Newly shed litters contain an abundance of extractable humus carbon in a subalpine forest on the eastern Tibetan Plateau

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Abstract. Humus is an important component of soil organic matter, but little attention has been paid to humus in newly shed litters. Moreover, the influence of climatic factors and chemical composition on the variation in humus carbon (HC) among different litter components and foliar litter in plant functional types is unknown. We conducted a field experiment in a subalpine forest on the eastern Tibetan Plateau in southwestern China from April 2016 to November 2016. Sixty litter collectors were fixed at three sampling sites that had been randomly established in the study area. The collected litter was classified as foliar litter (evergreen tree species versus deciduous tree species and tree species versus shrub species), twig litter, flower and fruit litter, and miscellaneous litter. The results clearly showed that extractable HC was abundant in the newly shed litters and exhibited significant seasonal trends. The concentrations of HC, humic acid carbon (HAC), and fulvic acid carbon (FAC) in the foliar litter were greater than those in the other plant components throughout the study period. In addition, the HC concentrations in four plant components peaked in July. In contrast, the HC concentrations in evergreen tree species stably remained at high levels, with a peak in July. The HAC concentrations in the foliar litter, twig litter, and miscellaneous litter exhibited irregular fluctuation trends, and maxima occurred in August. Furthermore, the total HC stock in the plant components in the study area was 1294.40 kg/hm², of which the HAC stock constituted 471.38 kg/hm² and the FAC stock constituted 820.02 kg/hm². The results presented here suggest that newly shed litters contain an abundance of extractable HC in this subalpine forest, revealing the initial state of organic carbon in the total alkaline solutions before it is transferred from the plant litter to the soil.

Key words: carbon fluxes; carbon stock; humic substances; litterfall; soil organic matter; subalpine forest.

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INTRODUCTION

As a basic carrier of nutrients and carbon, forest litterfall plays an important role in both maintaining the soil fertility and promoting the material cycles and nutrient balance of the forest ecosystem and is essential for the formation of soil organic matter (Stevenson 1994, Prescott et al. 2000, Neumann et al. 2018). Soil organic matter is mainly composed of humic substances that are enriched with humic acids and fulvic acids (Abakumov et al. 2013, Kölli and Rannik 2018). Humus is the main carrier of sequestering carbon and nutrient pools in forest ecosystems (Andreotta et al. 2018), and studies of humus are an innovative means of understanding soil function (Zanella et al. 2018a,b). Furthermore, humification is the main form of soil formation and can maintain material cycles and ecosystem balance (Lal 2005, Ponge 2013). However, much attention...
has been paid to humus characteristics in the soil, and during decomposition (Ni et al. 2015, Tatti et al. 2018), little information exists on the humus content in newly shed litters, and far fewer studies have investigated the variations in humus among plant functional types, components, and seasons.

The formation of soil organic matter and the processes of carbon sequestration in ecosystems are usually affected by climatic factors, such as temperature, precipitation, solar radiation, and other conditions (Wang et al. 2010, Ono et al. 2011). Climate is the main factor controlling the humus (Zanella et al. 2018a,b). The reduction in humidity and microbial activity caused by increases in temperature and solar radiation restricts the decomposition of litterfall, and more recalcitrant substances form and polymerize into humic substances in growing seasons (Prescott 2010, Ni et al. 2016). Furthermore, the growing seasons last longer and can be divided into the early growing season, the mid-growing season, and the late growing season based on the distributions of temperature, humidity, and other conditions (He et al. 2015). Meanwhile, the highest temperatures and strongest solar radiation occur in the mid-growing season, which contribute to the increased formation of humic substances. In addition, the late growing season is accompanied by a small amount of snowfall, which accelerates litterfall decomposition because of the insulator effect maintaining microbial activities, resulting in a reduction in humic substance accumulation (Kreyling 2013, Saccone et al. 2013). In addition, litter can be physically leached by precipitation, resulting in the loss of water-soluble or even acid-soluble substances (Cotrufo et al. 2013, Elliott 2013). The chemical and physical characteristics of litter are highly related to humus formation. The acid-unhydrolyzable residues may be the most significant factor affecting humus formation, and lignin, cutin, and phenolic compounds contribute to the synthesis of precursors that polymerize into humic substances (Prescott et al. 2000, Zanella et al. 2018a,b). Until now, research on litter humus has focused on humification in the process of litter decomposition. However, while numerous litter decomposition studies have evaluated the initial values of humus carbon (HC) in newly shed litters at a fixed time (Ono et al. 2013, Ni et al. 2015), it is still unclear whether any changes occur in the HC in newly shed litters among seasons. The formation and stability of humus partly depend on the recalcitrant litter types, and vegetation indirectly affects humus through changes in litter quality and litter quantity (Zanella et al. 2018a,b); therefore, the humus varies according to plant species (Ni et al. 2015). Accordingly, based on the results of previous studies on humus, we hypothesized that (1) the extractable HC would reach its highest level in the mid-growing season and would remain at a low level in the snowy season; and (2) the extractable HC in different litter components and plant functional types would change according to the season.

As humic substances, humic acids and fulvic acids are susceptible to variations in environmental factors (Ni et al. 2015). Additionally, fulvic acids are a group of substances that are more active than humic acids due to their small molecular weight, aromaticity, and stronger acidity (Wen 1984). However, in low O2, high moisture, and high CO2 conditions, acid-soluble fulvic acids are relatively stable and form easily, in contrast to alkaline-soluble humic acids (Dou et al. 2010). Once formed, acid-soluble fulvic acids are easily lost through physical leaching by rainfall and snowmelt water (Elliott 2013, Ni et al. 2015), and high temperature or year-round low temperature is not conducive to the accumulation of humic acids (Wen 1984). Therefore, we also predicted that the levels of fulvic acid carbon (FAC) decrease in the rainy seasons, whereas those of humic acid carbon (HAC) remain relatively stable under different climatic conditions, with the exception of an increase during the rainy seasons.

To test these hypotheses, we conducted an experiment in a subalpine forest on the eastern Tibetan Plateau in southwestern China. This region plays an important role in regulating the regional climate and water conservation (Wu et al. 2010), and litterfall is crucial for maintaining soil self-fertilization and productivity because of the slow formation of soil organic matter and low productivity (Yang et al. 2005). However, the composition characteristics of humic substances in litterfall, particularly newly shed litters, which act as nutrients in the soil, are not clear. In this study, we aimed to quantify the humic substance contents in newly shed litters to reveal the carbon sequestration and release in newly shed litters. In...
accordance with previous studies quantifying litter production, we also estimated the stock of HC. After a field experiment, we sought to explore the initial state of humus carbon in the process through which plants feed back to the soil.

**MATERIALS AND METHODS**

*Site description*

This study was conducted at the Long-term Research Station of Alpine Forest Ecosystems in the Miyaluo Nature Reserve (31°14′–31°19′ N, 102°53′–102°57′ E, altitude 2458–4619 m) located in Sichuan Province of the People’s Republic of China. This region is a transitional zone between the Tibetan Plateau and the Sichuan Basin (Yang et al. 2005). The annual mean temperature at the collecting sites is 2.7°C, and the maximum and minimum temperatures are 23°C (July) and −18°C (January), respectively. The annual mean precipitation is approximately 850 mm (Fu et al. 2017). The winter normally extends from late October to late April of the following year, and the growing season is from April to November (Wu et al. 2010). Seasonal snow cover occurs in November, remains from December to March of the following year, and melts in April (Tan et al. 2011). The dominant arboreal species at the experimental sites include *Picea asperata* and *Abies faxoniana*, and the associated species include *Cerasus duclouxii* and *Sorbus scalaris*. Representative shrubs include *Salix cupularis*, *Salix paraplesia*, *Rosa omeiensis*, and *Berberis silva-taroucana* among many others (Fu et al. 2017).

*Experimental design*

Three replicate 50 × 50 m collecting sites were randomly established in the study area in the subalpine forest. To ensure homogeneity, the three sites were at similar altitudes and slopes and were at least 50 m apart from one another. Twenty litterfall collectors were placed randomly at each site at the end of March 2016. The litter collectors were funnel-shaped, with an opening diameter of 1 m and a collection area of 0.785 m², and a litterbag was hung from the bottom of each collector. The daily mean air temperature and monthly precipitation were measured to quantitatively assess the environmental factors associated with the HC, HAC, and FAC (Fig. 1). The daily mean air temperature and monthly precipitation at the three collecting sites were measured using a weather station data logger (HOB0 U30-NRC Weather Station; Onset Computer Corporation, Bourne, Massachusetts, USA).

![Fig. 1. Daily mean air temperature and monthly precipitation in a subalpine forest on the eastern Tibetan Plateau from April 2016 to November 2016.](image-url)
Litter collection and treatments

From April 2016 to November 2016, the litter in each funnel-trap collector was collected twice a month (at the middle of the collecting month and the end of the collecting month) during the peak litter months, that is, May and October, and once a month (at the end of the collecting month) during the other months. All litter materials were air-dried at room temperature for one week and then classified as foliar litter, twig litter, or flower and fruit litter, and any unrecognized residue was classified as miscellaneous litter (including unidentified plant residues and animal waste). In addition, the foliar litter was characterized as being from either evergreen or deciduous species and then from tree species or shrub species. After the classification was complete, all litterfall materials were ground and passed through a 0.25-mm sieve in preparation for the extraction of HC and HAC.

Sample analysis

The HC was extracted using a 100 mL solution of 0.1 mol/L NaOH + 0.1 mol/L Na4P2O7 and 0.5 g of ground litter (Adani and Ricca 2004). The HAC and FAC fractions were separated using 0.5 mol/L H2SO4 at 80°C, after which the separated HAC was dissolved with a hot 0.05 mol/L NaOH solution. The HC and HAC fractions were passed through a 0.45-µm filter and then analyzed using a total organic carbon (TOC) analyzer (vario TOC cube/vario TOC select, Elementar Analysensysteme GmbH, Hanau, Germany). The chemical components used in the partial least squares (PLS) analysis were measured by the van Soest method and by calculating the remaining weight (Li et al. 2016).

Statistical analyses and calculations

The concentrations of HC and HAC were analyzed, and the concentration of FAC and the stocks of HC, HAC, and FAC were calculated for the letters during the observation period as follows:

$$C_{\text{FAC}} \text{ (g/kg)} = C_{\text{HC}} - C_{\text{HAC}}$$ (Gigliotti et al. 1999)

$$S \text{ (kg/hm}^2\text{)} = C \times M$$ (Huang et al. 2008)

$$C_{\text{HC}}, C_{\text{HAC}}, \text{ and } C_{\text{FAC}}$$ are the concentrations of HC, HAC, and FAC, respectively, $$S$$ is the stock of HC, HAC, and FAC, $$C$$ is the concentration of HC, HAC, and FAC, and $$M$$ is the litter production per unit area during the study period (Appendix S1: Table S1). The composition and formation rates of humic acids and fulvic acids during the process of humic substance formation are expressed as the HAC/FAC ratios (Abakumov et al. 2013).

Repeated-measures analysis of variance (ANOVA) with a Greenhouse-Geisser correction was used to test the effects of time and plant component (plant functional type), as well as their interactions, on the $$C_{\text{HC}}, C_{\text{HAC}}, \text{ and } C_{\text{FAC}}$$ throughout the observation period. One-way ANOVA was used to test for significant differences ($$P < 0.05$$) in the HC, HAC, and FAC concentrations among litter components for each month. The HC, HAC, and FAC concentrations of foliar litter in evergreen tree species versus deciduous tree species and in tree species versus shrub species were compared using independent-samples t-tests. A linear regression analysis was then used to test the relationships between the $$S_{\text{HC}}, S_{\text{HAC}}, \text{ and } S_{\text{FAC}}$$ and environmental factors across litter components. The above analyses were performed using SPSS 20.0 (IBM SPSS Statistics, Chicago, Illinois, USA). PLS analysis with PLS coefficients and variable importance was used to test the effects of litter chemical components and climatic factors on the concentrations of HC, HAC, and FAC and the HAC/FAC ratio in newly shed litters. The above analyses were performed using SIMCA 14.1 (Umetrics, Umeå, Sweden).

RESULTS

Concentrations of HC, HAC, and FAC

The concentrations of HC, HAC, and FAC in plant components significantly differed among months throughout the observation period (Table 1), and changes in the concentrations of

| Factor                  | df | $$F_{\text{HC}}$$ | $$F_{\text{HAC}}$$ | $$F_{\text{FAC}}$$ |
|-------------------------|----|-------------------|-------------------|-------------------|
| Collecting time         | 7  | 34.66***          | 39.88***          | 33.78***          |
| Plant components        | 3  | 121.79***         | 58.39***          | 94.94***          |
| Collecting time x plant components | 21 | 16.78***          | 7.13***           | 18.37***          |

*** $$P < 0.001$$.
HC, HAC, and FAC in the foliar litter significantly differed among plant functional types (Table 2). Moreover, in contrast to twig litter, flower and fruit litter, and miscellaneous litter, the foliar litter contained high concentrations of HC, HAC, and FAC throughout the entire study period (Fig. 2).

In addition, the HC concentrations in the foliar litter, twig litter, flower and fruit litter, and miscellaneous litter were unimodal, peaking in July, and they showed similar trends, with a small increase in October (Fig. 3A). The HC concentration in evergreen tree species remained at a high level throughout the observation period, but a small peak occurred in July, and the HC concentration in deciduous tree species showed a decline in September that was similar to that observed in evergreen tree species (Fig. 3B, C). Furthermore, the PLS analysis results showed that the HC concentration was significantly related to the water-soluble components ($P < 0.05$) but not to other components or climatic factors (Fig. 4).

Although the HAC concentrations in the foliar litter, twig litter, and miscellaneous litter exhibited similar dynamic patterns, these concentrations tended to fluctuate irregularly and peaked in August (Fig. 3D). In addition, the concentration of HAC in evergreen tree species significantly differed across months and peaked twice. The major peak occurred in August, and the smaller peak occurred in June. However, the concentration of HAC in deciduous tree species generally continually declined (Fig. 3E). In addition, the HAC dynamics in tree species were similar to

Table 2. Repeated-measures ANOVA of the concentrations of humus carbon (HC), humic acid carbon (HAC), and fulvic acid carbon (FAC) relative to time and foliar litter among plant functional types.

| Factor                          | df  | $F_{HC}$     | $F_{HAC}$    | $F_{FAC}$    |
|---------------------------------|-----|--------------|--------------|--------------|
| Collecting time                 | 7   | 309.90***    | 84.62***     | 258.37***    |
| Plant functional types          | 3   | 538.65***    | 66.04***     | 846.94***    |
| Collecting time × plant functional types | 21  | 126.59***    | 9.85***      | 103.69***    |

*** $P < 0.001$.

Fig. 2. The mean concentrations and stocks of humus carbon (HC), humic acid carbon (HAC), and fulvic acid carbon (FAC) in four litter components, evergreen tree species versus deciduous tree species, and tree species versus shrub species. The presented concentration values are the means of $N = 3$ observations; the error bars represent standard errors; the values are the percentages of the stocks of HC, HAC, and FAC in each component and each foliar litter in plant functional types.
those observed in the evergreen tree species (Fig. 3F). The PLS analysis results illustrated that the HAC concentration was significantly related to the monthly air temperature ($P < 0.001$), monthly precipitation ($P < 0.001$), acid-soluble substances ($P = 0.004$), and acid-unhydrolyzable residues ($P < 0.001$; Fig. 4). A peak in the FAC concentrations in all components occurred in July, and then, these concentrations decreased until September (Fig. 3G); the FAC concentrations in the evergreen tree species and tree species were similar to those in the litter components, and these concentrations in the deciduous tree species and shrub species steadily increased during the observation period (Fig. 3H, I). In addition, the PLS analysis results show that the FAC concentration was significantly related to the monthly air temperature ($P = 0.001$), water-soluble substances ($P < 0.001$), and acid-unhydrolyzable residues ($P < 0.001$; Fig. 4).

**HAC/FAC ratios**

The HAC/FAC ratios of foliar litter and twig litter exhibited similar continuous patterns in the mid-growing season (Fig. 5), but the HAC/FAC ratio in the foliar litter was greater than that in the twig litter. Moreover, the HAC/FAC ratios in the foliar litter and twig litter were greater than...
one; the peaks occurred in August, after which the ratios continuously decreased. The HAC/FAC ratio in the flower and fruit litter remained at a low level. The HAC/FAC ratios of evergreen tree species and tree species were less than one in the early growing season but were greater than one in the mid-growing season. At the same time, the patterns of the HAC/FAC ratio in evergreen tree species were similar to those in tree species: A peak occurred in August, which was also observed for the foliar litter. The HAC/FAC ratios in the deciduous tree species and shrub species were greater than one in the mid-growing season; conversely, the ratios were less than one in the late growing season. The maxima occurred in August, when the deciduous tree species began to lose their leaves, after which the ratio continuously decreased. Meanwhile, the PLS analysis results showed that the HAC/FAC ratio was significantly related to the monthly air temperature ($P < 0.001$) and acid-unhydrolyzable residues ($P < 0.001$; Fig. 4).

**HC, HAC, and FAC stocks**

The total HC stock in the study area was 1291.40 kg/hm$^2$, of which 471.38 kg/hm$^2$ was HAC stock and 820.02 kg/hm$^2$ was FAC stock, and the stocks of HC (1034.54 kg/hm$^2$), HAC (365.15 kg/hm$^2$), and FAC (669.40 kg/hm$^2$) in the foliar litter were larger than in the other components (Fig. 2).

The stock of HC in the foliar litter was unimodal and peaked in October, and the corresponding peak in the twig litter occurred in June. Moreover, flower and fruit litter exhibited a unimodal trend (Fig. 6A). In addition, the stocks of HAC and FAC in the foliar litter exhibited similar dynamics to that of the HC stocks (Fig. 6D, G). Moreover, the greatest percentages of total monthly stocks of HC, HAC, and FAC in the...
Fig. 5. Humic acid carbon (HAC)/fulvic acid carbon (FAC) ratios of four litter components and four plant functional types. The asterisk represents a significant difference between two or among more plant components, between evergreen tree species and deciduous tree species, or between tree species and shrub species.

Fig. 6. Monthly stocks of humus carbon (HC; A–C), humic acid carbon (HAC; D–F), and fulvic acid carbon (FAC; G–I) in four litter components (A, D, G), evergreen tree species versus deciduous tree species (B, E, H), and tree species versus shrub species (C, F, I). The error bars represent standard errors.
foliar litter were 98.08%, 98.07%, and 98.09%, respectively, which occurred in October (Fig. 7).

**DISCUSSION**

Our hypothesis that HC, HAC, and FAC concentrations and stocks are controlled by seasons and by the variations in litter components and plant functional types of foliar litter was partly supported by the results of this study. Firstly, the HC in newly shed litters varied according to the seasons: The HC peaked in July in the mid-growing season and exhibited a low level in snowy months. The HC in this study was greater than that from the decomposition of foliar litter in an alpine forest (Ni et al. 2014), possibly because the humus in newly shed litters has not formed a stable structure and water solubles and carbohydrates (cellulose, hemicellulose) abundantly exist in the newly formed humus (Zanella et al. 2018a, b). The results indicated that the process by which plants feed back to the soil was a process of carbon release, and a high level of organic carbon in alkaline solutions of newly shed litters was observed. Secondly, the HC, HAC, and FAC concentrations and stocks were highest in the foliar litter, which suggested that newly shed leaves had the strongest capacity for carbon sequestration. Thirdly, although the HC concentrations of foliar litter from evergreen tree species were larger than those of foliar litter from deciduous tree species (Fig. 2), the HC stock in the foliar litter from deciduous tree species (522.18 kg/hm²) remained larger than that from evergreen tree species (512.36 kg/hm²) due to their higher litterfall amount (Fig. 2; Appendix S1: Table S1), which confirmed the study results of Neumann et al. (2018) and Liu et al. (2004).
Concentrations of HC, HAC, and FAC

The extractable HC exhibited seasonal variations and varied with litter components and foliar leaching in plant functional types. Physical leaching caused by snowmelt water accelerated the loss of water-soluble substances and even acid-soluble materials in the newly shed litters in the early growing seasons (Ni et al. 2014), and PLS analysis found that the HC was positively correlated with water-soluble substances (Fig. 4). Afterward, the HC concentrations continued to increase and reached a peak in the mid-growing season (Fig. 3A). This might be due to the high temperature constraint on microbial activity and respiration in the early growing season (Grinhut et al. 2011) and due to the severe solar radiation and temperature constraint on the decomposition environment (Rey et al. 2005), leading to the polymerization of more refractory materials into humic substances (Ni et al. 2016). After the mid-growing season, the precipitation maintained an upward trend, which caused the decrement of acid-soluble substances (Elliott 2013). Furthermore, there was a small amount of snow in October and November, and the oxygen conditions under the snowpack were unfavorable for the stabilization of humic substances (Saccone et al. 2013). The HC concentrations in the foliar litter of evergreen tree species and tree species were higher than those of deciduous tree species and shrub species (Fig. 2). This finding could have occurred because evergreen tree species and tree species, which were conifer species in the present study, were not easily biodegraded because of the higher lignin content of the coniferous evergreen tree species (Neumann et al. 2018).

The concentrations of HAC showed correlations with temperature and precipitation; temperature was the most influential factor, followed by precipitation (Fig. 4). Higher HAC concentrations were observed with the temperature increase in the mid-growing season (Fig. 3D). This likely occurred because the low humidity caused by high temperature (Dou et al. 2010) and the increased activities of microbes (Sierra and Motisi 2012) both contributed to the stability of humic acids. In addition, the results also show that the HAC concentration was largely controlled by acid-unhydrolyzable residues and acid-soluble substances in the four chemical components (Fig. 4), which was consistent with results from a study of humic acids during humification in alpine forest (Ni et al. 2014). Acid-unhydrolyzable residues were positively related to HAC, while acid-soluble substances were negatively related to HAC (Fig. 4). This result illustrates that acid-unhydrolyzable residues polymerize humic acids, while acid-soluble substances run off with a large amount of precipitation in the mid-growing season. Moreover, the FAC concentrations were positively related to the water-soluble substances and negatively related to the monthly air temperature and acid-unhydrolyzable residues (Fig. 4). Although precipitation might indirectly affect the FAC concentration by affecting water-soluble substances (Elliott 2013), the FAC concentration declined and formed a valley in the mid-growing season (Fig. 3G). In addition, the increase in HAC and the reduction in FAC during the mid-growing season (Fig. 3D, G) indicated that a transformation might occur between humic acids and fulvic acids (Stevenson 1994). Furthermore, the HAC and FAC concentrations in the foliar litter of deciduous tree species and shrub species showed greater fluctuations than those in the foliar litter of evergreen tree species and tree species in the mid-growing season (Fig. 3E, F, H, I). A probable explanation for this observation is that deciduous tree species, which included broad-leaved species, were more affected by climatic factors than evergreen tree species (Catovsky et al. 2002, Lü et al. 2017).

HAC/FAC ratios

The change trends of the HAC/FAC ratios were similar to those of the HAC concentrations (Figs. 3D–F, 5). Overall, the HAC/FAC ratios of litter components in the early growing season were less than one (Fig. 5), and it seemed that fulvic acids formed faster than humic acids and that the FAC concentration was higher than the HAC concentration (Ikeya and Watanabe 2003). The low HAC concentrations and high FAC concentrations were caused by the relatively high moisture resulting from the low temperatures (Dou et al. 2010). Moreover, in the mid-growing season, the HAC/FAC ratios of the litter components were greater than one (Fig. 5), which indicated that humic acids form faster than fulvic acids in all components (Ikeya and Watanabe 2003). This might have occurred because acid-unhydrolyzable residues form more humic acids, and the soluble components removed a small
amount of the fulvic acids during precipitation (Elliott 2013). Furthermore, the occurrence of HAC/FAC ratios that were less than one in the litter components in the late growing season (Fig. 5) suggested that the formation rate of fulvic acid is faster than that of humic acid, leading to FAC concentrations that were greater than the corresponding HAC concentrations (Ikeya and Watanabe 2003). The HAC/FAC ratios of the foliar litter of evergreen tree species and tree species were less than one in the early growing season (Fig. 5), which indicated that the FAC concentration was greater than the HAC concentration during the early growing season. However, in the mid-growing season, the HAC/FAC ratios of the foliar litter of deciduous tree species and shrub species were lower than those of evergreen tree species and tree species (Fig. 5). This observation suggested that the HAC concentration of the foliar litter of the deciduous tree species and shrub species was lower than that of the evergreen tree species and that HAC formed more slowly in the foliar litter of deciduous tree species and shrub species. The HAC/FAC ratios of the deciduous tree species and shrub species were slightly higher than those of the evergreen tree species and tree species in the late growing season (Fig. 5), which indicated that the formation rate of HAC in the foliar litter from deciduous tree species was faster than that in the foliar litter from evergreen tree species.

**HC, HAC, and FAC stocks**

The stocks of HC, HAC, and FAC were 1291.40 kg/hm², 471.38 kg/hm², and 820.02 kg/hm², respectively, and the HC (80.11%), HAC (77.46%), and FAC (81.63%) stocks of foliar litter were larger than those of the other components due to the foliar litter being the largest component of the litterfall (Fig. 2). The results of the analysis suggested that the stocks of HC and FAC in the plant components and in the foliar litter of the different plant functional types were significantly negatively correlated with temperature and precipitation (Table 3), which were similar to the study results of Liu et al. (2004). The results showed that both the maxima and the greatest proportion in the HC stocks of foliar litter appeared in October (Fig. 7), which were consistent with the study results obtained for subalpine forest (Appendix S1: Table S1; Fu et al. 2017), indicating that the litterfall input was the main driver of the carbon stocks.

This finding could have occurred because the climatic factors indirectly affected the HC stocks by influencing litterfall amount. The peak stock in the foliar litter was related to the litterfall amount of foliar litter and agreed with that of the total stock (Fu et al. 2017). In addition, a large HC stock in twig litter occurred in June (Fig. 6A), likely due to the increase in twig litter production caused by snow (Fu et al. 2017). Moreover, the HC stock in the foliar litter of deciduous tree species (522.18 kg/hm²) remains larger than that of evergreen tree species (512.36 kg/hm²) due to their higher litterfall amount (Fig. 2; Appendix S1: Table S1), which confirmed the study results of Neumann et al. (2018) and Liu et al. (2004). Due to the expansion of shrub species to high altitudes (Pickering et al. 2008), the shrubs in this study area are mostly deciduous species, and the increase in deciduous species may lead to higher litter input (Neumann et al. 2018). Furthermore, deciduous species exhibited faster decomposition, with less humus and faster nutrient cycling (Zhang et al. 2008), thus promoting forest growth.

**Conclusions**

Newly shed litters contain an abundance of HC, and both the concentrations and stocks of HC, HAC, and FAC were highest in the foliar litter. The PLS analysis results suggested that temperature and precipitation were the key climatic factors, and acid-unhydrolyzable residues and soluble substances were the significant chemical component factors that drove the variations in humus. The HC stock was negatively related to temperature and precipitation, which affected

| Factor                      | $SHC$ | $SHAC$ | $SFAC$ |
|-----------------------------|-------|--------|--------|
| Plant components            | -0.434** | -0.350* | -0.458** |
| Temperature                 | -0.391** | -0.262 n.s. | -0.444** |
| Precipitation               | -0.366** | -0.236 n.s. | -0.421** |
| Plant functional types      | -0.107 n.s. | -0.069 n.s. | 0.121 n.s. |
| Temperature                 | -0.600** | -0.420* | -0.664** |
| Precipitation               | -0.575** | -0.396 n.s. | -0.639** |

Notes: n.s. $P > 0.05$, *$P < 0.05$, and **$P < 0.01$. 

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litterfall amount, illustrating that HC stock was driven by the litterfall amount. In summary, the results of this study present the initial quantities of carbon fluxes from plant detritus to soil organic matter, providing new information for the understanding of subsequent decomposition and humification processes. Based on the results provided here, further studies could focus on the humic substances in fresh litter layers and living plants combined with the relevant content of humic substances over the litter decomposition process. In this way, we can systematically discuss HC cycling in aboveground plants to further explore the correlation between HC and C cycling.

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Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2432/full