Plant Litter and Litter Carbon

Subjects: Soil Science | Forestry
Contributor: Wanqin Yang

Investigations on the budget of plant litter and litter carbon in forest streams can provide a key scientific basis for understanding the biogeochemical linkages of terrestrial–aquatic ecosystems and managing forest catchments.

litter input and output | litter carbon budget | mountain forest stream

1. Introduction

In the geosphere, streams cover less than 3% of the forest catchment area, but function as the bridges linking terrestrial–aquatic biogeochemical cycles [1]. In particular, plant litter from neighboring forests and riparian zones is the major source and carrier of carbon in forest streams and plays crucial roles not only in maintaining stream ecosystem productivity, but also in maintaining the structure and function of the butted aquatic ecosystem [2][3]. Additionally, litter decomposition in the forest stream ecosystem can contribute significantly to the global carbon cycle [4][5][6]. Therefore, understanding the budget of litter and litter carbon in forest streams can provide a key scientific basis for managing forest catchments and predicting the global carbon cycle.

The forest stream might act as a sink of plant litter and bioelements in the forest catchment. Theoretically, litter input to the stream is hierarchically regulated by three interactive factors: climate, forest type, and stream characteristics [7]. First, the climate has been considered the primary factor influencing litter production [8]. Generally, average litter production decreases gradually from tropical zones to boreal alpine zones along the climate gradient [9][10]. Compared to cold temperate zones, evergreen broadleaved forests in tropical regions often have larger amounts of litter production due to the higher temperature and moisture [11][12], implying that more litter can enter the stream. Second, the dynamics of litter input vary greatly with forest types, as different tree species have different phenological phases [7][13], which in turn determine the quantity and dynamics of litter input to the forest stream [13][14]. For instance, on a local scale, evergreen and deciduous forests usually show higher litter production than dark coniferous forests in the subalpine forest region [15][16]. Plant species composition in the riparian zone differs greatly from that in the mountain forest, and the litter production of shrub and herb species in the riparian zone is lower than that in the mountain forest [7][14], implying that the litter input to the stream in the riparian zone might be lower than that directly in the forest. Third, litter input is also modulated by the stream length and width [17], and longer and wider streams can receive more litter along the stream [18][19]. Although litter input to the stream has been systematically investigated in northern America [20][21][22], litter input to streams has not been fully investigated around the world, limiting our understanding of the biogeochemical linkages of mountain forest and riparian zones with streams and rivers.

The litter and litter carbon output from streams are known as the major carbon sources of butted rivers. That is to say, the forest stream also acts as the source of litter and litter carbon [23][24]. In theory, the litter output from forest streams is usually regulated by the stream litter quality and quantity, stream biological community, stream characteristics, and climate [8][25]. To begin with, the magnitude of litter input to the stream determines the size of the litter source of a butted river [4][5]. Meanwhile, the scouring action of stream water on litter can directly accelerate litter fragmentation [26], which may lead to the output and confluence characteristics of litter varying with the seasons [27][28][29]. For example, streams with lower flow rates and slower velocities always accompany faster litter decomposition and litter deposition, leading to smaller amounts of output, and vice versa [30]. In addition, the length and width of the streams, together with their microtopography, might significantly influence litter output [29]. Finally, forest stream characteristics, such as discharge and velocity, are always regulated by seasonal precipitation (rainfall, snowfall, and snowmelt), theoretically modulating the output of litter and litter carbon from the streams. In particular, the plant rhythm with seasonal changes accompanies the seasonal dynamics of precipitation and temperature, which play important roles in controlling the output of litter from a forest stream [7][31]. Therefore, investigations into the litter output from forest streams could facilitate a better understanding of the biogeochemical linkages of mountain forests and riparian zones with aquatic ecosystems.

Carbon is the basic component in both terrestrial and aquatic ecosystems. The dynamic pattern of litter carbon in forest stream ecosystems can reveal terrestrial–aquatic carbon biogeochemical linkages [30][32]. Past investigations have found that the carbon fractions derived from upstream and neighboring ecosystems are the two major sources of dissolved carbon (DC) in forest stream ecosystems [33][34]. Most investigations of carbon biogeochemical linkages between mountain forests and butted aquatic ecosystems have employed the small-scale runoff field method [35]. However, this method has difficulty revealing the roles of forest streams in terrestrial–aquatic carbon biogeochemical linkages, especially in geographically fragile mountainous regions [36]. First, due to geological fragmentation and serious soil percolation [37], surface runoff is rarely observed in most rainfall and snowfall events, while percolating water becomes an important biogeochemical link between mountain forest ecosystems and aquatic ecosystems in fragile mountainous regions. Second, forest streams can be directly involved in the biological carbon cycle rather than indirectly involved through surface runoff, since litter from forest and riparian vegetation is a major source of carbon input to the butted aquatic ecosystem [38]. Third, the riparian zone is an important domain in the forest stream ecosystem. The decomposition of allochthonous organic materials (e.g., foliar litter) in riparian zones is often a critical factor affecting the continued availability of carbon resources in these ecosystems [39]. Hence, the systematic investigation of litter carbon dynamics in streams and riparian zones will provide baseline data for further understanding of the biogeochemical linkages of terrestrial–aquatic ecosystems.

As the second largest forest region in China, the subalpine forest region in the eastern Qinghai-Tibet Plateau is the most important freshwater conservation area and headwater region of the Yangtze River, and plays paramount and irreplaceable roles in holding water, conserving soil, and maintaining the safety of water resources and downstream aquatic ecosystems [40][41]. These forest stream ecosystems are typically cold ecosystems that experience considerable seasonal freezing and thawing events, and seasonal changes are associated with distinct changes in environmental conditions [42][43]. Therefore, a deep investigation of the budget of litter and litter carbon in these forest stream ecosystems is key to revealing the carbon biogeochemical linkages between subalpine forests and aquatic ecosystems.

2. Site Description

This study was conducted at the Long-Term Research Station of Alpine Forest Ecosystem in the Bipenggou Valley (31°14′~31°19′ N, 102°53′~102°57′ E, 2458~4619 m above sea level (masl)), Li County, Southwest China, which is located in the alpine gorge area with frequent geological breaks, clear seasonal snow cover (the maximum snow depth was about 35 cm), and frequent freeze/thaw cycles [7] (**Figure 1**). The mean annual precipitation is approximately 850 mm, and the annual mean air temperature is approximately 3 °C, with maximum and minimum temperatures of 23 °C (July) and −18 °C (January), respectively. The frozen season lasts from November to April, and thaw begins in late April. This subalpine forest is dominated by Minjiang fir (*Abies faxoniana* Rehder & E.H.Wilson), larch (*Larix mastersiana* Rehder & E.H.Wilson), and cypress (*Sabina saltuaria* Rehder & E.H.Wilson), and is interspersed with shrubs of azaleas (*Rhododendron* spp.), willow (*Salix* spp.), and barberry (*Berberis sargentiana* C.K.Schneid). The herbaceous plants consist mainly of ferns (*Cystopteris montana* (Lam.) Bernh. ex Desv) [7]. The concentrations of carbon (C), nitrogen (N), and phosphorus (P) in the surface soil (5 cm depth) was 126.0, 5.8, and 1.2 g kg^{-1}, respectively.

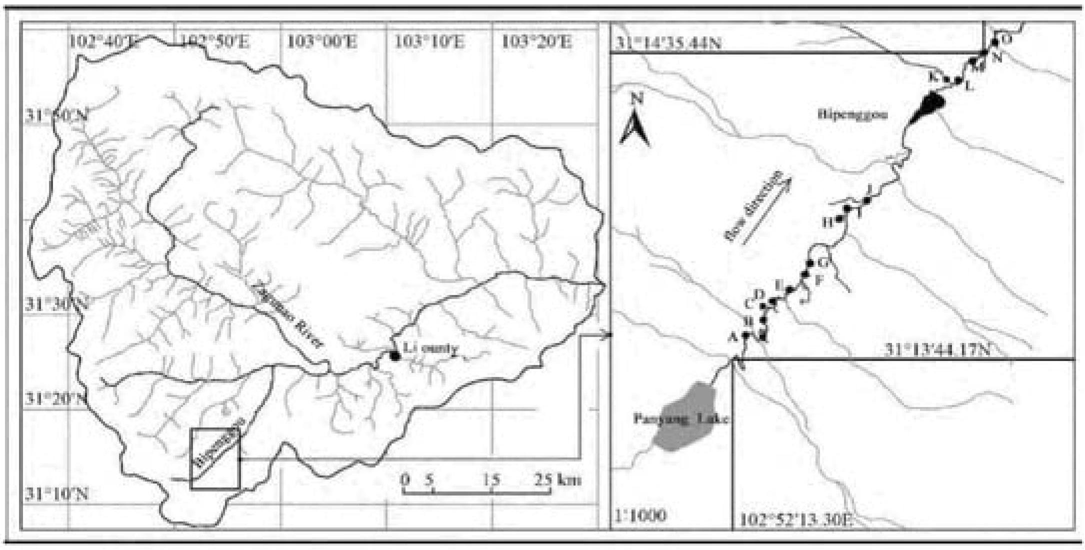

Figure 1. The investigated streams in the Bipenggou Valley, located in the upper reaches of the Yangtze River. The letters A–O indicate the 15 sampling streams [7].

3. Monitoring the Input and Output of Litter and Litter Carbon

In order to collect litter, according to the stream length, a quadratic litter collector (0.8 m × 0.8 m) was randomly installed at the source, middle, and end of the stream (when the stream width < 0.8 m, one litter collector was positioned; when the stream width > 0.8 m and <1.6 m, two litter collectors were positioned; the stream widths are shown in **Table 1**), and each was installed 0.5 m above the water or ground surface (**Figure 2**). To avoid litter decay in the litter collectors caused by rainfall, the litter samples were collected every 15 days, but the litter was collected only once in the cold winter since litterfall in winter was rare. All of the collected litter samples were put into precleaned polyethylene bags and transported to the lab. The samples were dried to a constant weight and stored at 65 °C for less than one week until analysis.

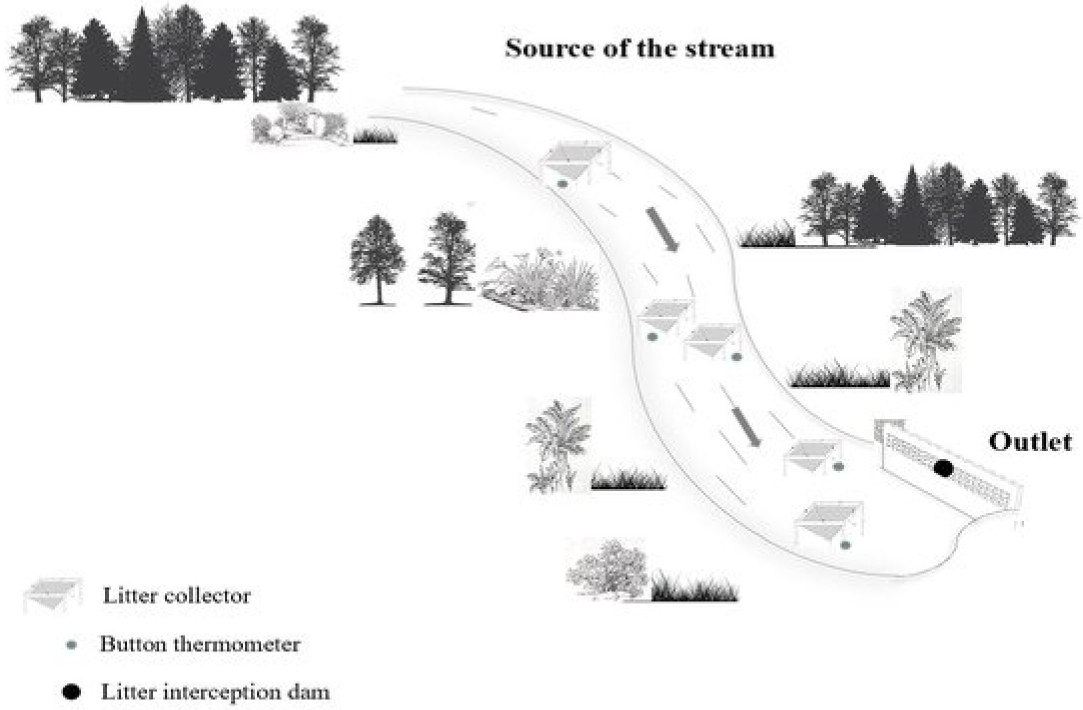

Figure 2. Litter and litter carbon input and output monitoring system in the investigated streams of the Bipenggou Valley, located in the upper reaches of the Yangtze River.

Table 1. Basic characteristics of 15 representative subalpine forest streams in the investigated subalpine forest catchment.

Stream	Elevation (m)	Length (m)	Width (m)	Water Level (cm)	Flow Velocity (m^3/s)	Main Plants
A	3668	220	0.63 ± 0.16	8.57 ± 3.20	0.11 ± 0.11	*A. faxoniana*, *Cyperus* spp., *S saltuaria*
B	3667	66	0.69 ± 0.14	5.15 ± 1.60	0.07 ± 0.07	*A. faxoniana*, *Cyperus* spp., *S. saltuaria*
C	3658	13	0.63 ± 0.22	7.16 ± 3.83	0.01 ± 0.02	*A. faxoniana*, *Cyperus* spp., *S. saltuaria*
D	3658	92.4	0.86 ± 0.19	4.81 ± 1.08	0.06 ± 0.07	*A. faxoniana*, *Cyperus* spp., *S. saltuaria*
E	3657	47	0.34 ±	3.73 ± 3.43	0.01 ± 0.01	*A. faxoniana*, *Cyperus* spp., *S.*

Stream	Elevation (m)	Length (m)	Width (m)	Water Level (cm)	Flow Velocity (m^3/s)	Main Plants
			0.30			*saltuaria*
F	3640	65	1.11 ± 0.30	6.90 ± 1.44	0.11 ± 0.12	*S. saltuaria*, *R. lapponicum*
G	3640	186	1.02 ± 0.33	8.96 ± 1.91	0.06 ± 0.06	*S. saltuaria*, *Carex* spp., *R. weginzowii*
H	3634	108	0.82 ± 0.28	6.73 ± 4.38	0.04 ± 0.07	*S. saltuaria*, *Carex* spp., *S. rufopilosa*
I	3634	256	1.02 ± 0.22	7.19 ± 1.80	0.13 ± 0.12	*S. saltuaria*, *R. weginzowii*, *Carex* spp.
J	3634	18	1.29 ± 1.00	3.85 ± 3.05	0.04 ± 0.07	*S. saltuaria*, *R. weginzowii*, *Carex* spp.
K	3611	36	1.00 ± 0.24	7.93 ± 2.32	0.10 ± 0.08	*R. lapponicum*, *S. saltuaria*
L	3611	11	0.93 ± 0.58	3.70 ± 1.89	0.03 ± 0.05	*R. lapponicum*, *S. saltuaria*
M	3610	12	0.85 ± 0.23	6.26 ± 1.42	0.03 ± 0.08	*R. lapponicum*, *S. saltuaria*
N	3607	28	0.84 ± 0.32	11.72 ± 4.88	0.15 ± 0.14	*S. mastersiana*, *Cyperus* spp., *S. rufopilosa*
O	3607	17	0.65 ± 0.41	4.34 ± 3.84	0.02 ± 0.04	*S. mastersiana*, *S. rufopilosa*, *Cyperus* spp.

4. Litter and Litter Carbon Input to the Stream

The litter input to the stream showed two peaks (**Figure 3**A). The maximum peak (101.40 g m^{-2}) was observed in the LGS and then decreased gradually, reaching the minimum value (18.91 g m^{-2}) in the SMS. The second peak (59.44 g m^{-2}) was found in the GS (**Figure 3**A), and these values were all averages per period. Meanwhile, the litter input to the stream ranged from 2.47 to 103.13 g m^{-2}, and the annual value was 20.14 g m^{-2} for the 15 investigated streams during this one-year investigation.

1. ... fish assemblage structure in four southern Appalachian streams. Freshw. Biol. 2002, 47, 1791–1805.
2. Gessner, M.O.; Swan, C.M.; Dang, C.K.; McKie, B.G.; Bardgett, R.D.; Wall, D.H.; Hattenschwiler, S. Diversity meets decomposition. Trends Ecol. Evol. 2010, 25, 372–380.
3. Wallace, J.B.; Eggert, S.L.; Meyer, J.L.; Webster, J.R. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. Science 1997, 277, 102–104.
4. Tranvik, L.J.; Downing, J.A.; Cotner, J.B.; Loiselle, S.A.; Striegl, R.G.; Ballatore, T.J.; Ballatore, T.J.; Dillon, P.; Finlay, K.; Fortino, K.; et al. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanograohy 2009, 54, 2298–2314.
5. Battin, T.J.; Kaplan, L.A.; Findlay, S.; Hopkinson, C.S.; Marti, E.; Packman, A.I.; Newbold, J.D.; Sabater, F. Biophysical controls on organic carbon fluxes in fluvial networks. Nat. Geosci. 2008, 1, 95–100.
6. Loreau, M.; Mouquet, N.; Holt, R.D. Meta-ecosystems: A theoretical framework for a spatial ecosystem ecology. Ecol. Lett. 2003, 6, 673–679.

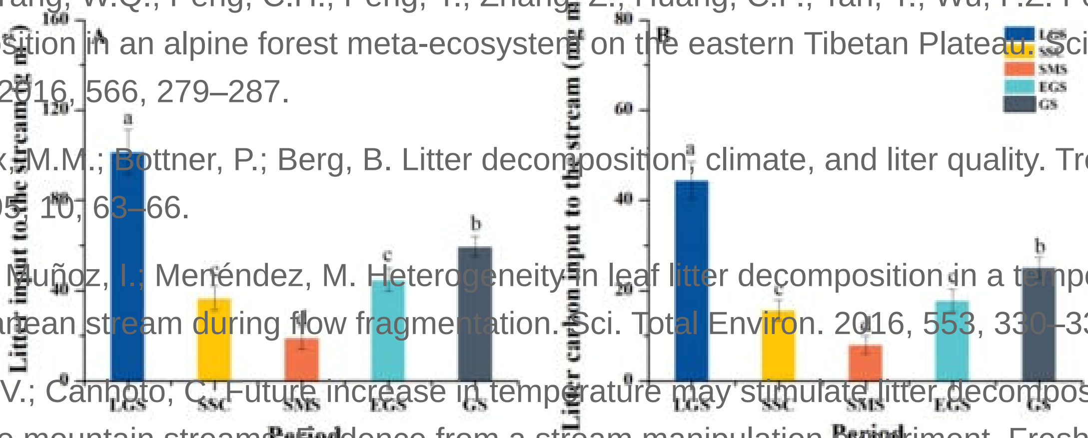

Figure 3. Dynamics of litter (**A**) and litter carbon (**B**) input to the subalpine forest streams in the upper reaches of the Yangtze River. LGS, SSC, SMS, EGS and GS indicate the sampling periods, i.e., later growing season (LGS: September to October), seasonal snow cover (SSC: November to April next year), snowmelt season (SMS: April to May), early growing season (EGS: May to June), and growing season (GS: July to August). The vertical coordinate is the mean of litter input accumulation of 15 streams during this period. Different lowercase letters indicate the significant difference among different periods ($p < 0.05$), while the same letter indicates no significant difference among each other.

Like litter input, the dynamic pattern of litter carbon in the streams increased gradually from September to November (LGS), reached its maximum value (44.39 mg m^{-2}), and then decreased gradually from April to June (SMS) to reach its minimum value (7.98 mg m^{-2}) in SMS (**Figure 3**B). The second peak (25.12 mg m^{-2}) of litter carbon input to the stream was observed in the GS (**Figure 3**B), and these values were all average of per period. For all streams, the litter carbon input to the streams ranged from 0.11 to 40.57 mg m^{-2}, and the annual value was 8.61 mg m^{-2} for all streams in this one-year investigation.

5. Litter and Litter Carbon Output from the Stream

The dynamic pattern of litter output from the stream also showed a similar pattern to that of the input. The maximum value (1.69 g m^{-2}) appeared in the LGS, and then the value decreased gradually, reaching the minimum value in the SMS (0.46 g m^{-2}). The second peak (1.72 g m^{-2}) was observed in the EGS (**Figure 4**A), and these values were all average of per period. The litter output from the all streams ranged from 0.02 to 22.30 g m^{-2}, and the annual average value was 0.56 g m^{-2} during this one-year investigation.

7. Yue, K.; Yang, W.Q.; Peng, C.H.; Peng, Y.; Zhang, Z.; Huang, C.P.; Tan, Y.; Wu, F.Z. Foliar litter decomposition in an alpine forest meta-ecosystem on the eastern Tibetan Plateau. Sci. Total Environ. 2016, 566, 279–287.
8. Coûteaux, M.M.; Bottner, P.; Berg, B. Litter decomposition, climate, and liter quality. Trends Ecol. Evol. 1995, 10, 63–66.
9. Abril, M.; Muñoz, I.; Menéndez, M. Heterogeneity in leaf litter decomposition in a temporary Mediterranean stream during flow fragmentation. Sci. Total Environ. 2016, 553, 330–339.
10. Ferreira, V.; Canhoto, C. Future increase in temperature may stimulate litter decomposition in temperate mountain streams: Evidence from a stream manipulation experiment. Freshw. Biol. 2015, 60, 881–892.
11. Berg, B.; Meentemeyer, V. Litterfall in some European coniferous forests as dependent on climate: A synthesis. Can. J. For. Res. 2001, 31, 292–301.
12. Louzada, J.N.C.; Schoereder, J.H.; Marco, J.P. Litter decomposition in semideciduous forest and Eucalyptus spp. crop in Brazil: A comparison. For. Ecol. Manag. 1997, 94, 31–36.
13. Bachega, L.R.; Bouillet, J.P.; Piccolo, M.C.; Saint-André, L.; Bouvet, J.M.; Nouvellon, Y.; Goncalves, J.L.M.; Robin, A.; Laclau, J.P. Decomposition of Eucalyptus grandis and Acacia mangium leaves and fine roots in tropical conditions did not meet the home field advantage hypothesis. For. Ecol. Manag. 2016, 359, 33–43.
14. Cornwell, W.K.; Cornelissen, J.H.C.; Amatangelo, K.; Dorrepaal, E.; Eviner, V.T.; Godoy, O.; Hobbie, S.E.; Hoorens, B.; Kurokawa, H.; Pérez-Harguindeguy, N.; et al. Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. Ecol. Lett. 2008, 11, 1065–1071.
15. Wei, X.; Yang, Y.; Shen, Y.; Chen, Z.; Dong, Y.; Wu, F.; Zhang, L. Litter production and its dynamic pattern in a dark coniferous forest in the alpine gorge region. Chin. J. Appl. Environ. Biol. 2017, 23, 745–752.
16. Guo, J.; Yu, L.H.; Fang, X.; Xiang, W.H.; Deng, X.W.; Lu, X. Litter production and turnover in four types of subtropical forests in China. Acta Ecol. Sin. 2015, 35, 4668–4677.
17. Rueda-Delgado, G.; Wantzen, K.M.; Tolosa, M.B. Leaf-litter decomposition in an Amazonian floodplain stream: Effects of seasonal hydrological changes. J. N. Am. Benthol. Soc. 2006, 25, 233–249.
18. Taylor, B.R.; Chauvet, E.E. Relative influence of shredders and fungi on leaf litter decomposition along a river altitudinal gradient. Hydrobiologia 2014, 721, 239–250.
19. Tiegs, S.D.; Akinwole, P.O.; Gessner, M.O. Litter decomposition across multiple spatial scales in stream networks. Oecologia 2009, 161, 343–351.

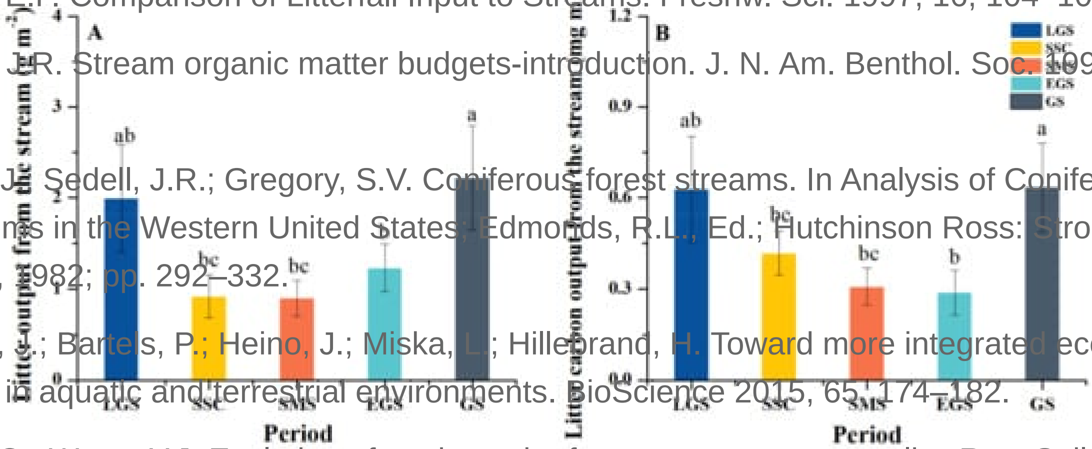

Figure 4. Dynamics of litter (**A**) and litter carbon (**B**) output from the subalpine forest streams in the upper reaches of the Yangtze River from 11 July 2015 to 2 August 2016. LGS, SSC, SMS, EGS and GS indicate the sampling periods, i.e., later growing season (LGS: September to October), seasonal snow cover (SSC: November to April next year), snowmelt season (SMS: April to May), early growing season (EGS: May to June), and growing season (GS: July to August). The vertical coordinate is the mean of litter input accumulation of 15 streams during this period. Different lowercase letters indicate the significant difference among different periods ($p < 0.05$), while the same letter indicates no significant difference among each other.

Consistent with the pattern of litter input to the stream, the output of litter carbon from the streams also had two peaks (**Figure 4**B), which also appeared in the LGS (0.63 mg m^{-2}) and EGS (0.64 mg m^{-2}), and the lowest point was observed in the SMS (0.31 mg m^{-2}) (**Figure 4**B), and these values were all average of per period. Additionally, the litter carbon output from all streams ranged from 0.01 to 4.53 g m^{-2}, and the annual value was 0.45 g m^{-2} during this one-year investigation.

6. The Ratios of the Input to Output of Litter and Litter Carbon

During the investigated period, the average ratios of input to output of litter and litter carbon were 188.17 and 270.01 at the forest catchment level, respectively. The ratios of litter input to output ranged from 23.85 to 619.67 (**Figure 5**A), and the ratios of the input to output of litter carbon ranged from 16.80 to 1147.91 (**Figure 5**B). Meanwhile, the ratios of both litter input to output and litter carbon input to output showed similar dynamic patterns with the two peaks appearing in the LGS (272.74, 329.70) and EGS (190.46, 304.13), and the lowest point observed in the SMS (37.99, 67.11) for litter and litter carbon, respectively. Additionally, the ratios of input to output for both litter and litter carbon varied greatly with the investigated streams, and the averaged ratios of input to output ranged from 16.42 to 577.91 for litter (**Figure 6**A), and from 16.80 to 1147.91 for litter carbon, respectively (**Figure 6**B).

20. Benfield, E.F. Comparison of Litterfall Input to Streams. Freshw. Sci. 1997, 16, 104–108.
21. Webster, J.R. Stream organic matter budgets-introduction. J. N. Am. Benthol. Soc. 1997, 16, 2–13.
22. Triska, F.J.; Sedell, J.R.; Gregory, S.V. Coniferous forest streams. In Analysis of Coniferous Forest Ecosystems in the Western United States; Edmonds, R.L., Ed.; Hutchinson Ross: Stroudsburg, PA, USA, 1982; pp. 292–332.
23. Soininen, J.; Bartels, P.; Heino, J.; Miska, L.; Hillebrand, H. Toward more integrated ecosystem research in aquatic and terrestrial environments. BioScience 2015, 65, 174–182.
24. Wang, Y.Q.; Wang, Y.J. Evolution of study on the forest stream water quality. Res. Soil Water Conserv. 2004, 10, 242–246.
25. Bünemann, E.; Bossio, D.; Smithson, P.; Frossard, E.; Oberson, A. Microbial community composition and substrate use in a highly weathered soil as affected by crop rotation and P fertilization. Soil Biol. Biochem. 2004, 36, 889–901.
26. Perakis, S.S.; Hedin, L.O. Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds. Nature 2002, 415, 416–419.
27. Zhang, M.H.; Cheng, X.L.; Geng, Q.H.; Shi, Z.; Luo, Y.Q.; Xu, X. Leaf litter traits predominantly control litter decomposition in streams worldwide. Glob. Ecol. Biogeogr. 2019, 28, 1469–1486.
28. Baldy, V.; Gobert, V.; Guerold, F.; Chauvet, E.; Lambrigot, D.; Charcosset, J.Y. Leaf litter breakdown budgets in streams of various trophic status: Effects of dissolved inorganic nutrients on microorganisms and invertebrates. Freshw. Biol. 2007, 52, 1322–1335.
29. Leroy, C.J.; Whitham, T.G.; Keim, P.M.; Jane, C. Plant genes link forests and streams. Ecology 2006, 87, 255–261.
30. Zhang, Y.; Yang, W.Q.; Tan, B.; Liang, Z.Y.; Wu, F.Z. Storage and content of organic carbon in alpine forest stream in the upper reaches of the Yangtze River. Fresenius Environ. Bull. 2017, 26, 3402–3408.
31. Yuan, Z.Q.; Li, B.H.; Bai, X.J.; Lin, F.; Shi, S.; Ye, J.; Wang, X.G.; Hao, Z.Q. Composition and seasonal dynamics of litterfalls in a broad-leaved Korean pine (Pinus koraiensis) mixed forest in Changbai Mountains, Northeast China. Chin. J. Appl. Ecol. 2010, 21, 2171–2178.
32. Skalny, A.V. Bioelementology as an interdisciplinary integrative approach in life sciences: Terminology, classification, perspectives. J. Trace Elem. Med. Biol. 2011, 25, S3–S10.
33. Finlay, J.C. Controls of stream water dissolved inorganic carbon dynamics in a forested watershed. Biogeochemistry 2003, 62, 231–252.

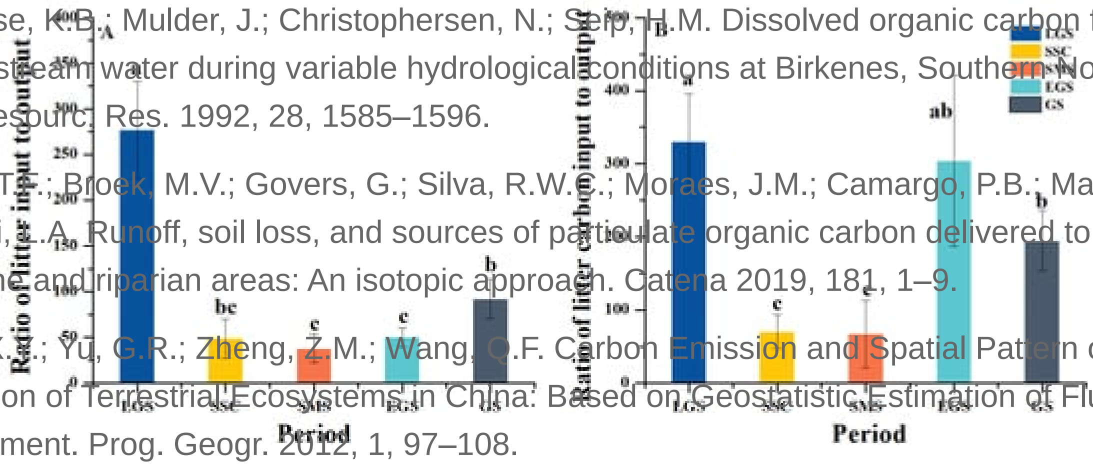

Figure 5. The ratios of input to output of litter (**A**) and litter carbon (**B**) in the subalpine forest streams in the upper reaches of the Yangtze River from 11 July 2015, to 2 August 2016. The value of each dot is the ratio of the average for the investigated streams during the sampling time. Different lowercase letters indicate the significant difference among different periods ($p < 0.05$), while the same letter indicates no significant difference among each other.

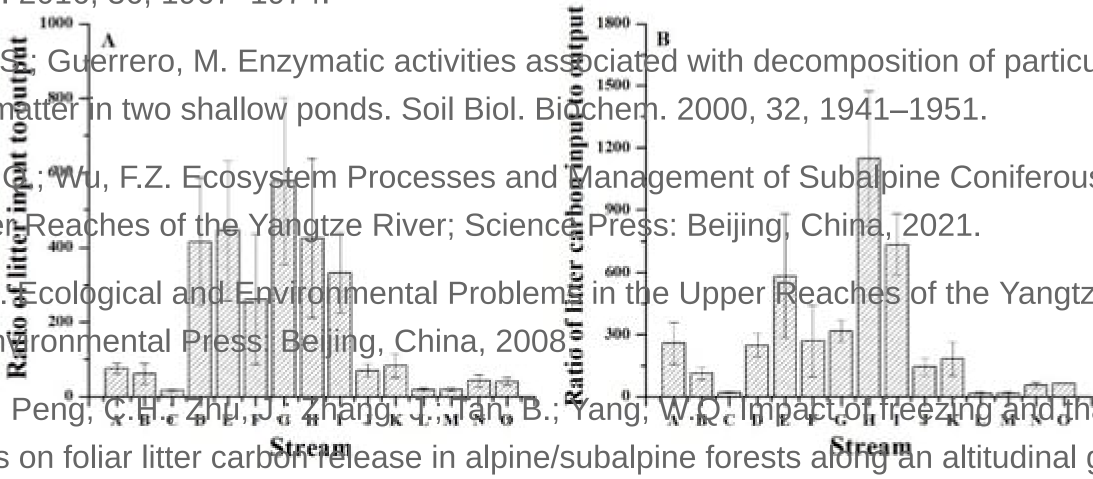

Figure 6. The ratios of input to output of litter (**A**) and litter carbon (**B**) in the subalpine forest streams in the upper reaches of the Yangtze River from 11 July 2015, to 2 August 2016. Each bar is the average of 13 sampling times for each forest stream. A–O are the sampled streams in the study.

34. Easthouse, K.B.; Mulder, J.; Christophersen, N.; Seip, H.M. Dissolved organic carbon fractions in soil and stream water during variable hydrological conditions at Birkenes, Southern Norway. Water Resourc. Res. 1992, 28, 1585–1596.

35. Gomes, T.F.; Broek, M.V.; Govers, G.; Silva, R.W.C.; Moraes, J.M.; Camargo, P.B.; Mazzi, E.A.; Martinelli, L.A. Runoff, soil loss, and sources of particulate organic carbon delivered to streams by sugarcane and riparian areas: An isotopic approach. Catena 2019, 181, 1–9.

36. Zhang, X.Z.; Yu, G.R.; Zheng, Z.M.; Wang, Q.F. Carbon Emission and Spatial Pattern of Soil Respiration of Terrestrial Ecosystems in China: Based on Geostatistic Estimation of Flux Measurement. Prog. Geogr. 2012, 1, 97–108.

37. Duan, L.; Zheng, W.; Li, M. Geologic hazards on the western Sichuan plateau and their controls. Sediment. Geol. Tethyan Geol. 2005, 25, 95–99.

38. Zhang, H.; Yang, W.Q.; Wang, M.; Liao, S. Carbon, nitrogen and phosphorus storage of woody debris in headwater streams in an alpine forest in upper reaches of the Mingjiang River. Acta Ecol. Sin. 2016, 36, 1967–1974.

39. Alvarez, S.; Guerrero, M. Enzymatic activities associated with decomposition of particulate organic matter in two shallow ponds. Soil Biol. Biochem. 2000, 32, 1941–1951.

40. Yang, W.Q.; Wu, F.Z. Ecosystem Processes and Management of Subalpine Coniferous Forest in the Upper Reaches of the Yangtze River; Science Press: Beijing, China, 2021.

41. Sun, H.L. Ecological and Environmental Problems in the Upper Reaches of the Yangtze River; China Environmental Press: Beijing, China, 2008.

42. Wu, F.Z.; Peng, C.H.; Zhu, J.; Zhang, J.; Tan, B.; Yang, W.Q. Impact of freezing and thawing dynamics on foliar litter carbon release in alpine/subalpine forests along an altitudinal gradient in the eastern Tibetan Plateau. Biogeosciences 2014, 11, 6471–6481.

43. Wu, F.Z.; Yang, W.Q.; Zhang, J.; Deng, R. Litter decomposition in two subalpine forests during the freeze–thaw season. Acta Oecol. 2010, 36, 135–140.