Precipitation controls on nutrient budgets in subtropical and tropical forests and the implications under changing climate

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ABSTRACT

Biological, geological and hydrological drivers collectively control forest biogeochemical cycling. However, based on a close examination of recent literature, we argue that the role of hydrological control particularly precipitation on nutrient budgets is significantly underestimated in subtropical and tropical forests, hindering our predictions of future forest nutrient status under a changing climate in these systems. To test this hypothesis, we analyzed two decades of monthly nutrient input and output data in precipitation and streamwater from a subtropical forested watershed in Taiwan, one of the few sites that has long-term nutrient input-output data in the tropics and subtropics. The results showed that monthly input and output of all ions and budgets (output – input) of most ions were positively correlated with precipitation quantity and there was a surprisingly greater net ion export during the wet growing season, indicating strong precipitation control on the nutrient budget. The strong precipitation control is also supported by the divergence of acidic precipitation and near neutral acidity of streamwater, with the former being independent from precipitation quantity but the latter being positively related to precipitation quantity. An additional synthesis of annual precipitation quantity and nutrient budgets of 32 forests across the globe showed a strong correlation between precipitation quantity and nutrient output-input budget, indicating that strong precipitation control is ubiquitous at the global scale and is particularly important in the humid tropical and subtropical forests. Our results imply that climate change could directly affect ecosystem nutrient cycling in the tropics through changes in precipitation pattern and amount.

Keywords: Biogeochemistry; Ecohydrology; Fushan Experimental Forest; Nutrient budget; Precipitation control; Tropical forests

1. Introduction

Nutrient cycling is a key ecosystem process that is closely linked to ecosystem structure and functions (Likens and Bormann, 1995). Elevated nitrogen availability through atmospheric deposition has been reported to reduce plant diversity in many ecosystems (Bobbink et al., 2010) and low nutrient availability associated with excessive water availability is considered to be the main factor constraining productivity in wet tropical forests (Schuur and Matson, 2001; Runyan et al. 2013). It has been demonstrated that strong biological control on nutrient cycling in forest systems is ubiquitous (Belillas and Rodá, 1991; Reynolds et al., 1991; Oyarzún et al., 2004; Homyak et al., 2014). Direct evidence of the role of biological control on nutrient cycling came from observations of the rapid decline of elevated nutrient concentrations in streamwater following forest re-vegetation after a disturbance. The nitrate concentration declined approximately 10% and 50% in the first and second year following revegetation at Watershed 2 at the Hubbard Brook Experimental Forest, which was one of the first watershed-scale manipulation experiments in the world (Likens and Bormann, 1995). Similar results have been supported by many subsequent studies (Vitousek, 1977; Reynolds et al., 1991; Fenn and Poth, 1999).

A number of later studies have also reported that precipitation (or streamflow) plays an important role in the control of export of nitrogen and dissolved organic carbon from forested watersheds (Fenn and Poth, 1999; Burt and Pinay, 2005; Goodale et al., 2009; Ohte, 2012; Duncan et al., 2015). It is not surprising that water is closely linked to biogeochemistry because water is the essential reactant, catalyst, or medium for many biogeochemical reactions (Wang et al., 2015). However, based on a close examination of results from work done in a range of humid tropical and subtropical forests (Bruijnzeel et al., 1993; Liu et al., 2003; Goller et al., 2006; Lu et al., 2011), which reported greater net loss of nutrients (output–input) not just input or output in the wet season than dry season, we argue the role of precipitation on nutrient cycling is significantly underestimated. If proven true, it will have important implications on how climate change may affect forest ecosystem dynamics in these systems. Many empirical studies and model projections indicate that a large part of the tropics and subtropics are likely to experience greater variability of precipitation and many countries around the western Pacific Ocean (especially northern Australia) and Indian Ocean (especially the India continent and East Africa) will have more precipitation in the wet season (Chou et al., 2013; Feng et al., 2013). Given the role we posit precipitation plays in controlling nutrient budgets, predicted shifts in precipitation quantity associated with climate change may have enormous effects on forest structure and function through alteration in the nutrient dynamics of the ecosystem. To explicitly test the hypothesis of strong precipitation control on nutrient budget and examine the underlying mechanisms, we analyzed two-decadal data (1994–2013) of nutrient input though bulk precipitation and output through streamwater at the Watershed 1 (WS1) of Fushan Experimental Forest (FEF) in northeastern Taiwan. We also synthesized annual nutrient budgets in relation to rainfall quantity for 32 forest sites across the globe to explore the role of precipitation control at a global scale.

2. Materials and methods

2.1. Study site

The FEF is located in northeastern Taiwan (24°34’N, 121°34’E) with an area of approximately 1000 ha (Fig. S1). It is a subtropical evergreen hardwood rainforest dominated by trees species in Lauraceae and Fagaceae family and characterized by high (4200 mm yr^{-1}) and frequent (> 220 days yr^{-1}) rainfall (Horng and Chang, 1996; Lin et al., 2011). Annual mean temperature of FEF is 18.2°C with the lowest in January (11.8°C) and highest in July (24.1°C) and annual mean relative humidity is 94% with the lowest in July (92%) and highest in February (95%). The 38 ha WS1 varies in elevation from 670 to 1100 m with a mean slope of 38% (Lin et al., 2011). The soil of WS1 is Typic Dystochrepts characterized as very acidic (pH 3.8–5.0) with low cation exchange capacity (19–25 cmol kg^{-1}) and very low base saturation (<2%) (Horng and Chang, 1996).

2.2. Bulk precipitation and streamwater sampling

Bulk precipitation was collected on an event basis between 1994 and 1996 and on a weekly basis thereafter using three pairs of collectors mounted on top of a 6-m tower in a forest clearing near the weir of WS1 (Fig. S1). Each pair, consisting of two 20-cm diameter funnels, was connected with polypropylene tubing to a 30-L plastic bucket on the ground (Lin et al., 1997). Each funnel had a 6 cm vertical lip and a 45° slope to minimize splashing. Streamwater was collected at a six-hour interval using an ISCO autosampler controlled by ISCO-3220 flow meter (ISCO Inc., Lincoln, NE, USA). Composite samples were taken weekly. Flow data was recorded using an ISCO-3220 flow meter (ISCO Inc., Lincoln, NE) measuring water level in a 90° V-notch weir. There were gaps in streamflow, especially between 2003 and 2005, mostly due to typhoon damages. The daily rainfall-streamflow relationship established using HBV (Hydrologiska Byråns Vattenavdelning) model (Nash-Sutcliffe efficiency> 0.75) (Nash and Sutcliffe, 1970; Seibert and Vis, 2012), was used to fill the streamflow gaps (approximately 14% of the data).

2.3. Throughfall and soil water sampling

Between November 2009 and October 2012, throughfall and soil solution were also collected on a weekly basis. Throughfall was collected in three 20 × 20 m plots located at the lower elevations (< 700 m) of the watershed (Fig. S1). Within each plot, six sets of throughfall collectors were constructed following a previous study at the same site (Lin et al., 1997, 2000). Each set consisted of three 20-cm diameter funnels 0.5 m apart and 1.5 m above the ground, kept level, arranged in a line connected to a 30-L bucket using polypropylene tubing. For soil solution collection, two sets of soil water collectors (Soilmoisture Equipment Corp. Santa Barbara, CA, USA) that were >10 m apart were installed within each throughfall collection plots. Each set had three lysimeters that sampled water at depths of 15, 30 and 60 cm. Each lysimeter has a ceramic cup epoxy bonded to PVC body (diameter 4.8 cm) and two ports on the top. One port is for the application of a vacuum or pressure and the other is for the delivery of collected water samples to the surface. The lysimeters were given a (negative) pressure at 0.05 Mpa one week prior to sampling (i.e., the pressure were applied after each sampling). The first sampling was taken three months after the installation of the lysimeters.

2.4. Chemical analyses and quality control

Water samples were kept in refrigerators at 4°C without preservatives prior to measurement. Conductivity and pH were measured on unfiltered samples. Two replicates of each filtered sample (Gelman Science GN-6 grid 0.45 μm sterilized filter paper) was analyzed for Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, and PO_4^{3-} using ion chromatography (Dionex Corp., Sunnyvale, CA) (Lin et al., 1997). Concentrations of PO_4^{3-} in precipitation were below or near the detection limit (0.5 μeq L^{-1}) and, thus, were not reported. The quality of the chemical data of water samples was checked using charge balance (i.e., [total cation charge – total anion charge]/[total cation charge + total anion charge]×100%). For both precipitation and streamwater if the imbalance is more than ± 20% the data was excluded from our analysis (Clow and Mast, 1999; Herckes et al., 2002). Following this criterion, 2.9% of the precipitation samples and 1.0% of the streamwater samples were excluded from the analysis. In terms of the water quantity not included in the analysis, it is 1.9% for precipitation and 1.1% for streamwater.

2.5. Data synthesis

In our global synthesis of nutrient input-output budgets along the latitude and annual precipitation gradients, we searched major academic databases including Thomson Reuters Web of Science and Google Scholar. The keywords used in our searches included "(acid) precipitation, and streamwater chemistry", "(acid) deposition, and streamwater chemistry", "nutrient, input, and output (or export)", "nutrient budget", and "nutrient cycling". Over 600 articles were downloaded and checked. We kept only those that analyzed the chemistry of all major cations (H^+, Na^+, K^+, NH_4^+, Mg^{2+}, Ca^{2+}) and anions (Cl^-, NO_3^-, SO_4^{2-}) for both "precipitation" and "streamwater" for at least one complete year. For studies spanning more than one year, the averages were used. Thirty-two studies met the criteria (Table S1) and were classified into six types based on their geographical location (latitude and elevation) including six climate types, boreal (latitude > 55°, *n* = 2), temperate (latitude: 40°–55°, *n* = 12), low elevation subtropical (latitude: 23.5°–40°; elevation < 1000 m, *n* = 7), high elevation subtropical (latitude: 23.5°–40°; elevation > 1000 m, *n* = 5), low elevation tropical (latitude < 23.5°; elevation < 1000 m, *n* = 4) and high elevation tropical (latitude < 23.5°; elevation > 1000 m, *n* = 2) (Table S1, Fig. S2). Data from the 32 studies were extracted and/or re-calculated to derive annual precipitation, annual VWM (volume-weighted mean) pH of precipitation and streamwater and an annual nutrient budget (output–input) (kg ha^{-1} yr^{-1}) of inorganic nitrogen (NO_3^- + NH_4^+) and base cations (Na^+ + K^+ + Mg^{2+} + Ca^{2+}). We re-calculated 13 sites that had volume-weighted mean concentrations and quantity of precipitation but no fluxes. Then, linear regression models were developed to explore the relationships between annual precipitation amount and annual VWM pH, streamwater pH, inorganic nitrogen budget as well as base cations budget under different climate types. The statistical significance level was set at $P < 0.05$.

3. Results

3.1. Precipitation quantity and nutrient input-output budget

The monthly input and output flux of all ions through bulk precipitation was positively correlated with rainfall quantity (Table 1). There were also positive correlations between monthly rainfall quantity and the input-output budget of all ions (i.e., lower retention or greater loss associated with higher rainfall) except H^+ and NH_4^+, and Cl^- (Table 1). The monthly input-output budget of H^+ and NH_4^+ were negatively correlated with rainfall, and that of Cl^- was not correlated to rainfall (Table 1). There were similar patterns between ion input, output and budget and rainfall quantity at the annual scale but only a few of them were statistically significant due to the small sample size (n = 20) (Table 1). Net export (output–input) of inorganic nitrogen (NH_4^+ + NO_3^-) and all other ions except Cl^- was higher in the wet warm season (growing season) than the relatively drier season at the FEF (Fig. 1).

Based on a synthesis of 32 studies across the globe, annual budgets (output–input) of inorganic nitrogen and base cations were positively correlated to rainfall quantity (Fig. 2(a) and (b)) across a very wide latitudinal range (0–59°, Table S1, Fig. S2). However, the patterns were largely driven by the results from tropical and subtropical sites because when analyzed for individual climate regions, only the patterns for the tropical and subtropical sites were significant (Fig. 2(a) and (b)).

3.2. Divergence of precipitation and streamwater acidity

There was a striking divergence in acidity between precipitation and streamwater over the two decades at FEF (Fig. 3(a)). The precipitation was acidic with 90% of the annual VWM pH being less than 5.0 (the criteria of acid rain) whereas the two decadal VWM pH was 4.63. However, streamwater showed no sign of acidification with the two decadal annual VWM pH of 6.95 (ranging from 6.6 to 7.5) (Fig. 3(a)).

The results from the global synthesis revealed that high precipitation acidity (i.e., low pH) was common worldwide and was independent of precipitation quantity (Fig. 2(c)). However, the pH of streamflow is positively correlated with precipitation quantity (Fig. 2(d)). The pattern is also largely driven by the results from tropical and subtropical sites because when analyzed for individual climate regions, only the patterns for the tropical and subtropical sites were significant (Fig. 2(c)). Notably, at the five forest sites that had annual precipitation greater than 2800 mm, streamwater pHs were always greater than 6.5 (Fig. 2(d)).

3.3. Change in water pH in relation to base cations

Water pH (± 1 standard deviation) increased from 4.6 (± 0.62) in precipitation to 5.2 (± 0.48) in throughfall in association with the enrichment in total base cations (Na^{+}+K^{+}+Ca^{2+}+Mg^{2+}) from 67 to 126 μeq L^{-1} at the FEF (Fig. 3(b) and (c)). Using the sodium ratio estimation method, the dry deposition at FEF was approximately 28% of bulk precipitation (Lin et al., 2000) or 24 μeq L^{-1} for all base cations combined. Thus, the rest (i.e., 35 μeq L^{-1}) of the enrichment (59 μeq L^{-1}) of base cations in throughfall relative to precipitation was from cation exchange with the canopy. There was little change in total base cation concentration from throughfall to soil solution and the pH was low in soil solution (Fig. 3(b)). Using the HBV model, the estimated contribution of groundwater to streamflow was approximately 40% during storm periods and 80% during rainless periods (Fig. S4).

4. Discussion

The positive correlation between water quantity and ion input via precipitation or output via streamwater is not surprising because water is the main vector of ion movement. However, to our knowledge, we are the first to report that the input-output budget is driven by precipitation quantity. The finding is of great significance because it means as water quantity increases the increase in ion output is greater than ion input and as such, changes in rainfall quantity resulting from climate change many lead to greater nutrient losses. We also show that the budgets for all the major ions (except PO_4^{3-} and Cl^-), not just nitrogen, are controlled by water quantity. In terms of the three exceptions, H^+ was negatively correlated with rainfall as it was retained by the watershed, NH_4^+ was negatively correlated with rainfall likely due to the very low level of NH_4^+ in streamwater resulting from nitrification (Table 1), and Cl^- was not correlated to rainfall because it was considered a conservative ion that by-passes the system with a net budget of near zero (Lovett et al., 2005).

The precipitation control over nutrient budgets was also supported by the greater net export of nitrogen and most ions in the wet warm season (growing season) than the relatively drier season. The change from net retention in the relatively drier months to net loss in the wetter months for inorganic nitrogen and to a lesser degree for potassium, two of the three elements that are in highest biological demand, is of particular importance. Greater net nitrogen export through streamwater in the growing season has been reported for many forest ecosystems (Ohrui and Mitchell, 1997; Goller et al., 2006; Yusop et al., 2006). Possible explanations include the warm and humid condition being favorable for nitrification, and high soil moisture and high runoff activating NO_3^- transport and discharge from soil to the drainage system (Goodale et al., 2009; Ohte, 2012).

The global pattern of positive correlation between the annual budget (output–input) of inorganic nitrogen and base cations and precipitation quantity across the very wide latitudinal range supports the strong and widespread precipitation control on a nutrient budget. The results from our watershed study and the data synthesis do not undermine the role of biological control (e.g., the input-output budget of NH_4^+ was clearly influenced by microbial transformation). However, our long-term empirical data in combination with global synthesis data clearly illustrate that the role of precipitation control on nutrient budgets, both nitrogen and other major ions, are much larger than previously realized.

The divergence in the acidity of precipitation and streamwater is in contrast to many reports from the temperate region in which acidification of precipitation was followed by acidification of streamwater (Driscoll et al., 1980; Herlihy et al., 1993; Likens et al., 1996; Nakahara et al., 2010). Cation exchange and weathering of base cations are two important processes that could buffer acid inputs in streams. The effect of cation exchange on buffering acid input is clearly illustrated in higher pH of throughfall (5.2) than precipitation (4.6) in association with the increase in base cations at the FEF. Part of the increases in total base cation from precipitation to throughfall was from dry deposition that was not collected by the bulk precipitation collectors. However, the little change in total base cation concentration from throughfall to soil solution and the low pH of soil solution (Fig. 3(b) and (c)) reflects the overall low cation exchange capacity of the soils at the FEF. Thus, cation exchange occurring in the soil cannot explain the near neutral acidity and high base cation content (480 μeq L^{-1}) of streamwater at FEF. The high contribution of groundwater to streamflow suggest that the observed higher pH and base cation concentration in streamwater compared to precipitation, throughfall and soil solution was most likely the result of the constant exchange of cations between groundwater and streamwater. The contribution of groundwater on neutralizing acidity is supported by a study of groundwater chemistry of storm events (11–350 mm) which reported that base cation concentration in groundwater was 455–634 μeq L^{-1} and the pH was 6.43–6.74 (Cheng, 2000).

The important role of precipitation in regulating nutrient budgets has vital implications for ecosystems experiencing the effects of climate change. Based on a synthesis of 125 studies on recent changes and projections of future changes in precipitation, the wet-gets-wetter and dry-gets-drier scenarios and increases in rainfall intensity or extreme rainfall events in wet summer and decreases in dry winter-spring were generally supported at a global scale (Table S2). This pattern is also applicable to Taiwan in which the wetter northern Taiwan (where the FEF is located) has been reported and projected to become wetter, especially in the wet season, while the drier southern Taiwan is becoming drier, especially in the dry season (Table S2). Increases in atmospheric CO_2 concentrations may enhance plant growth and thereby increase nutrient retention via uptake (Lewis et al., 2009; Keenan et al., 2013; Forkel et al., 2016). However, the response of the vegetation may be limited due to nutrient losses associated with higher rainfall in wet regions. Although increases in precipitation could also increase nutrient input, the positive relationship between rainfall quantity and nutrient input-output budget (or net loss of nutrients) at the FEF and a variety of forests across the globe showed that there will be a disproportionally higher export of nutrients. Previous studies have shown that there was a disproportionally higher export of nitrate and base cations during heavy storms (Lin et al., 2011; Chang et al., 2013). As a consequence, the system switched from a nitrogen balanced stage during base flow periods to net loss stage during heavy storms, and the system had greater net losses of base cations during heavy storms (Chang et al., 2013; Huang et al., 2016). Nutrient cation content is, in general, negatively related to precipitation and soil acidity (James et al., 2016). Given the low cation exchange capacity (19–25 cmol kg^{-1}) and very low base saturation (< 2%) of the FEF (Horng and Chang, 1996) and many tropical and subtropical forests, enhanced leaching loss of nutrient cations may lead to further acidification of the already acidic soils and the depletion of nutrient cations. This in turn could negatively affect net primary production and, therefore, carbon sequestration.

5. Conclusions

Our long-term monitoring of nutrient input and output and a global synthesis indicate that nutrient budgets are all under strong precipitation control and such control is widespread. Many studies projected increases in rainfall quantity and intensity in wet regions that already have low soil pH and nutrient cations. The positive relationship between precipitation and the nutrient budget (output–input) indicates that ecosystems in wet regions such as the humid tropical and subtropical forests may experience even greater losses of critical nutrients. The consequences of such changes in nutrient budget on net primary productivity deserve more attentions. Our results also highlight the importance of recognizing the isolation of the soil-vegetation system from the streamwater system in which the rock weathering cannot replenish the loss of nutrient cations from the soils that might be common in many humid tropical and subtropical forests.

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Table 1

Correlations between ion flux through rainfall input and streamflow output (kg ha^{-1}) and budget (output–input) and precipitation (mm) at monthly and annual scales at Fushan Experimental Forest during 1994–2013.

	Input		Output		Budget	
	Monthly	Annual	Monthly	Annual	Monthly	Annual
H^+	0.35**	0.18	0.57**	0.38	–0.38**	–0.40
SO_4^{2-}	0.54**	0.61**	0.60**	0.53*	0.67**	0.34
NO_3^-	0.24**	0.28	0.58**	0.24	0.66**	0.29
Cl^-	0.65**	0.43	0.61**	0.53*	0.08	0.34
Na^+	0.66**	0.30	0.68**	0.56*	0.64**	0.52*
NH_4^+	0.32**	0.37	0.23**	–0.21	–0.25**	–0.62**
K^+	0.50**	0.25	0.68**	0.42	0.52**	0.12
Mg^{2+}	0.50**	0.33	0.67**	0.54*	0.76**	0.51*
Ca^{2+}	0.51**	0.30	0.62**	0.51*	0.75**	0.52*

* and ** indicate significant with two-tailed test at P-value < 0.05 and < 0.01, respectively.

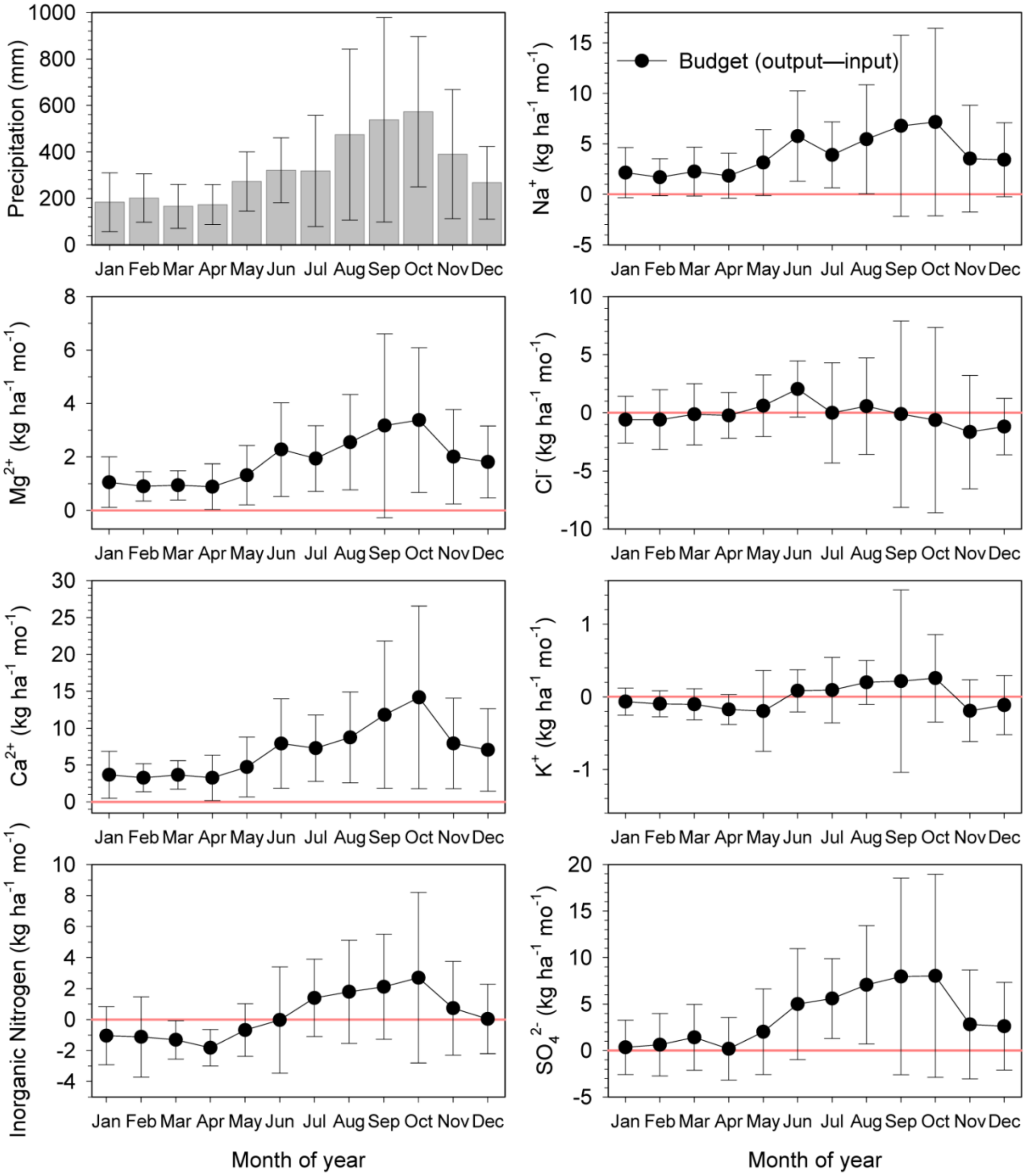

Fig. 1. Mean monthly nutrient budget (output through streamwater – input via bulk precipitation) at the Fushan Experimental Forest between 1994 and 2013. Error bars indicate one standard deviation. Note that there were no significant temporal trends in annual/seasonal precipitation during the study period.

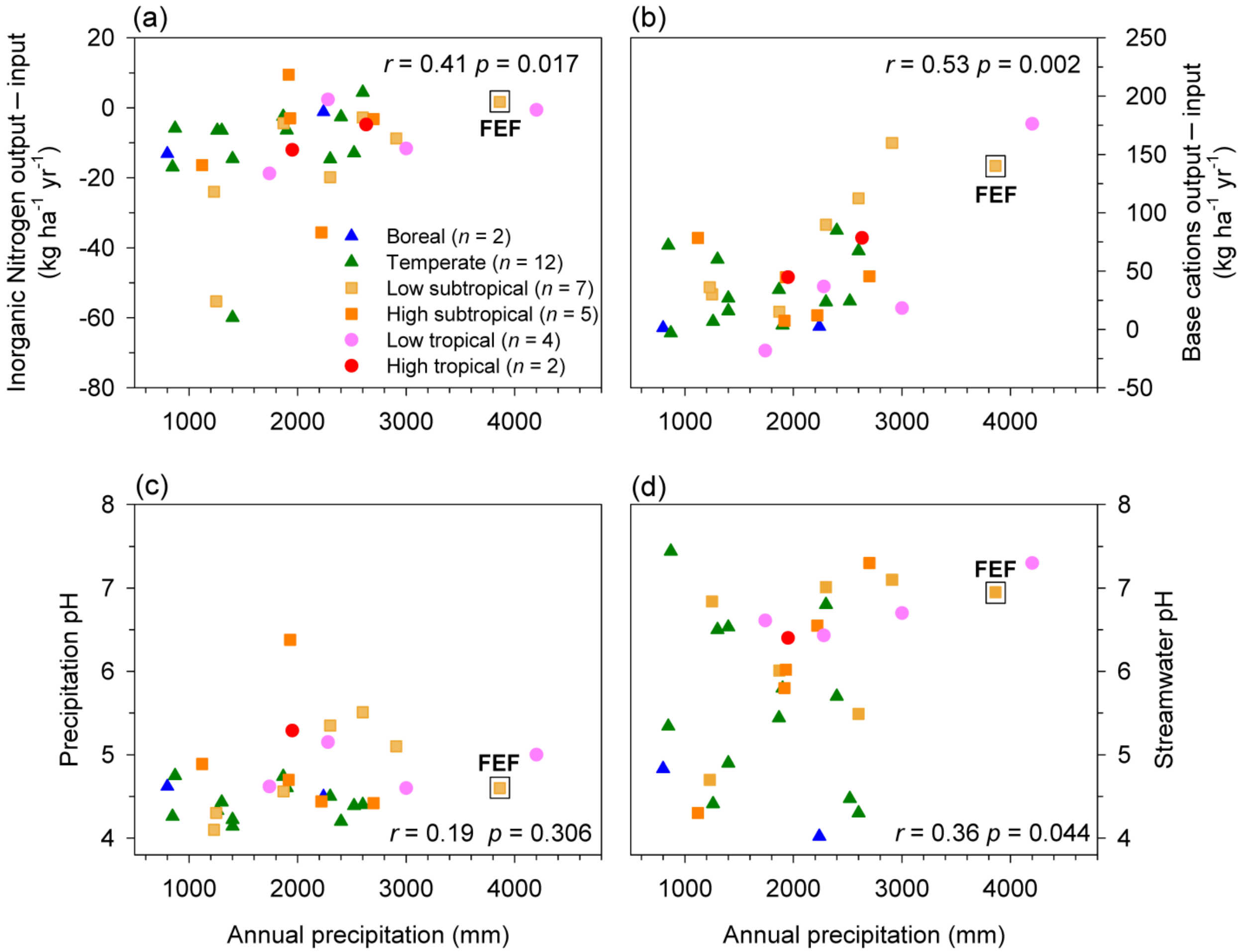

Fig. 2. Relationship between annual precipitation and net ecosystem budget (output–input). (a) Relationship between annual precipitation and inorganic nitrogen ($NH_4^+ + NO_3^-$). (b) Relationship between annual precipitation and total base cations (i.e., $Na^+ + K^+ + Ca^{2+} + Mg^{2+}$). (c) Relationship between annual precipitation and pH of precipitation. (d) Relationship between annual precipitation and pH of streamwater. The data is from our synthesis based on studies from 32 forests in which chemistry of both precipitation and streamwater are available (see Table S1 for the detailed information of the 32 forests).

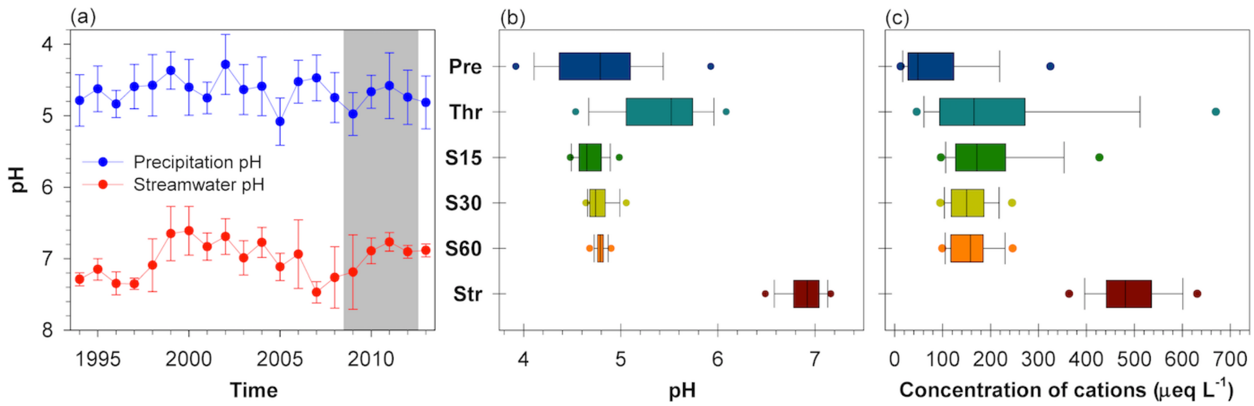

Fig. 3. (a) The annual volume weighted mean (VWM) pH of precipitation and streamwater during 1994–2013 (with 2009–2012 shaded in gray). Error bars indicate one standard deviation. (b) Changes in pH, and (c) concentration of total base cations (Na^+ + K^+ + Ca^{2+} + Mg^{2+}) along the hydrological path at the Fushan Experimental Forest. The components include precipitation (Pre), throughfall (Thr), soil water in depths of 15 cm (S15), 30 cm (S30), and 60 cm (S60), and streamwater (Str) between 2009 and 2012. Note that there are no differences in annual/seasonal precipitation patterns between the four shaded years (2009–2012) and the full 20-year dataset (Fig. S3).

Highlights

1. Precipitation exerts strong control on nutrient budgets (output–input) in tropics

2. Acidity diverges between precipitation (acidic) and streamwater (neutral)

3. Climate change may largely affect nutrient cycling through altering precipitation regime

Summary statement for “Short Communication” in AWR

Through analysis of 20-yr data from a subtropical forest and a global synthesis of 32 forest sites, we report strong precipitation control not only on nutrient input and output (which is not surprising because water is the main vector of nutrient movement) but also on the nutrient budget. The results suggest that climate change could have major impact on nutrient cycling through altering precipitation regime.

Precipitation controls on nutrient budget in subtropical and tropical forests and the implications under changing climate

Supplementary Materials

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Table S1 The detailed information of the 32 forest sites in Fig. 2

Sites (Reference)	Location (Elevation, m)	Tree species		Sampling Period
		Coniferous	Hardwood/deciduous	
Pedra Preta, Brazil (1)	0°5' N, 51°5' W (200)		Undisturbed rainforest	1993–1994
Loja, Ecuador (2)	4°0' S, 79°1' W (320)		Lauraceae, Rubiaceae, Melastomataceae, Euphorbiaceae,	2004–2005
Mull, Jamaica (3)	18°1' N, 76°4' W (1809)		Alchornea latifolia, Chaetocarpus globosus, Clethra occidentalis	1995
Luquillo, Puerto Rico (4)	18°2' N, 64°5' W (390)		Dacryodes excelsa Vahl	1984–1985
Cunha-Indaiá, Brazil (5)	23°1' S, 45°5' W (1050)		Sebastiania commersoniana, Lithraea brasiliensis, Zanthoxylum rhoifolium, Myrcia sp.	2000–2002
Liu Xi He, China (6)	23°3' N, 133°4' E (500)		Cunninghamia lanceolata	2001–2003
Guandaushi, Taiwan (7)	23°4' N, 120°5' E (1200)		Helicia formosana, Litsea acuminate	1995–1997

Leinhuachi, Taiwan (8)	23°5’ N, 120°5’ E (760)	Cunninghamia lanceolata		2005–2010
Xujiaba, China (9)	24°1’ N, 101°1’ E (2500)		Lithocarpus xylocarpus Markg, Castanopsis wattii A. Camus	1998–1999
Fushan, Taiwan (This study)	24°3’ N, 121°3’ E (680)		Cryptocarya chniesis, Diospyros morrisiana, Engelhardtia roxburghiana	1994–2013
Lei Gong Shan, China (6)	26°2’ N, 108°1’ E (1700)	Pinus massioniana		2001–2003
Liu Chon Guang, China (6)	26°4’ N, 106°4’ E (1300)	Pinus massioniana		2001–2003
Caj Jia Tang, China (6)	27°5’ N, 112°3’ E (480)	Pinus massioniana		2001–2003
Tie Shan Ping, China (6)	29°4’ N, 104°4’ E (470)	Pinus massioniana		2001–2003
Kawai, Japan (10)	33°2’ N, 132°5’ E (700)	Cryptomeria japonica, Chamaecyparis obtuse, Pinus densiflora		1996–2004

Table S1 Continued.

Sites (Reference)	Location (Elevation, m)	Tree species		Sampling Period
		Coniferous	Hardwood/deciduous	
Coweeta, USA (11)	35°0’ N, 83°2’ W (350)		Quercus prinus, Quercus rubra, Quercus alba, Quercus velutina	1972–1983
Great Smoky Mt, USA (12)	35°3’ N, 83°2’ W (1750)	Pices rubens		1991–2006
Kajikawa, Japan (13)	37°5’ N, 139°2’ E (100)	Cryptomeria japonica D Don.		2003–2006
Montseny, Spain (14)	41°5’ N, 2°2’ E (1275)		Holm-oak	1984–1986
Cone pond, USA (15)	43°5’ N, 71°4’ W (550)		Fagus grandifolia, Betula alleghaniensis, Acer	1992–1994
HBEF, USA (16)	43°5’ N, 71°5’ W (750)		Fagus grandifoia Ehrh., Acer saccharum Marsh., Betula alleghaniensis Britt.	1963–2009
HJ Andrews, USA (17)	44°1’ N, 122°2’ W (500)	Pseudotsuga menziesii (Mirb.) Franco		1973–1975
Mont Lozere, France (18)	44°2’ N, 3°5’ E (1250)		Fagus sylvatica	1981–1985
Sleepers River, USA (15)	44°2’ N, 72°0’ W (620)		Fagus grandifolia, Betula alleghaniensis, Acer	1992–1994

Schluchsee, Germany (19)	47°5’ N, 8°1’ E (1200)	Picea abies		1988–1998
Strengbach, France (20)	48°1’ N, 7°1’ E (1000)	Picea abies Karst, Abies alba Mill	Fagus sylvatica L.	1989–1990
Haney, Canada (21)	49°2’ N, 122°3’ W (300)	Tsuga heterophylla, Thuja plicata, Pseudotsuga menziesii		1971–1972
Krusne hory, Czech (22)	50°3’ N, 13°1’ E (700)	Picea abies, Larix decidua		1983–1997
Afon Hore, UK (23)	52°1’ N, 2°5’ W (550)	Picea abies, Picea sitchensis, Pinus cntoria, Larix kaempferi		1984–1990
Beddgelert, UK (24)	53°0’ N, 4°1’ W (330)	Picea sitchensis (Bong.) Carr.		1983–1984
Kelty, UK (25)	56°0’ N, 4°2’ W (250)	Picea sitchensis		1985–1987
Kindla, Sweden (26)	59°5’ N, 14°5’ E (350)	Picea abies		1997

Table S2 The current developments and projections of global patterns of precipitation. The table was created via the synthesis of articles published in the field of "Meteorology & Atmospheric Sciences (84 journals)" in the Thomson Reuters Web of Science. The keywords used in the search contained "global precipitation", "global pattern of precipitation", and "trend of precipitation in America (Europe, Asia, Africa or Australia)". Over 500 studies were downloaded and examined, and only studies focused on global or continental scale were kept. We organized the results by the geographical regions, including global scale (wet and dry regions), temperate, wet subtropical and dry subtropical, and tropical regions in both North and South Hemisphere. We focused on the annual and seasonal precipitation amount, precipitation intensity, and extreme events (but it was not defined in most studies). We also searched for the articles about trend and/or projection of precipitation in Taiwan. In total, 125 related studies were used to create the table.

	Precipitation			Seasonal rainfall, heavy or extreme events			
	Amount	Intensity	Heavy/Extreme	Spring	Summer	Autumn	Winter
Global	Δ[27–31] ↓[32] ↑[30,33]	↑[34,35]	↑[36] ↑[34,37]	↓[31,38]	↑[38]	↑[38]	↓[38]
Wet regions	↑[39–42] ↑[43,44]	↑[45]	↑[46,47]				
Dry regions	↓[39–41] ↓[43]		↓[46]				

North Hemisphere							
Boreal	Δ[48] ↑[49–51] ↑[49,52,53]	↑[54]	Δ[55] ↑[54,56–58]		↑[59] ↑[60]	↑[61]	↑[62] ↑[60,61,63–65]
Temperate	Δ[48] ↑[49,50,66,67] ↑[49,52,68]	Δ[69] ↑[45] ↑[54,70,71]	Δ[72] ↓[73] ↑[54,57,66,74–82] ↑[83,84]	↑[85] ↑[86–88]	↑[89] ↓[60,90–92] ↑[86,93–95]	↓[85] ↑[86,88]	↑[62,67,85,96] ↑[71,87,88,92,94] ↓[60]
Wet Subtropics	Δ[51,97] ↑[66,98–100] ↑[98–101] ↓[53]	↑[102] ↑[70]	Δ[72] ↑[73,74,79,80,102–105] ↑[79,83,97,104,106–108]	↑[85] ↓[109]	↑[109] ↑[90,93,95,110] ↓[65]	↓[85]	↑[85] ↓[109] ↓[71,110]
Dry Subtropics	Δ[51,111] ↑[112,113] ↓[66,9,100,114,115] ↓[52,53,99,100,106,116–118]	↑[119] ↑[70]	Δ[72] ↓[81] ↑[75,79,120] ↑[79,83,108,120]		↓[121] ↑[122]	↑[122]	
Tropics	Δ[123] ↑[50,115,124–127] ↓[128] ↓[52,128]	↑[127] ↑[70]	↑[129,130] ↑[83,108,131]	↓[132]	↑[133] ↓[134] ↑[110,135] ↓[136]		↑[137,132] ↓[110]
South Hemisphere							
Boreal							
Temperate	↑[52]				↓[138]		
Wet Subtropics	Δ[51] ↑[52,101,139] ↓[53]	↑[45] ↑[70]	Δ[72] ↑[140]		↑[138]	↓[141]	↓[141]
Dry Subtropics	Δ[51] ↓[50,98,115,142] ↓[53,98,118,143]	↑[144]	Δ[72]		↑[138] ↓[145]		
Tropics	↑[115,124] ↑[52]	↑[70,144]	Δ[72]		↑[146]		

Taiwan		↑[147]	↓[148] ↓[148]	↑[148,149] ↑[148,149]	↓[148] ↓[148]
North	↑[150,151] ↑[150]				
South	↓[150] ↓[150]				

The subtropics are divided into wet and dry sub-categories. The dry subtopics include subtropical deserts and semi-arid regions and wet subtropics includes central-south China, south of Japan, south of America, south-east South America, south-east Australia (152). The pink (↓) and red (↓) arrows indicated that there are declining trends of precipitation from observed and projected results. The cyan (↑) and blue (↑) arrows indicated that there are increasing trends of precipitation from observed and projected results respectively. The gray (Δ) and black triangle (**Δ**) suggested that there were no significant trends of observed and projected simulations.

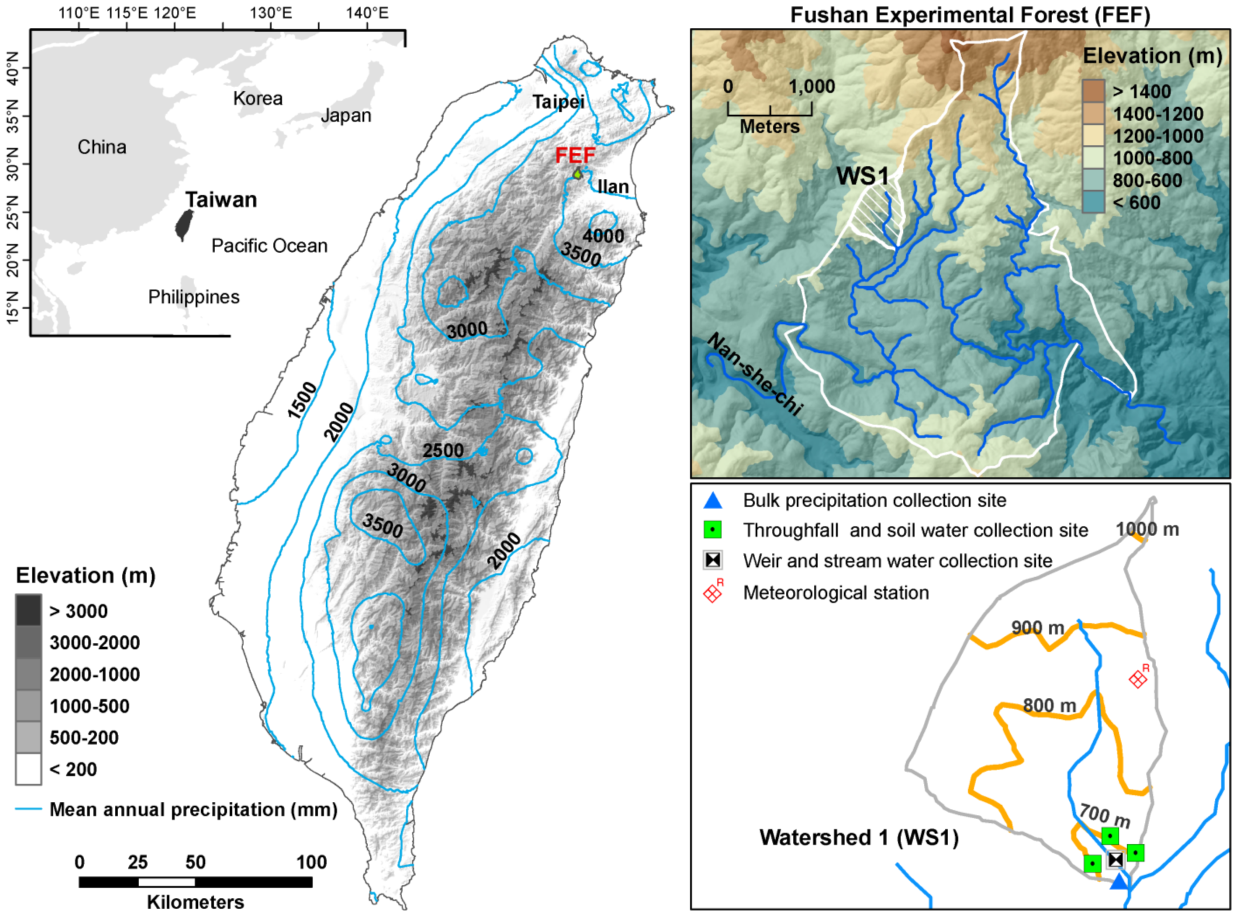

Fig. S1. The geographical location map of Fushan Experimental Forest (FEF) and sampling sites in watershed one (WS1).

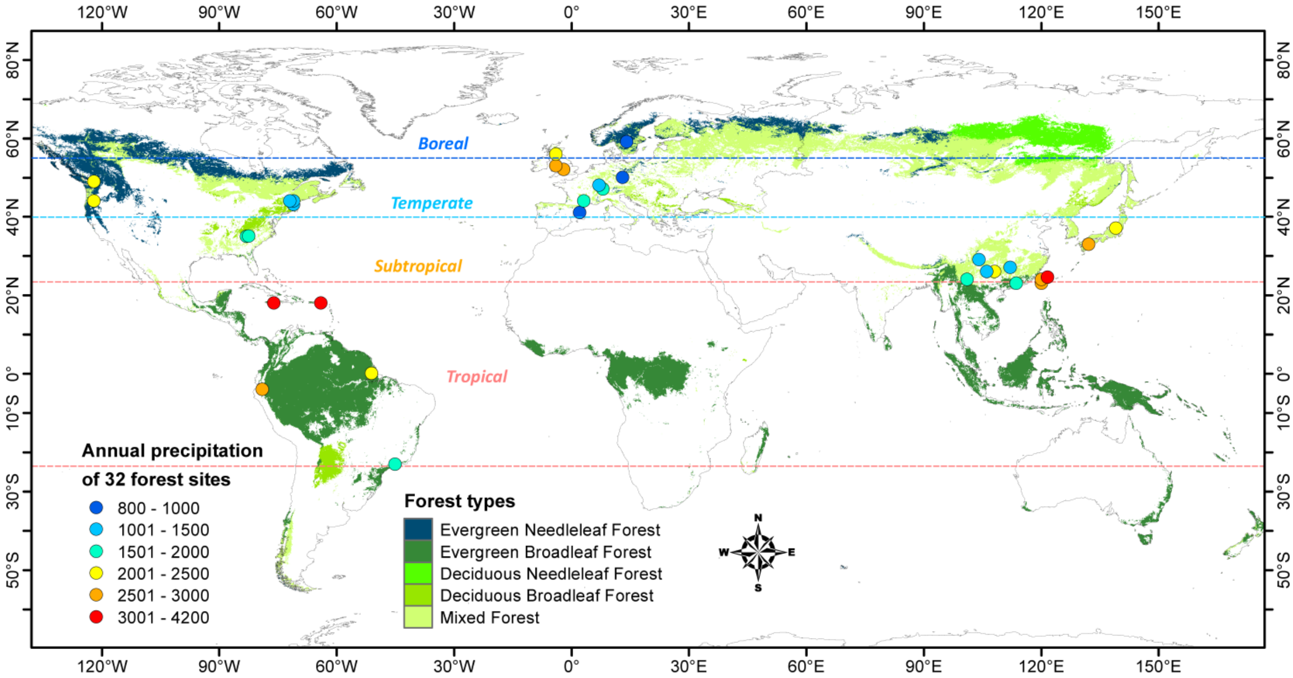

Fig. S2. Distribution, forest type and precipitation of the 32 forest sites in Figure 2 and Table S1. (Source of forest types in background: Global Land Cover Facility: www.landcover.org) (153).

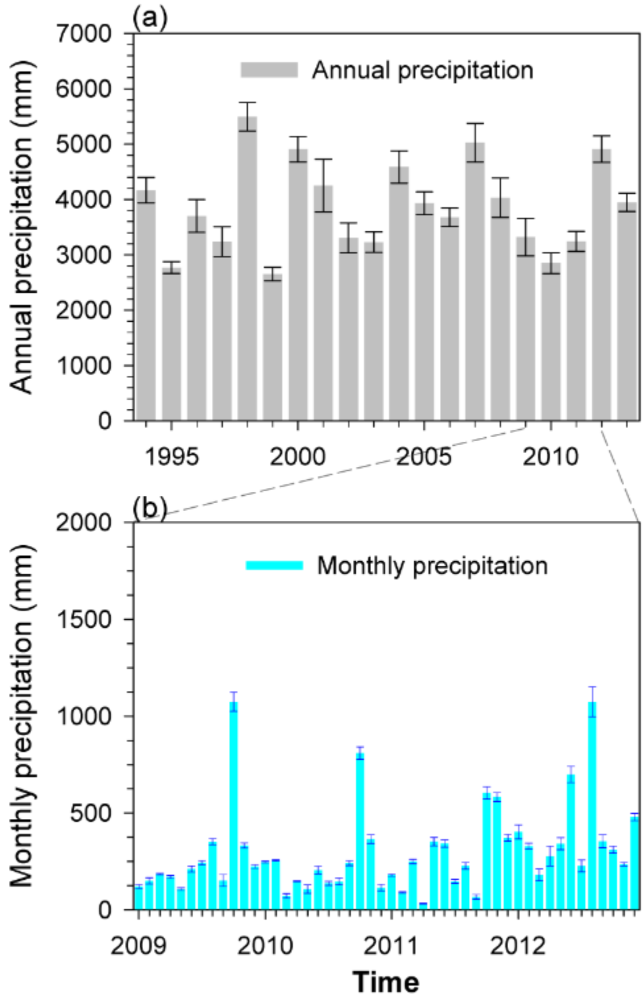

Fig. S3. Annual precipitation during 1994–2013 and monthly precipitation during 2009–2012 at the Fushan Experimental Forest. Error bars indicate one standard deviation.

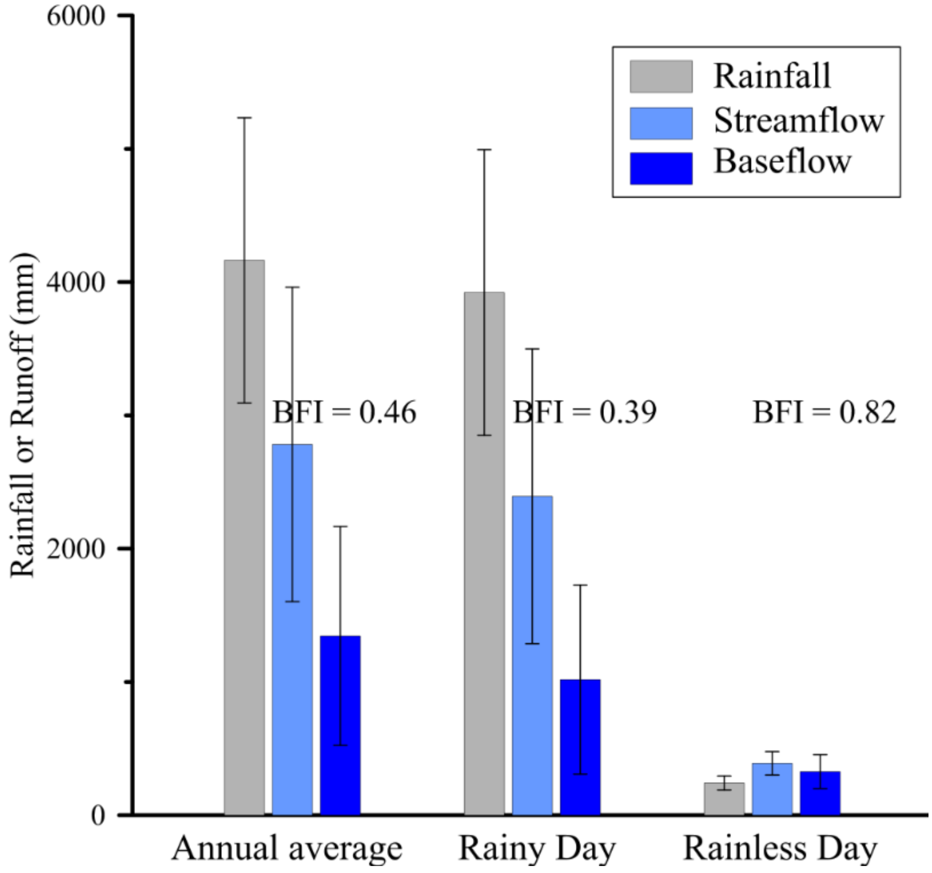

Fig. S4. Estimated annual contribution of base flow (i.e., groundwater) input (BFI) to streamflow (i.e., through groundwater recharge) during rainy days and rainless days. The result was derived from a hydrological model (HBV-2) (154) using data from seven years (1995, 1996, 1998, 2007, 2008, 2010 and 2011). In the analysis, rainy days were defined as a successive raining period with the amount of rain over 10 mm. Error bars indicate one standard deviation.

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