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Discussions

Impacts of tropical cyclones on hydrochemistry of a subtropical forest

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Abstract

Tropical cyclones (typhoons/hurricanes) have major impacts on the biogeochemistry of forest ecosystems, but the stochastic nature and the long intervals between storms means that there are limited data on their effects. We characterized the impacts of 14 typhoons over six years on hydrochemistry of a subtropical forest plantation in Taiwan, a region experiencing frequent typhoons. Typhoons contributed 1/3 of annual rainfall on average, but ranged from 4 % to 55 %. The stochastic nature of annual typhoon related precipitation poses a challenge with respect to managing the impacts of these extreme events. This challenge is exacerbated by the fact that typhoon-related rainfall is not significantly correlated with wind velocity, the current focus of weather forecasts. Thus little advance warning is provided for the hydrological impacts of these storms.

The typhoons we studied contributed approximately one third of the annual input and output of most nutrients (except nitrogen) during an average 9.5 $\mathrm{d\,yr^{-1}}$ period, resulting in nutrient input/output rates an order of magnitude greater than during non-typhoon period. Nitrate output balanced input during the non-typhoon period, but during the typhoon period an average of 10 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ nitrate was lost. Streamwater chemistry exhibited similarly high variability during typhoon and non-typhoon periods and returned to pre-typhoon levels one to three weeks following each typhoon. The streamwater chemistry appears to be very resilient in response to typhoons, resulting in minimal loss of nutrients.

1 Introduction

Tropical cyclones (hurricanes and typhoons) are known to have major and even catastrophic effects on ecosystem structure and function. Although some have suggested that inclusion of rainfall into to the classification of storm intensity would be useful (Scatena and Larsen, 1991), historically tropical cyclones have been classified exclusively by barometric pressure and the wind velocity at the center of the cyclone. The

Saffir-Simpson Hurricane Scale uses the speed of sustained winds to classify hurricanes into five intensity categories and is the most commonly used predictor of potential damage and flooding resulting from hurricanes (Simpson and Riehl, 1981; NWS, 2009). It is assumed that tropical cyclones with higher winds have greater potential to cause damage (Bell et al., 2000; Powell and Reinhold, 2007).

Forest ecosystem damage caused by uprooting, bole-snapping, and defoliation has been shown to be directly related to wind velocity (Everham and Brokaw, 1996; Cook and Goyens, 2008). Yet, at wind-speeds below site and tree species specific thresholds damages can be minimal (Lin et al., 2003; Ancelin et al., 2004). In a study of wind-induced failure of Sitka spruce, velocities $> 30\,\mathrm{m\,s^{-1}}$ caused stem breakage in un-thinned 52 yr-old stands (Moore and Quine, 2000). In a subtropical rainforest in northeastern Taiwan, typhoons with maximum wind velocities $> 51\,\mathrm{m\,s^{-1}}$ accounted for 83 % of the inter-annual variation in litterfall and those with lower wind speeds accounted for none of the observed variability using a regression model (Lin et al., 2003).

In spite of the wind-induced damage associated with tropical cyclones, heavy rains associated with cyclones often have greater impacts on human and natural systems. For example, the 56 deaths and up to $6 billion in property damage caused by the 1999 category 2 hurricane Floyd in the US was mainly due to extensive flooding (Atallah and Bosart, 2003). The more than 400 deaths caused by the 2009 typhoon Morakot in southern Taiwan was a result of severe landslides and debris flows induced by the nearly 3000 mm of precipitation over just three days (Tsou et al., 2011; C. W. Lin et al., 2011). Forest systems also show a strong relationship between the severity of storm induced damage and rainfall quantity (Scatena and Larsen, 1991; West et al., 2011). Saturated soils resulting from high amounts of rainfall have been suggested as a major cause of increased tree mortality during hurricane disturbances in Virginia, North Carolina, northeastern United States and Australia (Trousdell et al., 1965; Cremer, 1977; Foster, 1988). Although landslides, massive tree falls, and debris flows can be catastrophic when they occur, such disasters are localized in impact compared to the much larger area experiencing heavy rainfall during a tropical cyclone event. Even if the heavy rainfall does not cause catastrophic damages, it might cause major shifts in regional hydrology and biogeochemistry. Dramatic shifts in streamwater chemistry during and following tropical cyclones have been observed in Puerto Rico and Taiwan (Wang et al., 1998; Schaefer et al., 2000; Tsai et al., 2009). The annual export of K^+, NO_3^- and NH_4^+ in the year following hurricane Hugo (1989) increased more than 100 % and the effect was greater than that caused by canopy gaps and selective cutting (Schaefer et al., 2000; McDowell, 2001; Beard et al., 2005). Despite the potential impacts that cyclone-induced rains might have on ecosystem biogeochemistry, few studies have explored these impacts.

The fact that human-induced global climate change is projected to increase climate extremes, e.g. drought, flooding, heat weaves and the intensity of tropical cyclones, is of growing concern. The lack of empirical data on the effects of tropical cyclones on hydrology and nutrient cycling limits our understanding of the potential effects of climate change on ecosystem structure and function.

Understanding the effects of tropical cyclones on ecosystem biogeochemistry and hydrology requires having a good understanding of streamwater patterns, which in turn requires long-term data. Yet, the unpredictability, in space and time, of tropical cyclones has resulted in a limited amount of empirical data on the effects of tropical cyclones on ecosystem hydrochemistry. Without confidence that tropical cyclones will impact a site on a regular basis, it is difficult to justify the effort required to collect long-term data, except at maybe a few sites, in the hope that a tropical cyclone will impact the site.

Given that differences in site and cyclone characteristics affect the comparability of ecosystem responses among sites, it is difficult to assemble a large enough data set capable of providing useful models of the impacts of typhoons/hurricanes on hydrochemical and physiological processes (Everham and Brokaw, 1996; Hornbeck et al., 1997; Lin et al., 2003; Likens and Buso, 2006; Feller, 2010). Further compounding this challenge is the fact that, data from a single or even a couple of tropical cyclones at a single site may not capture the full range of ecosystem responses and elucidate the underlying mechanisms, even at that site. Currently, much of our understanding of the effects of tropical cyclones on ecosystem biogeochemistry comes from studies of a few tropical cyclones, e.g. 1989 hurricane Hugo in central America (Schaefer et al., 2000; Heartsill-Scalley et al., 2007), 1938 hurricane in northeast USA (Foster et al., 1997; Aber et al., 2002), 2005 hurricane Katrina in southeast USA (Chambers et al., 2007; Shiller et al., 2012), 2006 tropical cyclones Monica and Larry in Australia (Gleason et al., 2008; Wallace et al., 2009). Examining cyclone-ecosystem interactions with data from numerous tropical cyclones impacting the same site has the potential to provide a critical and comprehensive window on ecosystem impacts that is currently lacking. Taiwan, 36 000 km^2, is an ideal location to study the effects of typical cyclones on forest ecosystems as there are, on average, three to six typhoons making landfall annually (T. C. Lin et al., 2011). Every year a large proportion of Taiwan experiences heavy rainfall caused by typhoons, thus most forests on the island experience the influence of typhoons on a regular basis. Several studies have examined the hydrochemical responses to typhoon disturbance in Taiwan, but most report the influences of only a single typhoon (Wang et al., 1998, 1999; Tsai et al., 2009).

Here we present a study on the effects of 14 typhoons on hydrochemical cycling in a first-order gauged forested watershed between 2005 and 2010, the largest such study of its kind. Our objectives were to (1) quantify the influence of typhoons on water and nutrient input and output budgets, and (2) characterize the effects of typhoons on temporal variation of streamwater chemistry and its post-typhoon recovery.

2 Material and methods

2.1 Study site

The study was conducted at Watershed #4 (W4, 5.9 ha) of the 460 ha Lienhuachi Experimental Forest (120° 54′ E, 23° 54′ N) in central Taiwan (Fig. 1). Two hundred and sixty ha of the Experimental Forest are natural hardwood forests, the only such remaining forests in the central Taiwan's lowlands (Hwong et al., 2002), dominated by

Fagaceae and Lauraceae tree species. The vegetation on the remaining 200 ha of the Experimental Forest is largely monoculture conifer plantations (Hwong et al., 2002). The mean annual precipitation is 2200 mm, and mean annual temperature is 20.8 °C, lowest in January at 14.9 °C and highest in July at 25.4 °C (1961 to 1998 averages; Lu et al., 2000). There is a distinctive dry season between October and February with mean precipitation of 230 mm or approximately 10 % of the annual precipitation (Lu et al., 2000).

Prior to 1978, the entire Lienhuachi Experimental Forest could be characterized as natural evergreen hardwood forest, with anthropogenic disturbances limited to small-scale selective logging and bamboo plantations. W4 was clear-cut from November 1978 to March 1979 using skyline logging (Koh et al., 1978) after which the natural regeneration was periodically cut until 1981 when it was planted with *Cunninghamia lanceolata*. *C. lanceolata* is a native conifer widely grown in low elevations of south-eastern China and Taiwan. The planting was carried out using standard protocols for the period, herbaceous plants and shrubs were removed followed by mechanical site preparation (leveling and litter removal), and one-year old 30 cm seedlings were planted at 2400 trees ha^{-1} using 2 m × 2 m spacing. Between 1982 and 1985 weeds were cut several times a year and new seedlings planted to replace those that died. In 1986 suppressed, damaged or poor-growth trees were cut, resulting in a density of 1000–1200 trees ha^{-1}. There has been no management of the watershed since 1986.

In 1967 a 90° V-notch weir was constructed directly on top of the sandstone and shale bedrock. The watershed is assumed to be watertight based on the small difference between streamflow measurements at the weir (1971–1975), 1190 mm yr^{-1} and streamflow derived from subtracting calculated evapotranspiration, from rainfall (1961–1996), 1020 mm yr^{-1} (Hwong et al., 2002). Stilling pond water levels were recorded using a Submersible Pressure Transmitter (PS98i Instrumentation Northwest, Kirland, WA) and flow rates calculated from an empirically validated stage-discharge curve (Hsiao et al., 2007). There is year around streamflow, but the frequent heavy storms, particularly typhoons, cause data gaps due to sediment filling the stilling pond. During the 2005–2010 study period we have complete streamflow data from 2008 and 2009.

2.2 Methods

The Central Weather Bureau of Taiwan issued warnings for a total of 35 typhoons between 2005 and 2010. Even when the path of a typhoon was distant from Lienhuachi Experimental Forest, the storm's air mass often brought additional rainfall. We considered precipitation typhoon-induced if there was > 50 mm of precipitation during the period between the first and last warnings for a specific typhoon issued by the Central Weather Bureau of Taiwan. Because changes in streamflow lag rainfall in W4 by only a couple hours we also defined typhoon-induced stream flow as the flow occurred between the first and last warnings. For example, following typhoon Norris (1980) which brought a total of 390 mm rainfall, the amount of streamflow returned to pre-typhoon level five hours after the rain stopped (Liaw et al., 1998). Similarly, following typhoon Talim (2005) which brought a total of 200 mm rainfall, the amount of streamflow returned to the very low pre-storm levels five hours after the rain stopped (Tsai et al., 2009). Precipitation resulting from southwestly airflow associated with typhoons that had already passed Taiwan was not included in our study, as these winds led to heavy storm warnings not typhoon warnings. Thus, typhoon-induced rainfall and streamflow reported in our study are minimum estimates.

Between 2005 and 2010 weekly precipitation samples were collected 2 km from the watershed using a wet-only collector (Modified Anderson wet-dry collector with a polypropylene bucket – diameter 29.7 cm, height 26.8 cm – a metal lid covers the bucket when it is not raining). Weekly streamwater samples were collected manually above the stilling pond in the natural stream immediately following collection of precipitation samples. We did not collect precipitation samples in November and December 2006 and there were no stream water samples collected between October 2006 and February 2007 (there were no typhoons during this period). All water samples were collected in 250 mL, acid-washed, polyethylene bottles, and immediately stored at 4 °C without preservatives. The pH and conductivity were measured on unfiltered samples in an on-site laboratory. The precipitation samples went to National Central University for chemical analysis and streamwater samples went to Endemic Species Research Institute in Nantou for chemical analysis. Samples were stored at 4 °C prior to analysis. Filtered samples (Gelman Science GN-6 grid 0.45 µm sterilized filter paper) were analyzed for major anions and cations using Dionex 4000 ion chromatographs (Dionex Crop., Sunnyvale, CA) following King and Yang (1984) and Wang et al. (1998).

Ion concentrations were multiplied by the quaintly of rainfall and streamflow to calculate ion fluxes on a weekly basis. The weekly sampling did not allow us to directly characterize typhoon-induced precipitation and streamflow, as typhoon-induced rainfall and streamflow typically lasted less than a week and thus some non-typhoon induced rainfall and stream water was included to varying degrees in the weekly samples. Three typhoons spanned two weekly samples. The contribution of typhoon-induced nutrient input and output in each of the two weeks was calculated by multiplying the weekly concentration by the amount of typhoon-induced precipitation/streamflow falling in the respective week. The contributions in both weeks were added together to give the total contribution of the typhoon.

For the few months when samples were not acquired due to logistical problems, monthly mean concentration values were used from the same month in the other years for which there were data. This monthly average approach was used to generate 2.7 % of rainfall and 6.9 % of streamflow data over the six years. The two streamwater samples with NH_4^+ concentrations more than an order of magnitude higher than all other samples were considered outliers and not included in the analysis. These two streamwater samples represented < 1 % of the annual streamflow and thus their exclusion had no discernable influence on the quantity or patterns of NH_4^+ output.

3 Results

The number of typhoons observed per year ranged from one in 2009 and 2010 to four in 2008 with a six-year average of 2.3 typhoons yr^{-1} (Table 1). Twelve typhoons occurred between mid-July and mid-September, one in late September and one in early October.

Weekly rainfall varied from 0 mm to 820 mm and both extremes occurred between 2008 and 2009 for which there was uninterrupted streamflow data. Using 2008 and 2009 data we determined the relationship between weekly precipitation and weekly stream discharge ($Y = 9.91 + 0.33X + 5.00X^2 + 0.20X^3 - 0.36 \times 10^{-4}X^4 + 1.6 \times 10^{-7}X^5$, both in mm, $R^2 = 0.93$, $p < 0.001$, Fig. 2a). During 2008 and 2009 weekly discharge ranged from 0.01 mm to 400 mm, encompassing the full range of observations between 2005 and 2010. Based on the strength of this relationship we used weekly precipitation to calculate weekly stream discharge.

3.1 Typhoon rainfall and streamflow characteristics

The 14 typhoon storms brought 5370 mm precipitation or 1/3 of the total rainfall over an average of 9.5 $\text{d}\,\text{yr}^{-1}$ (Table 1). There was very high inter-annual variation in typhoon-induced rainfall in terms of absolute quantity (Fig. 2b) and the proportion of the annual rainfall with 4 % (76 mm) in 2010 and 55 % (2140 mm) in 2008. The intensity of both the rain and wind of the typhoons observed also varied considerably (Table 1). The 2008 typhoon Sinlaku had 960 mm rainfall, with a daily maximum of 500 $\text{mm}\,\text{d}^{-1}$, the highest of the 14 typhoons. Typhoon Kalmaegi (2008) had a maximum hourly rainfall of 96 $\text{mm}\,\text{h}^{-1}$ the highest among the 14 typhoons and a total rainfall of 480 mm. In contrast the 2010 typhoon Fanapi had the lowest hourly and daily maximum rainfall rates, 13 $\text{mm}\,\text{h}^{-1}$ and 28 $\text{mm}\,\text{d}^{-1}$, respectively (Table 1).

The total typhoon storm runoff was 3300 mm or 31 % of total streamflow during the six-year period. The mean annual runoff ratio was 0.60 ± 0.03 (mean ± standard error) over the entire six year period and did not differ between typhoon periods (0.55 ± 0.03) and non-typhoon periods (0.63 ± 0.07) (paired-t test, $t = -1.69$, $p = 0.15$). Interannual variation in the contribution of typhoon-induced runoff was comparable to the variation in typhoon-induced rainfall ranging from 3.1 % (2010) to 58 % (2008). In three of the six years the highest monthly rainfall and four of the six years the highest monthly streamflow was associated with typhoons (Fig. 2b). September 2008 had the highest monthly rainfall (1520 mm) and streamflow (930 mm) during the 6-yr record with 1440 mm of the rainfall and 860 mm of the streamflow contributed by two typhoons.

The maximum wind velocity of the 14 typhoons was not significantly correlated with any of the three key precipitation parameters: total rainfall, maximum hourly rainfall and maximum daily rainfall ($r = -0.17$ to -0.24, $p = 0.42$–0.57).

3.2 Typhoon influence on streamwater chemistry

There was a clear wet-dry season variation in ion concentrations in streamwater (Fig. 3). Most ions (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}) had significantly higher concentrations in the dry season than the wet season ($F = 3.02$–23.3, all p values < 0.05) whereas NO_3^- had higher concentrations in the wet season ($F = 36.7$, $p < 0.001$). The wet-dry season pattern of ion concentration at least partly resulted from the differences in flow rate. The weekly concentration of all ions except NO_3^- was negatively related to flow rate and the relationship was significant for Na^+, Ca^{2+}, Mg^{2+} and SO_4^{2-} (logarithm regression models, $R^2 = 0.04$–0.20, all p values < 0.01). The concentration of NO_3^- was positively and significantly related to flow rate (logarithm regression models, $R^2 = 0.10$, $p < 0.01$).

Typhoon induced fluctuation of ion concentration in stream water was barely observable on a monthly scale (Fig. 3). At a weekly scale, typhoon storms clearly resulted in very high flows for short periods of time and they caused major, but short-lived, changes in stream water ion concentrations (Fig. 4). Ion concentrations varied considerably among typhoons. Except for NO_3^-, the concentrations of all analyzed ions decreased dramatically in streamwater during each typhoon-affected week, but returned to pre-typhoon levels within one to a few weeks (Fig. 4) indicating very high resilience of streamwater chemistry to typhoon disturbance. The concentration of NO_3^- increased considerably during the typhoon-affected week, but also returned to pre-typhoon levels in one to a few weeks (Fig. 4). The greatest fluctuations among all ions during the 6 yr were during non-typhoon periods (Fig. 3).

3.3 Contribution to nutrient balances

Mean proportional contribution of typhoon storms to hydrological inputs was not statistically different from the input of ions (paired-*t* tests, all p values > 0.10, Table 2) except for NH_4^+ and NO_3^-, which are largely of anthropogenic origin. The input of NO_3^- and NH_4^+ via typhoon-induced rainfall was proportionally less than non-typhoon precipitation (18 % for both, paired-*t* test $p = 0.08$ for NH_4^+ and $p = 0.01$ for NO_3^-) suggesting that typhoon air masses are relatively "clean" with much less anthropogenic contamination. The dilution effect caused by the "clean" air masses is evident from the tight negative relationship between the quantity of typhoon rainfall and concentrations of NO_3^- ($R^2 = 0.55$, $p < 0.001$; Fig. 5a) and NH_4^+ ($R^2 = 0.47$, $p < 0.001$; Fig. 5b). Proportional contribution of typhoons to the annual stream discharge (31 %) relative to ion output was not different (26–37 %, paired-*t* tests, p values > 0.10, Table 2) except for H^+ and Ca^{2+}. Proportionally more H^+ (26 %) and less Ca^{2+} (20 %) were exported during typhoon periods (one-tail paired-*t* test both p values < 0.01, Table 2).

Differences in the output: input ratio between typhoon and non-typhoon periods can be used to evaluate typhoon impacts on ecosystem level retention/export of nutrients. The mean annual output: input ratio did not differ between typhoon and non-typhoon periods for all ions examined (paired-*t* test p values > 0.15) except for NO_3^- indicating that typhoons did not change the ion export pattern. For NO_3^-, the output: input ratio was consistently and significantly greater during typhoon periods than non-typhoon periods (Fig. 6; one tail paired-*t* test, $p = 0.035$). The mean annual output: input ratio of NO_3^- during non-typhoon period was 0.95 and was not significantly different from one (one sample t test $t = -0.23$, $p = 0.83$). However, during typhoons the output: input ratio was consistently and considerably greater than 1 (one sample t test $t = 4.24$, $p = 0.008$; Fig. 6) with a mean ratio of 3.1 and a loss as high as 31 kg ha^{-1} month^{-1} NO_3^--N (or 1 kg ha^{-1} d^{-1}) during the two-month typhoon period between 2005 and 2010 (Table 2). The amount of NO_3^- output during the typhoon periods can be predicted by streamflow ($R^2 = 0.64$, $p < 0.001$; Fig. 5c) suggesting that leaching largely determines NO_3^- loses.

4 Discussion

4.1 The need for rainfall to be included in the cyclone impact forecasting system

The lack of a significant correlation between wind velocity and rainfall associated with typhoons indicates that the Saffir-Simpson wind-velocity based classification system is not very useful for predicting the influence of tropical cyclones on ecosystem hydrochemistry. Because the flooding associated with tropical cyclones often causes more property and ecosystem damage than do high winds (Trousdell et al., 1965; Cremer, 1977; Foster, 1988; Atallah and Bosart, 2003; C. W. Lin et al., 2011; Tsou et al., 2011; West et al., 2011), a storm rating system that includes rainfall would be far more useful in preparing for, and understanding, the impacts of tropical cyclones on human and natural systems.

4.2 Variation in typhoon-induced rainfall and streamflow

In the absence of typhoons mean annual precipitation and stream runoff would both be about 1/3 less in central Taiwan. Because the typhoon season in central and southern Taiwan is followed by a dry period, typhoons most likely mitigate drought stress, as the soil is fully saturated at the beginning of the dry season. This effect is of great ecological importance because early spring, following the dry period is the period of new leaf growth and increasing evapotranspiration. This is also the time for planting rice and a soil water deficit would negatively impact plant growth. However, the annual contribution of typhoons to rainfall and stream runoff is highly variable ($< 5\,\%$ to $> 50\,\%$) and stochastic. The high inter-annual variability in typhoon caused recharge of ground water highlights the importance of developing water resource management plans that take this stochasticity in cyclone-induced rainfall into consideration. Increases in climate extremes, including shifts in tropical cyclone intensity as suggested by several studies (Webster et al., 2005; Knuston et al., 2010), can realistically be expected to increase variability in cyclone-induced rainfall, making water resource management even more challenging.

4.3 Nutrient cycling during typhoon and non-typhoon periods are quantitatively and qualitatively different

The similar proportional contribution of typhoons to the input and output of water and most ions suggests that the influence of typhoons on nutrient input and output could be accurately estimated by the amount of water they contribute. However, the flux of water and ions are very different between typhoon and non-typhoon periods, with typhoons contributing approximately 30 % of water and most ions to the larger landscape over a roughly two-month period of the six-year period. On average the flux rates of water and most ions into and out of the watershed were an order of magnitude greater during the two-month typhoon period than the fifty-month non-typhoon period between 2005 and 2010.

Unlike other ions, patterns of NO_3^- input and output were different between typhoon and non-typhoon periods. The forest was a NO_3^- balanced system during non-typhoon period but lost a large amount of NO_3^- during typhoon period based on hydrological inputs and outputs. Because nitrogen is a macro-essential nutrient with very high biological demand the loss of, on average, $10\,\mathrm{kg\,ha^{-1}\,yr^{-1}}$ NO_3^--N during the typhoon period ($9.5\,\mathrm{d\,yr^{-1}}$) could be important as it accounts for more than 1/4 of the annual output occurring at an average rate of 1 kg ha^{-1} d^{-1} NO_3^--N. Some of the NO_3^- lost was directly from precipitation input but not all. Although frequent typhoon disturbance with high rainfall is characteristic to our study site high concentrations of nitrogen in atmospheric input did not occur until the late 20th century, when Taiwan began to experience rapid industrialization. Prior to industrialization, NO_3^- deposition via precipitation in Lienhuachi was likely to be < 7 kg ha^{-1} yr^{-1} which is the current deposition rate measured in high elevation forests in central Taiwan, areas largely uninfluenced by local industrial activities (Ding et al., 2011). The NO_3^- loss resulting from soil and foliar leaching during typhoon periods might be enhanced as a result of recent anthropogenic activities, which could lead to higher foliar and soil N content (Pitcairn et al., 1998, Lovett and Rueth, 1999), and could have adverse effects on down stream ecosystems and water uses. Nitrogen pulses following fertilization and snowmelt have been shown to negatively affect water quality of municipal wells and groundwater (Exner et al., 1991; Ohte et al., 2004). Although we did not analyzed PO_4^{3-} concentrations, a study in northeastern Taiwan indicates that more than 20 % of dissolved phosphorus and 60 % of particulate phosphorus output in streamwater occurred during typhoon periods (Wang et al., 2001). Such typhoon-induced pulses of the most common limiting nutrients (i.e. N and P) are likely to affect down stream primary productivity, but to our knowledge has not been examined.

Increased NO_3^- concentrations during high flow periods are typically attributed to enhanced leaching from foliage and litterfall (Fenn et al., 1998; Balestrini et al., 2006). Although typhoons do not cause high tree mortality in Taiwan, defoliation is common (T. C. Lin et al., 2011). In northeastern Taiwan canopy leaf area index dropped as much as 2/3 following six typhoons in 1994 (T. C. Lin et al., 2011) and in the current study site it dropped 20 % following typhoon Haitang in 2005 (Chen et al., 2007). Because typhoons are unpredictable there is likely little retranslocation before the leaves fall as a result of high winds. Thus, leaching from these relatively nutrient-rich leaflitter could be substantial and led to high levels of NO_3^- export during typhoons. This implies that typhoon disturbances fundamentally alter the forest ecosystem to a more open (leaky) system. It is important to evaluate how climate induced changes in tropical cyclone frequency and intensity (Webster et al., 2005; Knuston et al., 2010), might affect ecosystem biogeochemistry.

4.4 Ecosystem resilience and resistance

The dramatic fluctuation in ions concentration before and after typhoons indicates that the typhoons greatly impact streamwater chemistry but the fluctuations are short-lived, lasting only a few weeks at most. In this regard, streamwater chemistry at the Lienhuachi Experimental Forest is highly resilient to typhoon disturbance. Although the fluctuations were dramatic they were not greater than the fluctuations during non-typhoon periods. Given that annual peak flows usually occur during typhoons (four out of six years), the lack of more dramatic fluctuations during typhoon periods suggests that streamwater chemistry at Lienhuachi Experimental Forest is relatively resistant to typhoon disturbance.

Studies of typhoon disturbance at Fushan Experimental Forest of northeastern Taiwan suggest that structural resistance (low tree mortality) contributes to functional resilience (quick recovery of streamwater chemistry) and together they contribute to the maintenance the ecosystem stability (T. C. Lin et al., 2011). Without high mortality the changes in streamwater chemistry is mostly associated with leaching caused by the heavy rainfall, while plant uptake of nutrients is largely unaffected, allowing streamwater chemistry to recover quickly (T. C. Lin et al., 2011). The results reported here suggest that streamwater chemistry exhibits both high resilience and high resistance with the former being evident at a weekly time scale and the latter at a seasonal or annual scale. For regions experiencing high tropical cyclone frequencies such as Taiwan, high resistance and resilience are crucial for maintaining ecosystem structure and function. If the elevated concentration of NO_3^- lasted for more than a year as reported following hurricane Hugo at Luquillo Experimental Forest (McDowell, 2001), the ecosystem of Lienhuachi Experimental Forest as well as those in many parts of Taiwan would be continuously losing large quantities of nitrogen and in turn causing large-scale ecosystem degradation. The high variation in streamwater chemistry response among typhoons further supports that the notion that there is not such thing as a typical tropical cyclone event that can be used to characterize tropical cyclone-ecosystem interactions.

Regardless of the high resilience, frequent disturbance can still lead to losses of large amounts of nitrogen even when biological demand is high and can therefore contribute to the development of nitrogen limitation (Vitousek et al., 2010). Maintaining fluctuations within bounds, as observed in the current study, helps to minimize nitrogen loss from the ecosystem and delay the development of nitrogen limitation.

5 Conclusions

1. Typhoon storms contribute approximately 1/3 of the precipitation and stream runoff during an average year, though it is highly variable ranging over a six-year period from 4 % to 58 %. Typhoons most likely ameliorate drought stress in early spring when water demand from both natural and agriculture ecosystems increase. Water resource management plans based on long-term typhoon precipitation averages are problematic given the highly variable frequency and characteristics of typhoons.

2. The quantity of rainfall associated with typhoons is not correlated with their intensity as defined by wind velocity. Because rainfall and the associated runoff often cause more damage than do the associated high winds in natural ecosystems and human infrastructure the current tropical cyclone classification/warning systems cannot accurately predict tropical cyclone damages.

3. Typhoons contributed approximately 30 % of the input and output of most nutrients over an approximately two month period. On a monthly basis, nutrient input-output rates during typhoon periods were an order of magnitude greater than non-typhoon periods.

4. Typhoon storms contributed 18 % of the total NO_3^- input but about 40 % of output. One quarter of total output (10 $kg\,ha^{-1}\,yr^{-1}$) occurred during the typhoon period, at an average rate of 1 $kg\,ha^{-1}\,d^{-1}$, leading to stream NO_3^- pulses that could be having adverse effects on downstream ecosystems.

5. Streamwater chemistry changes during typhoons, but returns to pre-typhoon concentrations rapidly, suggesting that the ecosystem is highly resilient. However, the magnitude of fluctuation in streamwater chemistry during typhoon periods is no greater than during non-typhoon periods, an indication of high resistance of streamwater chemistry to typhoon disturbance. The high resilience and resistance of streamwater chemistry helps to minimize nutrient loss at Lienhuachi Experimental Forest despite experiencing frequent typhoons.

6. Typhoon-induced changes in streamwater chemistry varied considerably among events. Given this variation and the fact that our current understanding of tropical cyclone-ecosystem interactions is largely derived from studies of individual or at most a couple of tropical cyclones we need to consider if our understanding is potentially spurious.

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Table 1. Wind velocity ($\mathrm{m\,s^{-1}}$) at the typhoon center, and rainfall (mm) and stream flow (mm) of typhoons between 2005 and 2010 at Lienhuachi Experimental Forest.

Year	date	Names	Max. wind velocity	Total rainfall	Max. rainfall intensity		Total Stream flow
					$\mathrm{mm\,d^{-1}}$	$\mathrm{mm\,h^{-1}}$	
2005	16–20 Jul	Haitang	55	475	300	26	270
	3–6 Aug	Matsa	40	500	350	34	290
	30 Aug–1 Sep	Talim	53	140	110	32	70
2006	12–15 Jul	Bilis	25	440	240	27	260
	14–16 Sep	Shanshan	48	92	35	22	60
2007	16–19 Aug	Sepat	53	170	82	12	90
	17–19 Sep	Wipha	48	230	170	18	140
	4–7 Oct	Krosa	51	300	160	44	180
2008	16–18 Jul	Kalmaegi	33	480	450	96	270
	26–29 Jul	Fungwong	43	220	200	39	180
	11–16 Sep	Sinlaku	51	960	500	85	590
	26–29 Sep	Jangmi	53	480	380	41	270
2009	5–10 Aug	Morakot	40	800	440	49	540
2010	17–20 Sep	Fanapi	45	76	28	13	50

Table 2. Mean annual water (mm) and nutrient (kg ha^{-1}) input through rainfall and output through streamwater at Lienhuachi Experimental Forest in central Taiwan between 2005 and 2010. Numbers in parenthesis are standard errors.

Rainfall	H_2O	H^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	NH_4^+	Cl^-	NO_3^-	SO_4^{2-}
Rainfall										
Total	2600 (380)	0.21 (0.044)	3.5 (0.64)	2.2 (0.29)	0.47 (0.06)	3.7 (1.03)	12 (1.8)	5.7 (0.37)	27 (2.2)	27 (3.8)
Typhoon										
quantity	890 (290)	0.081 (0.028)	1.1 (0.26)	0.81 (0.32)	0.15 (0.04)	0.83 (0.28)	2.1 (0.59)	2.0 (0.51)	4.9 (1.4)	8.3 (3.4)
%	34 (8)	39 (8.5)	31 (5.5)	37 (9.7)	32 (6.9)	22 (7.0)	18 (6.3)	35 (6.8)	18 (4.5)	31 (7.4)
Streamflow										
Total	1570 (140)	0.05 (0.02)	24 (6.2)	6.3 (1.6)	33 (7.6)	59 (14.7)	0.23 (0.03)	16 (2.5)	36 (6.7)	66 (9.3)
Typhoon										
quantity	490 (180)	0.013 (0.006)	7.4 (2.8)	2.0 (0.81)	8.8 (3.0)	12 (4.7)	0.083 (0.023)	4.9 (1.2)	15 (4.5)	17 (4.1)
%	31 (8.2)	26 (8.2)	31 (6.9)	32 (6.5)	27 (5.9)	20 (5.6)	37 (9.1)	31 (7.2)	42 (11)	26 (7.7)
Output: input ratio										
Typhoon	0.55 (0.031)	0.16 (0.11)	6.7 (1.7)	2.5 (0.76)	59 (11)	14 (5.6)	0.039 (0.018)	2.5 (0.51)	3.1 (0.70)	2.1 (0.82)
Non-typhoon	0.63 (0.068)	0.29 (0.15)	6.9 (2.0)	3.1 (1.5)	76 (42)	16 (8.8)	0.015 (0.0071)	3.0 (0.52)	0.95 (0.20)	2.6 (0.62)

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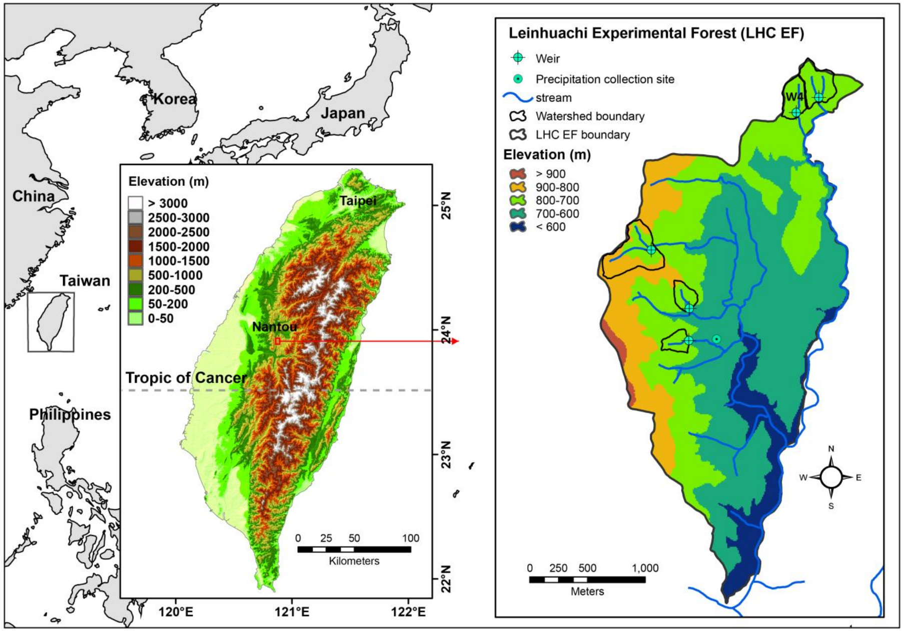

Fig. 1. Location map of study site – Leinhuachi Experimental forest of central Taiwan.

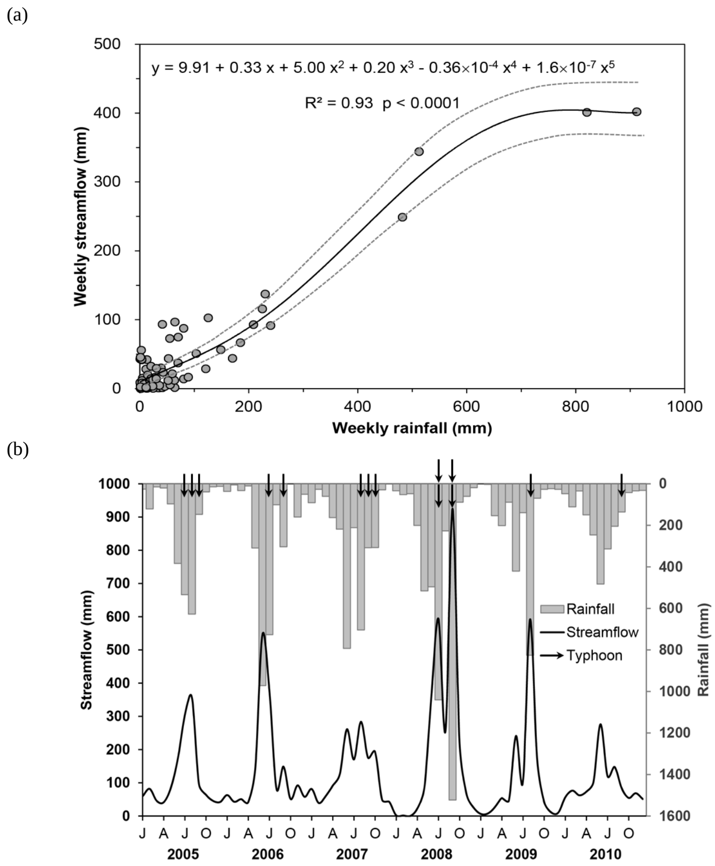

Fig. 2. (a) The relationships between weekly rainfall and streamflow between 2008 and 2009, and **(b)** the monthly rainfall and streamflow between 2005 and 2010. Each arrow indicates the occurrence of a typhoon.

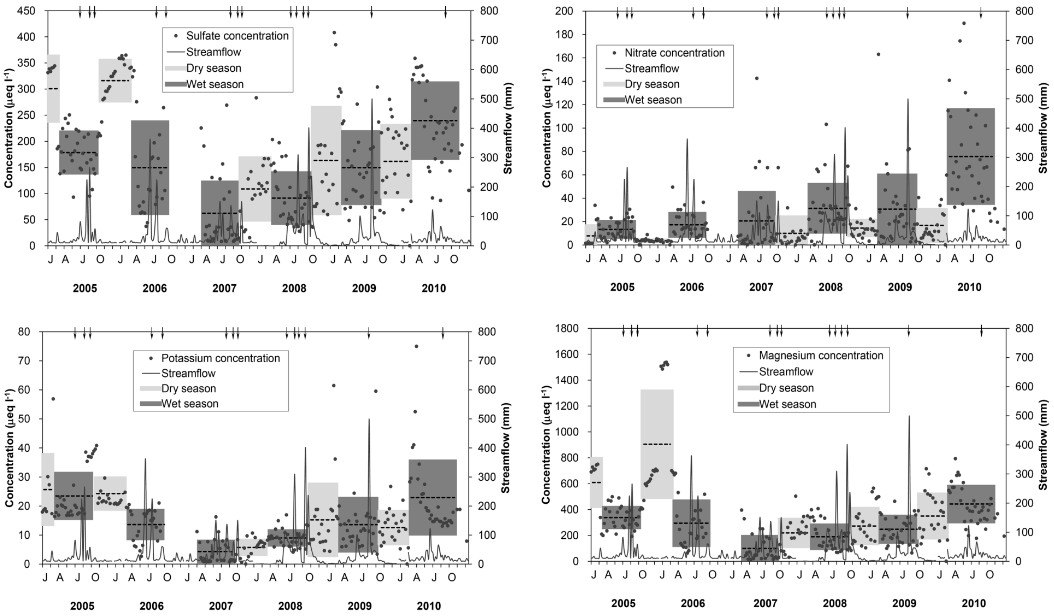

Fig. 3. Weekly streamwater chemistry between 2005 and 2010. Each arrow indicates a typhoon. Dash lines and gray rectangles represent the mean and one standard deviation of ion concentration during dry (October–February) and wet (March–September) seasons.

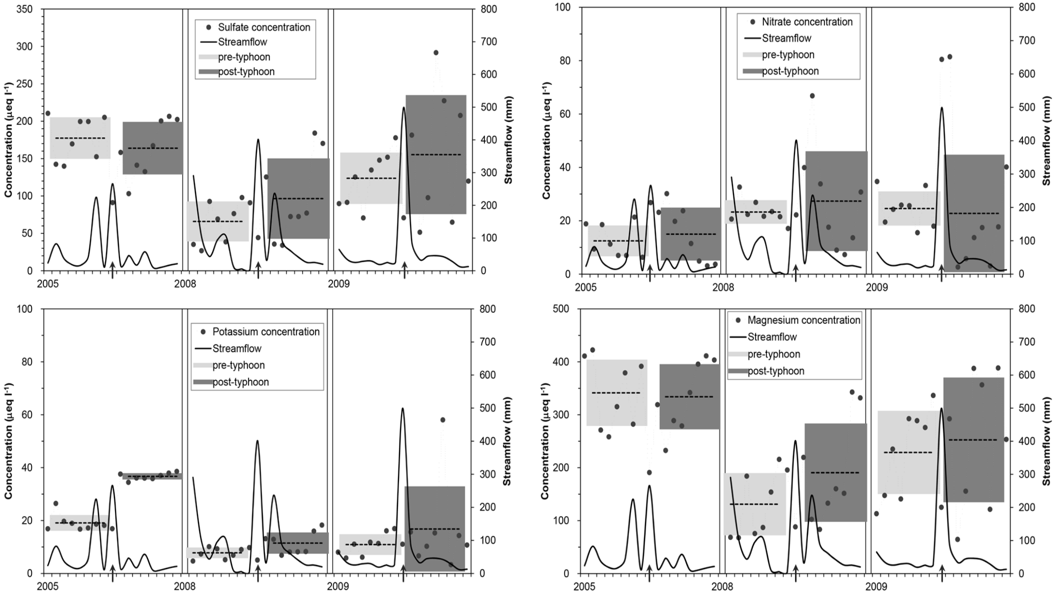

Fig. 4. Weekly streamflow and mean streamwater chemistry of the 8 weeks before and 8 weeks after the three typhoons with the highest amount of rainfall between 2005 and 2010 (Matsa in 2005, Sinlaku in 2008 and Morakot in 2009). Each arrow indicates the week of typhoon occurrence. Dash lines and gray regions represent the mean and one standard deviation of ion concentration of the 8 weeks before and after typhoons.

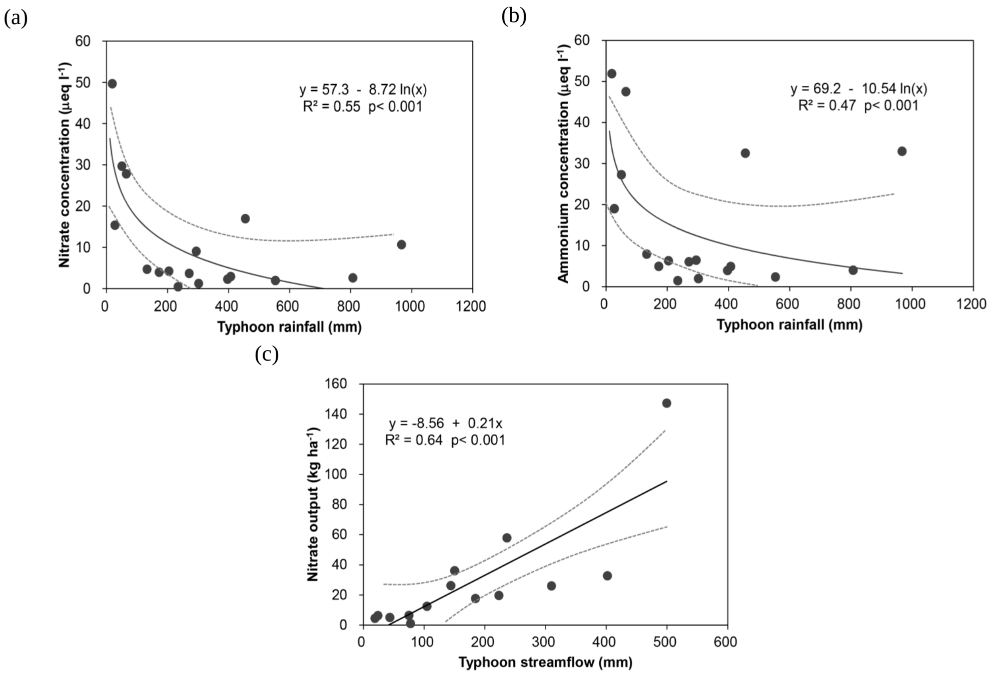

Fig. 5. The relationships between concentration and water quantity of NO_3^- and NH_4^+ in typhoon rainfall **(a)** and **(b)** and between NO_3^- output and typhoon streamflow **(c)**.

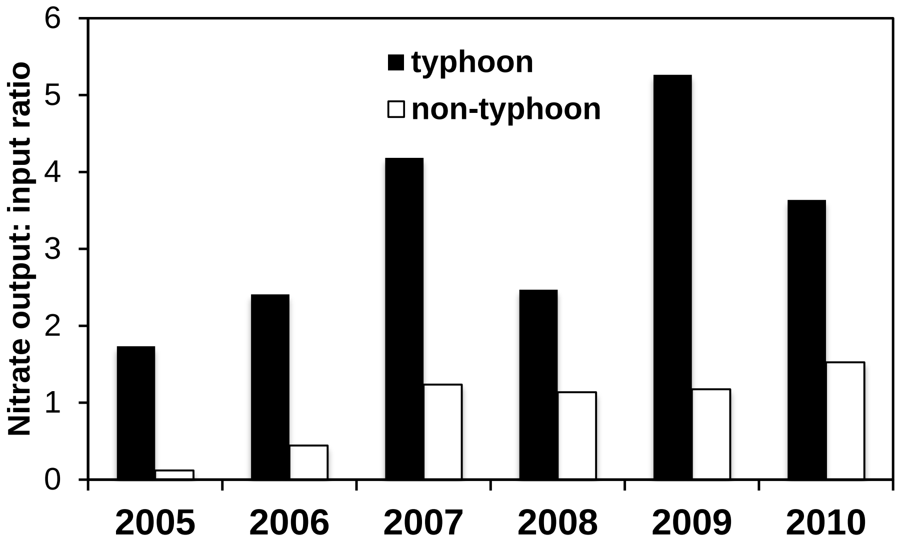

Fig. 6. The output: input ratio of NO_3^- during typhoon- and non-typhoon periods between 2005 and 2010.