions due to lower bulk density and reduced leaching.

The tree layer dominated vegetation carbon and nitrogen storage (57.00%–83.34% of vegetation carbon), consistent with other studies [17, 51–52]. AF tree layer carbon storage (346.24 tC/hm<sup>2</sup>) was lower than some tropical forests but within the range reported for mature forests (169.23–435.57 tC/hm<sup>2</sup>) [24]. Restored forests showed carbon storage of 44.49–52.71 tC/hm<sup>2</sup>, lower than similar-aged plantations in other regions but higher than some secondary forests [51].

Plant residues are important ecosystem components, contributing 4.40%–9.83% to ecosystem carbon storage and 2.94%–7.08% to nitrogen storage. Woody debris is often overlooked [54] but contributed significantly, especially in PB and NS (71.31% and 63.23% of plant residue carbon, respectively). The moss layer also contributed 1.09–2.75 tC/hm<sup>2</sup>, higher than the herb layer in some forests, due to moist understory conditions.

Ecosystem carbon allocation between vegetation and soil depends on stand origin. AF, with long-term vegetation development, stored more carbon in vegetation than soil, consistent with tropical primary forest studies [19, 41]. Restored forests showed soil > tree layer > plant residue layer > understory vegetation patterns, matching other plantation [35, 51–52], mixed [17, 52], and secondary forest [50] studies.

The three restored forest types have substantial carbon sequestration potential. The belowground/aboveground carbon storage ratio was 1.06 for AF, but 2.78, 3.77, and 3.40 for PB, NS, and PA, respectively, indicating greater aboveground storage potential in restored forests. The high carbon and nitrogen storage in AF warrants protection. Natural secondary forest benefits soil carbon accumulation, while *P. asperata* plantation shows higher tree layer carbon storage. However, from an ecosystem perspective, natural restoration is more beneficial for overall carbon and nitrogen sequestration. The abundant woody debris and litter in study forests may release carbon during decomposition, affecting forest carbon balance and requiring further attention under climate change scenarios.

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