Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Biogeosciences
Discussions
Open Access

The dynamics and export of dissolved organic carbon from subtropical small mountainous rivers during typhoon and non-typhoon periods

Tsung-Yu Lee[1]*, Li-Chin Lee[2], Jr-Chuan Huang[2], Shih-Hao Jien[3], Thomas Hein[4,8], Franz Zehetner[5], Shuh-Ji Kao[6], Fuh-Kwo Shiah[7]

[1] Department of Geography, National Taiwan Normal University, Taipei, Taiwan

[2] Department of Geography, National Taiwan University, Taipei, Taiwan

[3] Department of Soil and Water Conservation, National Pingtung University of Science and Technology, Pingtung, Taiwan

[4] Institute of Hydrobiology and Aquatic Ecosystem Management, University of Natural Resources and Life Sciences, Vienna, Austria

[5] Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna, Austria

[6] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China

[7] Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan

[8] WasserCluster Lunz, Dr. Kupelwieser-Prom. 5, 3293 Lunz am See, Austria

*Correspondence should be addressed to Dr. Tsung-Yu Lee

Professor, Department of Geography, National Taiwan Normal University, Taipei, Taiwan

E-mail address: tylee@ntnu.edu.tw Tel: +886-2-7734-1667 Fax: +886-2-2369-1770

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Abstract

Small mountainous rivers (SMRs) are important conveyors of the land-to-ocean organic carbon export. However, relatively few studies have focused on dissolved organic carbon (DOC) compared to particulate organic carbon. In a long-term project (2002 to 2014), stream DOC was monitored in three neighboring subtropical small mountainous rivers of Taiwan. The objective was to relate DOC concentrations to water discharge and to quantify DOC flux during typhoon and non-typhoon periods. Seasonal fluctuations of DOC concentrations were closely correlated with air temperature at all sampling stations. During non-typhoon periods, increasing water discharge led to decreasing DOC concentrations due to a dilution effect. However, during typhoon periods, DOC concentrations increased with some lead time along the hydrograph and reached the annual maximum which likely sources from a significant input of litter and upper soil layers. The mean DOC concentration of the studied systems (<1.0 mg L^{-1}), is ranked in the lowest 1% among the world rivers. However, mean DOC yield (~30 kg ha^{-1} y^{-1}), is ranked in the top 30%, which is attributed to high rainfall and substantial organic carbon stocks in the watersheds. Up to 25±5.6% of the annual DOC flux was contributed by typhoon events, which occupied ~3% of the monitoring period. We conclude that typhoon events are important drivers for the land-to-ocean export of dissolved organic matter. Predicted future increases in frequency and magnitude of typhoon events will likely accelerate the release of terrestrial carbon and enhance its land-to-ocean transfer via dissolved organic matter.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

1. Introduction

Small mountainous rivers (SMRs) have been shown to be important conveyors of terrestrial organic carbon to the ocean, contributing approx. 20 – 40% of the global land-to-ocean export of organic carbon (Lyons et al., 2002; Schlünz and Schneider, 2000). Most of the studies on SMRs focus on the fluvial export of particulate organic carbon (POC), while the export of dissolved organic carbon (DOC) has received much less attention. DOC yield in SMRs, normalized to the watershed area, is comparable to that observed the large rivers (Lloret et al., 2013). Unlike POC, which is thought to be buried in marine sediments and influences the carbon cycle in geological time scales (Hilton et al., 2012; Kao et al., 2014), the dynamics of DOC, which can be less recalcitrant than POC, might contribute more to the contemporary carbon cycle (Lefèvre et al., 1996). The DOC dynamics are influenced by the rates of microbial respiration and organic matter decomposition, which may be increased by global warming (Freeman et al., 2001; Tian et al., 2013; Huntington et al., 2016).

Hydrology exerts strong control on the nutrient export in subtropical SMRs (Huang et al., 2012; Kao et al., 2004; Lee et al., 2013). The rainfall-driven mixture of water from various flow pathways determines streamwater chemistry (Lee et al., 2015a). The DOC from organic soil layers infiltrates into the mineral soil, contributing to the soil carbon pool in deeper soil horizons (Kalbitz and Kaiser, 2008; Michalzik et al., 2001). Upper soil horizons have been shown to be the primary source of DOC in streamwater (Boyer et al., 1997), consequently affecting carbon export through riverine transport (Huang et al., 2013; Liu et al., 2014). Increased DOC concentrations along with stormflow and snowmelt have been observed in different forest-dominated catchments (Boyer et al., 1997; Brown et al., 1999; Buffam et al., 2001; Inamdar et al., 2004; Zhang et al., 2007). However, the relationship, magnitude and timing varies worldwide because of varying geographic characteristics and climatic conditions (Buffman et al., 2001).

Both DOC production and carbon mineralization increase exponentially with rising temperatures when soil moisture is not limiting the microbial processes (Christ and David, 1996; Rey et al., 2005).

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

In a laboratory experiment increasing temperature increased the leaching of DOC in humic layers (Andersson et al., 2000). A positive correlation between stream DOC concentration and temperature has been observed in peatlands (Billett et al., 2006), (sub)boreal regions (Worrall and Burt, 2007) and subtropical forests (Huang et al., 2013). Nevertheless, the dynamics of stream DOC in subtropical regions has received less attention due to the relatively low DOC concentrations (Huang et al., 2013; Schmidt et al., 2010) compared to the temperate region (Borken et al., 2011; Fröberg et al., 2006; van den Berg et al., 2012; Yano et al., 2004).

In this study, we investigated the dynamics and export of DOC from three neighboring subtropical SMRs during typhoon and non-typhoon periods. Our objectives were 1) to analyze DOC concentration in relation to water discharge and temperature, and 2) to understand the effects of typhoon events on DOC dynamics and flux in subtropical SMRs. Rapid responses of fluvial export to watershed environmental changes in SMRs help us to infer their effects on the carbon cycle at the watershed scale. Typhoons of varying magnitude in this study enable us to assess how fluxes change during different events. Our study shall provide a basis for the prediction of fluvial DOC export as typhoons striking East and Southeast Asia will intensify further (Mei and Xie, 2016) and associated nutrient fluxes are known to be significant and increasing for Oceania rivers (Carey et al., 2005; Schlünz and Schneider, 2000).

2. Materials and methods

2.1. Study area

The study area is located in Beishi Creek watershed, Northern Taiwan (121˚42' E, 24°56' N), which is dammed up by the Feitsui Reservoir supplying water to 5.7 million people living in Taipei, the capital of Taiwan (Lee et al., 2014). In this study, three neighboring watersheds in the upstream of the Feitsui Reservoir were investigated, i.e. Pin-Lin (PL), Dai-Yu-Ku (DYK) and Gin-Gua-Liao

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

(GGL) watershed (Fig. 1). PL station is located in the main stream of Beishi Creek before the convergence of DYK Creek and GGL Creek, representing a drainage area of 110 km^2. DYK and GGL stations are located at the outlet of DYK Creek (drainage area = 78 km^2) and GGL Creek (22 km^2), respectively. All the sampling stations have discharge gauges maintained by the Feitsui Reservoir Administration. The average daily discharge for PL, DYK and GGL stations during 2002-2015 is 12.71, 7.70 and 2.01 m^3 s^{-1}, respectively (Table 1). The average daily discharge during the wet/dry season is 13.64/11.76, 9.53/5.88 and 2.59/1.40 m^3 s^{-1}, respectively. Air temperature records were obtained from a weather station near PL station, maintained by Central Weather Bureau. The mean daily air temperature is ~20 °C with an average of ~24 °C in the wet season (May to October) and ~16 °C in the dry season (November to April). The annual rainfall is ~2,000 – 4,000 mm, and ~65 % of the rainfall occurs during the wet season when typhoon events substantially contribute. The three watersheds have similar land use patterns with more than 90% forest area. Besides, tea farms occupy 5.0%, 2.2% and 5.4% of the watershed area in PL, DYK and GGL watershed, respectively.

2.2. Streamwater sampling and chemistry

Discrete streamwater samples were collected from Jan 2002 to Dec 2014. During the non-typhoon periods, samples were taken twice per week. During the typhoon periods, samples were taken every three hours. There were on average ~4 typhoons per year during the observation period (Table 4). Typhoon samples were taken from four typhoons, i.e. Saola (Jul 31 – Aug 3, 2012), Soulik (Jul 12 – Jul 13, 2013), Trami (Aug 21 – Aug 23, 2013), and Matmo (Jul 22 – Jul 24, 2014). Depth-integrated water samples were obtained using a vertically mounted 1 L bottle attached to a weighted metal frame that was gradually lowered from a bridge. After collection, water samples were immediately filtered through 0.45 μm pore-size GF/F filter and the filtrate was transported in a cooler to the laboratory. The filtrate for DOC analysis was preserved by addition of 0.5 ml 85% ortho-phosphoric acid and stored at room temperature. DOC concentration was determined by wet chemical oxidation

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

using an auto TOC analyzer with detection limit of 4 μg L^{-1} (Multi N/C 3100, Analytik Jena AG).

2.3. Flux calculation

The DOC flux is the total amount of DOC export from a watershed within a given period. The DOC concentrations measured in the stream are transformed into flux by multiplying by the corresponding discharge. A flux estimator is needed when there is a lack of continuous measurement (e.g., daily) of a constituent's concentration and water discharge, which is the case for the DOC measurements. The rating curve method is one of the most appropriate flux estimation methods and has been widely applied to rivers in Taiwan because the strongly fluctuating discharge usually dominates the fluvial material export (Kao et al., 2004). This method presumes that a power function (i.e., $F = aQ^b$) exists between the observed DOC flux (F) and discharge (Q). The coefficients of the power function, a and b, can be derived from the observed DOC fluxes and the water discharge rates by the log-linear least-square method. In this study, two rating curves were developed for non-typhoon and typhoon periods at each sampling station, respectively. Daily discharge was used for the non-typhoon rating curves and hourly discharge for the typhoon rating curves. Hence, daily discharge and hourly discharge (for all the typhoon events in a year) were substituted into the non-typhoon and typhoon rating curves, respectively, to calculate DOC fluxes. The sum of the DOC fluxes within a year is the annual DOC flux, which may be converted to DOC yield by normalizing to watershed area. The water discharge data were provided by the Taipei Feitsui Reservoir Administration.

3. Results

Air temperature in Taiwan shows a distinct seasonality. During the observation period, daily air temperature in the dry (November – April) and wet seasons (May – October) varied from 5.0 to 25.8 ℃ (with a mean of 16.3±4.0 ℃) and from 14.0 to 29.5 ℃ (with a mean of 24.2±2.8 ℃), respectively (Fig. 2). Water discharge showed spiky patterns resulting from rapid rainfall-runoff response and fluctuated by 3-orders of magnitude mostly during the invasion of tropical cyclones, i.e. typhoons, in summer and autumn. The measured maximum water discharge in the dry/wet seasons was 168/280, 70/363 and 24/84 $m^3 s^{-1}$ at PL, DYK and GGL station, respectively, with means of 11.8/13.6, 5.9/9.5 and 1.4/2.6 $m^3 s^{-1}$. The measured minimum water discharge was below 0.1 $m^3 s^{-1}$ at all stations.

3.1. Temporal variation of DOC concentrations

During the observation period, the running mean DOC concentration (of 5 adjacent samples, grey curve in Fig. 2) more or less followed the annual air temperature cycle, peaking in the wet season and with lowest values in the dry season. The observed DOC concentrations ranged from 0.23 to 2.91 mg L^{-1}, 0.22 to 4.11 mg L^{-1}, and 0.20 to 2.89 mg L^{-1}, respectively, at PL, DYK, and GGL station. Most of the DOC concentrations in the wet season were significantly higher than those in the dry season (Table 1) and the typhoon samples generally showed the highest DOC concentrations. The variation in DOC concentration could be linked to the water discharge variation. The DOC concentration dropped coincidentally with increasing water discharge (Fig. 2). Simultaneous increase of both, DOC concentration and water discharge, was only observed during the typhoon periods.

3.2. The relationship of DOC concentration and runoff

The DOC concentration – water discharge (C-Q) relation showed a clear dilution effect on DOC concentration with increasing water discharge for the non-typhoon samples in both the wet and dry season (Fig. 3). Conversely, the C-Q relation for the typhoon samples did not show any obvious trends (Fig. 3). Yet, during typhoon events, elevated DOC concentrations were observed; the mean DOC concentration during the typhoon period (>1.0 mg L^{-1} for all typhoon events, Table 2) was much higher compared to the non-typhoon period (Table 1). At a given discharge, higher DOC concentrations were generally observed in the wet season (warm season) than in the dry season (cool season), possibly reflecting the influence of temperature on DOC concentrations (Fig. 3). An effect

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

of temperature on DOC concentration is also indicated by statistically-significant positive correlations between monthly mean DOC concentrations and monthly mean air temperature (Fig. 4a), while statistically-significant negative correlations were found between monthly mean DOC concentrations and monthly mean discharge (Fig. 4b). And there is no linear relation between monthly mean air temperature and monthly mean discharge (data not shown).

3.3. DOC concentration during typhoon periods

Fig. 5 illustrates the time series of DOC concentrations along the hydrograph of the sampled typhoon events and Table 2 shows characteristics of water discharge and DOC concentration during the typhoons. For typhoon Saola, two peaks were observed in the hydrograph at PL, DYK and GGL station (Fig. 5a-1, 5b-1, 5c-1). This event also produced the highest peak discharge among the 4 sampled typhoons, reaching 641, 592 and 135 m^3 s^{-1}, respectively, at PL, DYK and GGL station. Although the DOC concentrations along the hydrograph showed some variability, two descending trends could be observed, which start before each discharge peak. The DOC concentration responded rapidly to variations in water discharge with pronounced rises at the beginning of the typhoon (compared to the last pre-typhoon sample) and rose again before the 2nd peak of the hydrograph (Fig. 5a-1, 5b-1, 5c-1).

For typhoon Soulik (Fig. 5a-2, 5b-2, 5c-2), the hydrograph showed the highest fluctuations among the four sampled typhoons, spanning three orders of magnitude. The peak DOC concentration during this typhoon was also the highest concentration among all the samples, reaching 2.79, 4.11, and 2.89 mg L^{-1} at PL, DYK, and GGL station, respectively. The DOC concentration again peaked 3 - 9 hours before the peak discharge. Additionally, at a given water discharge, higher DOC concentrations were observed for the rising limb of the hydrograph than for the recessing limb, resulting in a clockwise hysteresis loop (not shown).

For typhoon Trami (Fig. 5a-3, 5b-3, 5c-3), the hydrograph and DOC concentrations showed similar

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

patterns as for typhoon Saola, i.e. two peaks for water discharge and DOC concentration (and two hysteresis loops for the C-Q relationship). Moreover, the first peak discharge of both typhoons triggered the highest DOC concentration in the respective typhoon event (except for Saola at PL, Fig. 5a-1). However, unlike typhoon Trami, the first peak discharge in typhoon Saola was smaller than the second one, which, however, did not trigger higher DOC concentrations. For typhoon Matmo (Fig. 5a-4, 5b-4, 5c-4), the narrow double peak of discharge was not reflected by variations in DOC concentration, resulting in similar patterns as found for typhoon Soulik.

3.4. DOC fluxes during typhoon and non-typhoon periods

Although a hysteresis loop existed in the C-Q relation of typhoon samples, the relation of DOC flux to water discharge generally followed a power function with $R^2 \geq 0.92$ for typhoon samples and $R^2 \geq 0.83$ for non-typhoon samples (Fig. 6 and Table 3). At each sampling station, all the typhoon and non-typhoon samples, respectively, were pooled to derive two rating curves that allow predicting DOC flux from water discharge. We presumed that the two rating curves for each station remained unchanged during the observation period. Larger *a* and *b* in the power function was found for the typhoon period than for the non-typhoon period, indicating disproportionately higher DOC fluxes during typhoon events.

Table 4 shows the DOC yields during the typhoon and non-typhoon periods. As for the mean annual DOC yield, the highest value of 37.08 kg ha^{-1} y^{-1} was found at DYK station, followed by 33.48 kg ha^{-1} y^{-1} at PL and 22.19 kg ha^{-1} y^{-1} at GGL station. Typhoon/non-typhoon periods yielded 7.21/29.87, 7.44/26.04 and 7.37/14.82 kg ha^{-1} y^{-1} at DYK, PL and GGL, respectively; hence, approx. 21 – 31% of the total annual DOC export was flushed out during typhoon events, which lasted for only 3 – 23 days (i.e. 0.8 – 6.3% of the observation time). However, typhoons contributed on average approx. 16 – 23% of the total annual water discharge. Depending on the number of typhoon invasions in every

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

observation year, we can calculate that the historical typhoon events transported 5.5 – 45.2% of the total annual DOC export. Among the three stations, GGL showed the highest typhoon contribution to both water discharge and DOC flux but had the lowest annual DOC yield.

4. Discussion

4.1. Effects of temperature on streamwater DOC

Soil water is an important source of DOC in streams (Clark et al., 2010), and it has been observed that DOC concentration in soil water increases with increasing temperature around the world regardless of soil type, geological region and land use (Worrall and Burt, 2007; Zaman and Chang, 2004). Increase in temperature enhances soil microbial and enzymatic activity and hence breakdown of litter and soil organic carbon (SOC), accelerating carbon turnover in soil (Subke et al., 2003). Schimel and Weintraub (2003) suggested that microbial activity and SOC be included in models that describe the dynamics of DOC in soil. In Taiwan's forest soils, SOC is >100 t ha^{-1} within 1 m depth (Chen and Hseu, 1997). Given the abundant SOC stocks, temperature fluctuations may trigger strong responses of DOC release in these soils. Our results show that at each of the three stations, DOC concentration was more than 30% higher in the warmer wet season than in the cooler dry season (>6 ℃ difference in mean temperature; Table 1) despite the dilution effect of increasing discharge (Fig. 4b).

Given the prediction of increasing air temperature by global climate models (IPCC, 2014), rates of heterotrophic microbial activity will be accelerated, increasing the efflux of CO_2 to the atmosphere and the export of DOC to streams by hydrologic leaching (Bardgett et al., 2008). We speculate that the watershed carbon cycle might speed up even more in forested catchments because the amount of litterfall is also positively correlated to air temperature (Lu and Liu, 2012), and increasing litterfall resulted in enhanced annual seepage flux of DOC in a Taiwanese *Chamaecyparis* forest (Chang et al.,

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

2007). Also, typhoon events contribute significantly to the annual litterfall in Taiwan (Wang, 2013); hence, the carbon cycle might be further accelerated by increasing magnitude of typhoons, which has been reported by several studies (Chien and Kuo, 2011; Liu et al., 2009; Tu and Chou, 2013; Mei and Xie, 2016).

4.2. Influence of hydrology on DOC concentration

The changes of geochemical signatures in streamwater have been linked to the mixing of different water sources, i.e. groundwater, subsurface or soil, and surface runoff (Lee et al., 2015a; Salmon et al., 2001). Hydrological controls on streamwater solute concentrations usually exhibit one of the following three general C-Q relations, i.e. dilution, enhanced hydrological access, or hydrologically constant conditions (Salmon et al., 2001). In our study, we found increases in DOC concentration in the rising limb of the hydrograph during typhoons. This is probably due to enhanced hydrological access, which is commonly shown for solutes found in areas of a watershed that are only hydrologically active during periods of high flows (Salmon et al., 2001). Stormflow is likely to accentuate the contribution of DOC sources near the organic-rich soil surface resulting in increased concentrations of DOC (Qualls and Haines, 1991). Although DOC concentration in soil water was not measured in this study, it is well known that DOC concentration generally decreases with increasing soil depth (Inamdar et al., 2004), and also confirmed for natural and secondary hardwood forests in central Taiwan, where DOC concentrations of 20 mg L^{-1} were found at 15 cm and 10 mg L^{-1} at 60 cm soil depth (Liu and Sheu, 2003). Besides, the litter layer in the forest floor is a substantial DOC source where DOC concentration can be up to 35 mg L^{-1} (Chang et al., 2007).

It is presumed that flow paths and available sources control the concentrations of dissolved matter during typhoon events (Buffam et al., 2001; Zhang et al., 2007), and our results suggest the following processes. Before typhoon events, groundwater likely dominates flow discharge; the groundwater in our study area had DOC concentrations <0.7 mg L^{-1} (data not published yet). In the rising limb of the typhoon hydrograph, streamwater DOC concentration rises with discharge until a maximum is reached that probably coincides with the saturation of the upper soil and litter layers where DOC concentrations are highest. After the soil is saturated, continuing rainfall generates saturation-excess runoff with significantly lower DOC concentrations (Liu and Sheu, 2003), thus, diluting the DOC concentration in the stream. In the recession period, DOC concentration keeps decreasing as groundwater gradually dominates the flow discharge again. Lee et al. (2013) also addressed similar hydrological processes in three watersheds in central Taiwan but nitrate and phosphate were used as tracers.

In our study, DOC concentrations responded rapidly to variations in water discharge and increased before every peak in the hydrograph (Fig. 5a-1, 5b-1, 5c-1, 5a-3, 5b-3, 5c-3). Such rapid response may reflect a fast increase in contribution from near-surface components with DOC-enriched water. Interestingly, the second peak of the hydrograph induced lower DOC concentrations even if the second peak discharge was higher (Fig. 5b-1, 5c-1). Perhaps most of the DOC in the soil had been flushed off during the rising limb of the 1st peak discharge, as explained by Buffam et al. (2001) addressing that soil water DOC concentration would be depleted over time, while the soil was saturated.

In the studied watersheds, DOC peaked prior to the peak discharge, resulting in a clockwise C-Q hysteresis loop. The loop is typical for rivers (Meybeck, 1993), which can be explained by a simple mixing model consisting of three constant concentration reservoirs (Evans and Davies, 1998). Buffam et al. (2001) used the three-component mixing model to explain the C-Q relations for stream storm events, which are very similar to ours, based on the relative concentrations of DOC in three source reservoirs, i.e. surface runoff (in the litter layer), soil water, and groundwater. However, we propose that the surface runoff be divided into initial flush-off from the litter layer and the following saturation-excess runoff that leads to the dilution of DOC concentration in the period between the peaks of DOC concentration and water discharge.

During non-typhoon periods, increasing discharge did not enhance but rather diluted the DOC concentration in streams (Fig. 2 and 3), opposite to the findings during typhoon events. As mentioned above, soil water should contribute to increasing discharge not only during typhoon events but also during non-typhoon periods (Lee et al., 2013; 2015a). Higher DOC concentration in the soil water, compared to the groundwater, should elevate the streamwater DOC. In our study, however, streamwater DOC concentration seemed to approach the groundwater DOC concentration, i.e. <0.7 mg L^{-1}, with increasing discharge during non-typhoon periods, implying that groundwater influence gradually increases. On the other hand, in the low-end flow regime, i.e. <1 m^3 s^{-1} at our study sites, where discharge should be only originating from groundwater, streamwater DOC concentration was much higher than groundwater DOC concentration (Fig. 3). A previous study has suggested that in-stream production of DOC can be an important source of streamwater DOC concentration, particularly at low discharge (Mulholland and Hill, 1997). At high discharge, in-stream processes would tend to be less important regulators of streamwater DOC concentration because shorter water residence time and more water from the watershed should reduce the effect of in-stream biological processing. However, currently we do not have evidence to prove that in-stream processes did indeed cause the high stream DOC concentrations during low flow periods. Nevertheless, our results do suggest that soil water input does not play a significant role during rising discharge in non-typhoon periods as it does during typhoon periods (Fig. 3). We speculate that the high infiltration capacity of the soils, mainly Entisols (~50 mm h^{-1} of infiltration rate), Inceptisols (~40 mm h^{-1}), and Ultisosls (~30 mm h^{-1}), promote rapid infiltration to the subsoil or groundwater recharge before the water begins to accumulate in the soil. However, this is not the case during typhoon periods when rainfall intensity and amount are much higher.

4.3. DOC export in small mountainous rivers

Despite the relatively scattered C-Q relation (Fig. 3), the tightly positive correlations between DOC flux and water discharge illustrate that hydrology exerts a strong control on DOC export during both typhoon and non-typhoon periods in the studied SMR watersheds (Fig. 6). Although the DOC concentration is diluted by increasing discharge during non-typhoon periods, the 3-order magnitude increase in discharge compensates the dilution effect (less than 1-order magnitude decrease in concentration) and leads to higher DOC export. A continuous supply of DOC is likely in the forest ecosystems of Taiwan because of abundant SOC stocks (>100 t ha^{-1}; Chen and Hseu, 1997). The DOC yield ranged from 9 to 80 kg ha^{-1} yr^{-1} (Table 4), amounting to <0.1 % of the SOC stored in the watershed. Even if the rainfall-driven export of POC, i.e. 210 kg ha^{-1} yr^{-1}, from forested hillslopes (bedrock excluded) is taken into account (Hilton et al., 2012), such abundant storage of SOC cannot be depleted by the DOC and POC export off the watershed.

Although DOC concentration in our study watersheds and other small mountainous watersheds (Lloret et al., 2013) is much lower than the global river mean, i.e. 5.29 mg L^{-1}, estimated by Dai et al. (2012), the DOC yield is comparable to other world rivers. Among the 118 world rivers investigated by Dai et al. (2012), DOC concentration in this study, i.e. <1.0 mg L^{-1}, is ranked in the lowest 1%, but DOC yield, ~30 kg ha^{-1} y^{-1}, is ranked in the top 30%. Such high DOC yield can be attributed to the abundant rainfall in combination with substantial carbon stocks in the watershed, and demonstrates the significance of SMRs in delivering terrestrial organic carbon to the ocean involving not only the particulate phase but also the dissolved phase.

A recent study has analyzed the trends of water and sediment discharge off of Taiwan island over the past four decades (Lee et al., 2015) and revealed magnified responses to increased rainfall intensity. On average for the 16 major rivers in Taiwan, the extremes of water discharge rose by 6.5 – 37% in the recent two decades compared to the previous two decades, and the extremes of sediment discharge rose by 62 – 94%. As water and sediment are carriers of DOC and POC, respectively, Taiwan rivers might have delivered much more DOC (and POC) from the terrestrial to the ocean. Moreover, a recent study has demonstrated that typhoons striking Taiwan will intensify further in the future (Mei and Xie, 2016), which suggests that DOC (and POC) export will further increase in the decades to come.

5. Conclusions

Oceania is a global hotspot of land-to-ocean export of both POC and DOC (Schlünz and Schneider, 2000; Seitzinger et al., 2005), and Taiwan, having relatively abundant observations, is often taken as a role model (Milliman and Syvitski, 1992; Dadson et al., 2003; Hilton et al., 2012; Bao et al., 2016). However, much less attention has been paid to DOC, which is masked by the overwhelming POC yield along with the highest sediment yield in the world (Milliman and Farnsworth, 2013). We found that the DOC concentrations in the studied subtropical SMRs indeed lie on the lower end, i.e. <1.0 mg L^{-1}, of the spectrum of global stream DOC concentrations; however, the DOC yields, ~30 kg ha^{-1} y^{-1}, are ranked in the top 30% among 118 world rivers, which is due to high rainfall and high SOC stocks. Taking into account both the POC yield (~210 kg ha^{-1} y^{-1}; Hilton et al., 2012) and the DOC yield calculated in our study, we estimate the residence time of SOC at approx. 400 year (100 t ha^{-1} SOC stocks divided by 0.24 t ha^{-1} y^{-1} POC+DOC yield), which is the shortest among the world large river basins (Lloret et al., 2013). We think that due to their rapid responses subtropical SMRs might be the best experimental sites for studying the impacts of environmental changes on watershed carbon cycles in the future. Our study demonstrates that the DOC yield needs to be considered in overall budgets of carbon transport. Also, DOC might be more biodegradable than POC, likely causing more direct impacts on aquatic ecosystems (Raymond and Bauer, 2001).

We also found that DOC concentrations increase with rising temperatures and are elevated during typhoon events. Extreme climatic conditions, like heat waves and severe typhoon events, are very likely to be more frequent in the future as a result of global warming (Mei and Xie, 2016). We therefore infer that more DOC will be exported by subtropical SMRs, although the in-stream production/consumption could not be accounted for in our study. Our observational data supplement the global river database and serve as a scientific background for better understanding and modeling nutrient export from small mountainous watersheds.

6. Acknowledgments

This study was supported by Taiwan's Ministry of Science and Technology (102-2923-M-002-001-MY3, 104-2116-M-003-005, 105-2116-M-003-006)(http://www.most.gov.tw/) and by the Austrian Science Fund (FWF; http://www.fwf.ac.at) through the project ECATA (grant number I 1396-B16). We also thank Feitsui Reservoir Administration for providing hydrological records.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

7. References

Andersson, S., Nilsson, S.I., and Saetre, P.: Leaching of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in mor humus as affected by temperature and pH, Soil Biology & Biochemistry, 32(1), 1–10, 2000.

Bardgett, R.D., Freeman, C., and Ostle, N.J.: Microbial contributions to climate change through carbon cycle feedbacks, The Isme Journal, 2(8), 805–814, 2008.

Billett, M.F., Deacon, C.M., Palmer, S.M., Dawson, J.J.C., and Hope, D.: Connecting organic carbon in stream water and soils in a peatland catchment, Journal of Geophysical Research-Biogeosciences, 111, doi:10.1029/2005JG000065, 2006.

Borken, W., Ahrens, B., Schulz, C., and Zimmermann, L.: Site-to-site variability and temporal trends of DOC concentrations and fluxes in temperate forest soils, Global Change Biology, 17(7), 2428–2443, 2011.

Boyer, E.W., Hornberger, G.M., Bencala, K.E., and McKnight, D.M.: Response characteristics of DOC flushing in an alpine catchment, Hydrological Processes, 11(12), 1635–1647, 1997.

Brown, V.A., McDonnell, J.J., Burns, D.A., and Kendall, C.: The role of event water, a rapid shallow flow component, and catchment size in summer stormflow, Journal of Hydrology, 217(3–4), 171–190, 1999.

Buffam, I., Galloway, J.N., Blum, L.K., and McGlathery, K.J.: A stormflow/baseflow comparison of dissolved organic matter concentrations and bioavailability in an Appalachian stream, Biogeochemistry, 53(3), 269–306, 2001.

Carey, A.E., Gardner, C.B., Goldsmith, S.T., and Lyons, W.B. and Hicks, D.M.: Organic carbon yields from small, mountainous rivers, New Zealand, Geophysical Research Letters, 32, doi:10.1029/2005GL023159, 2005.

Chang, S.C., Wang, C.P., Feng, C.M., Rees, R., Hell, U., and Matzner, E.: Soil fluxes of mineral elements and dissolved organic matter following manipulation of leaf litter input in a Taiwan

Chamaecyparis forest, Forest Ecology and Management, 242, 133–141, 2007.

Chen, Z.S., and Hseu, Z.Y.: Total organic carbon pool in soils of Taiwan, Proceeding of the National Science Council, ROC, 21(3), 120–127, 1997.

Chien, F.C., and Kuo, H.C.: On the extreme rainfall of Typhoon Morakot, Journal of Geophysical Research: Atmospheres, 116, doi:10.1029/2010JD015092, 2011.

Christ, M.J., and David, M.B.: Temperature and moisture effects on the production of dissolved organic carbon in a Spodosol, Soil Biology & Biochemistry, 28(9), 1191–1199, 1996.

Clark, J.M., Bottrell, S.H., Evans, C.D., Monteith, D.T., Bartlett, R., Rose, R., Newton, R.J., and Chapman, P.J.: The importance of the relationship between scale and process in understanding long-term DOC dynamics, Science of the Total Environment, 408, 2768–2775, 2010.

Dadson, S.J., Hovius, N., Chen, H.G., Dade, W.B., Hsieh, M.L., Willett, S.D., Hu, J.C., Horng, M.J., Chen, M.C., Stark, C.P., Lague, D., and Lin, J.C.: Links between erosion, runoff variability and seismicity in the Taiwan orogeny, Nature, 426, 648–651, 2003.

Dai, M., Yin, Z., Meng, F., Liu, Q., and Cai, W.J.: Spatial distribution of riverine DOC inputs to the ocean: an updated global synthesis, Current Opinion in Environmental Sustainability, 4, 170–178, 2012.

Evans, C., and Davies, T.D.: Causes of concentration/discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry, Water Resources Research, 34(1), 129–137, 1998.

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., and Fenner, N.: Export of organic carbon from peat soils, Nature, 412, 785–785, 2001.

Fröberg, M., Berggren, D., Bergkvist, B., Bryant, C., and Mulder, J.: Concentration and fluxes of dissolved organic carbon (DOC) in three Norway spruce stands along a climatic gradient in Sweden, Biogeochemistry, 77(1), 1–23, 2006.

Hilton, R.G., Galy, A., Hovius, N., Kao, S.J., Horng, M.J., and Chen, H.: Climatic and geomorphic controls on the erosion of terrestrial biomass from subtropical mountain forest, Global Biogeochemical Cycles, 26, doi:10.1029/2012GB004314, 2012.

Huang, J.C., Lee, T.Y., Kao, S.J., Hsu, S.C., Lin, H.J., and Peng, T.R.: Land use effect and hydrological control on nitrate yield in subtropical mountainous watersheds, Hydrology and Earth System Sciences, 16, 699–714, doi:10.5194/hess-16-699-2012, 2012.

Huang, J.C., Lee, T.Y., Lin, T.C., Hein, T., Lee, L.C., Shih, Y.T., Kao, S.J., Shiah, F.K., and Lin, N.H.: Effects of different N sources on riverine DIN export and retention in a subtropical high-standing island, Taiwan, Biogeosciences, 13(6), 1787–1800, 2016.

Huang, W., McDowell, W.H., Zou, X.M., Ruan, H.H., Wang, J.S., and Li, L.G.: Dissolved Organic Carbon in Headwater Streams and Riparian Soil Organic Carbon along an Altitudinal Gradient in the Wuyi Mountains, China, Plos One, 8(11), 1–8, 2013.

Huntington, T.G., Balch, W.M., Aiken, G.R., Sheffield, J., Luo, L., Roesler, C.S., and Camill, P.: Climate change and dissolved organic carbon export to the Gulf of Maine, J. Geophys. Res. Biogeosci., 121, 2700–2716, doi:10.1002/2015JG003314, 2016.

Inamdar, S.P., Christopher, S.F., and Mitchell, M.J.: Export mechanisms for dissolved organic carbon and nitrate during summer storm events in a glaciated forested catchment in New York, USA, Hydrological Processes, 18(14), 2651–2661, 2004.

IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], IPCC, Geneva, Switzerland: 151, 2014.

Kalbitz, K., and Kaiser, K.: Contribution of dissolved organic matter to carbon storage in forest mineral soils, Journal of Plant Nutrition and Soil Science - Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 171(1), 52–60, 2008.

Kao, S.J., Hilton, R.G., Selvaraj, K., Dai, M., Zehetner, F., Huang, J.C., Hsu, S.C., Sparkes, R., Liu, J.T., and Lee, T.Y.: Preservation of terrestrial organic carbon in marine sediments offshore Taiwan: mountain building and atmospheric carbon dioxide sequestration, Earth Surface Dynamics, 2, 127–39, 2014.

Kao, S.J., Shiah, F.K., and Owen, J.S.: Export of dissolved inorganic nitrogen in a partially cultivated

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

subtropical mountainous watershed in Taiwan, Water, Air, and Soil Pollution, 156, 211–228, 2004.

Kitayama, K., and Aiba, S.I.: Ecosystem structure and productivity of tropical rain forests along altitudinal gradients with contrasting soil phosphorus pools on Mount Kinabalu, Borneo, Journal of Ecology, 90(1), 37–51, 2002.

Lal, R.: Soil carbon sequestration impacts on global climate change and food security, Science, 304, 1623–1627, 2004.

Lee, T.Y., Huang, J.C., Kao, S.J., and Tung, C.P.: Temporal variation of nitrate and phosphate transport in headwater catchments: the hydrological controls and land use alteration, Biogeosciences, 10, 2617-2632, doi:10.5194/bg-10-2617-2013, 2013.

Lee, T.Y., Hong, N.M., Shih, Y.T., Huang, J.C., and Kao, S.J.: The sources of streamwater to small mountainous rivers in Taiwan during typhoon and non-typhoon seasons, Environmental Science and Pollution Research, doi 10.1007/s11356-015-5183-2, 2015a.

Lee, T.Y., Huang, J.C., Lee, J.Y., Jien, S.H., Zehetner, F., and Kao, S.J.: Magnified Sediment Export of Small Mountainous Rivers in Taiwan: Chain Reactions from Increased Rainfall Intensity under Global Warming, Plos One, 10(9), doi:10.1371/journal.pone.0138283, 2015b.

Lee, T.Y., Shih, Y.T., Huang, J.C., Kao, S.J., Shiah, F.K., and Liu, K.K.: Speciation and dynamics of dissolved inorganic nitrogen export in the Danshui River, Taiwan, Biogeosciences, 11(19), 5307–5321, 2014.

Lefèvre, D., Denis, M., Lambert, C.E., and Miquel, J.C.: Is DOC the main source of organic matter remineralization in the ocean water column?, Journal of Marine Systems, 7, 281–291, 1996.

Liu, C.P., and Sheu, B.H.: Dissolved organic carbon in precipitation, throughfall, stemflow, soil solution, and stream water at the Guandaushi subtropical forest in Taiwan, Forest Ecology and Management, 172(2–3), 315–325, 2003.

Liu, S.C., Fu, C., Shiu, C.J., Chen, J.P., and Wu, F.: Temperature dependence of global precipitation extremes, Geophysical Research Letters, 36, doi:10.1029/2009GL040218, 2009.

Liu, W., Xu, X., McGoff, N.M., Eaton, J.M., Leahy, P., Foley, N., and Kiely, G.: Spatial and Seasonal Variation of Dissolved Organic Carbon (DOC) Concentrations in Irish Streams: Importance of Soil and Topography Characteristics, Environmental Management, 53(5), 959–967, 2014.

Lloret, E., Dessert, C., Pastor, L., Lajeunesse, E., Crispi, O., Gaillardet, J., and Benedetti, M.F.: Dynamic of particulate and dissolved organic carbon in small volcanic mountainous tropical watersheds, Chemical Geology, 351, 229–244, 2013.

Lu, S.W., and Liu, C.P.: Patterns of litterfall and nutrient return at different altitudes in evergreen hardwood forests of Central Taiwan, Annals of Forest Science, 6, 877–886, 2012.

Lyons, W.B., Nezat, C.A., Carey, A.E., and Hicks, D.M.: Organic carbon fluxes to the ocean from high-standing islands, Geology, 30, 443–446, 2002.

Mei, W., Xie, S.P.: Intensification of landfalling typhoons over the northwest Pacific since the late 1970s, Nature Geoscience, 9(10), 753-757, 2016.

Meybeck, M.: Riverine transport of atmospheric carbon: Sources, global typology and budget, Water, Air, and Soil Pollution, 70(1), 443–463, 1993.

Michalzik, B., Kalbitz, K., Park, J.H., Solinger, S., and Matzner, E.: Fluxes and concentrations of dissolved organic carbon and nitrogen - a synthesis for temperate forests, Biogeochemistry, 52(2), 173–205, 2001.

Milliman, J.D., and Syvitski, J.P.M.: Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers, Journal of Geology, 100, 525–544, 1992.

Milliman, J.D., and Farnsworth, K.L.: River Discharge to the Coastal Ocean: A Global Synthesis, Cambridge University Press, 2013.

Mulholland, P.J., and Hill, W.R.: Seasonal patterns in streamwater nutrient and dissolved organic carbon concentrations: Separating catchment flow path and in-stream effects, Water Resources Research, 33(6), 1297–1306, 1997.

Ostrofsky, M.L., Weigel, D.E., Hasselback, C.K., and Karle, P.A.: The significance of extracellular production and winter photosynthesis to estimates of primary production in a woodland stream community, Hydrobiologia, 382, 87–96, 1998.

Owen, J.S., King, H.B., Wang, M.K., and Sun, H.L.: Net nitrogen mineralization and nitrification rates in forest soil in northeastern Taiwan, Soil Science and Plant Nutrition, 56, 177–185, 2010.

Qualls, R.G., and Haines, B.L.: Geochemistry of dissolved organic nutrients in water percolating through a forest ecosystem, Soil Science Society of America Journal, 55(4), 1112–1123, 1991.

Raymond P.A., and Bauer, J.E.: Use of ^{14}C and ^{13}C natural abundances of evaluating riverine, estuarine, and coastal DOC and POC sources and cycling: a review and synthesis, Organic Geochemistry, 32, 469–485, 2001.

Rey, A., Petsikos, C., Jarvis, P.G., and Grace, J.: Effect of temperature and moisture on rates of carbon mineralization in a Mediterranean oak forest soil under controlled and field conditions, European Journal of Soil Science, 56(5), 589–599, 2005.

Salmon, C.D., Walter, M.T., Hedin, L.O., and Brown, M.G.: Hydrological controls on chemical export from an undisturbed old-growth Chilean forest, Journal of Hydrology, 253(1–4), 69–80, 2001.

Schimel, J.P., and Weintraub, M.N.: The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model, Soil Biology & Biochemistry, 35(4), 549–563, 2003.

Schmidt, B.H.M., Wang, C.P., Chang, S.C., and Matzner, E.: High precipitation causes large fluxes of dissolved organic carbon and nitrogen in a subtropical montane *Chamaecyparis* forest in Taiwan, Biogeochemistry, 101(1–3), 243–256, 2010.

Schlünz, B., and Schneider, R.R.: Transport of terrestrial organic carbon to the oceans by rivers: Re-estimating flux and burial rates, International Journal of Earth Sciences, 88, 599–606, 2000.

Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., and Bouwman, A.F.: Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application, Global Biogeochemical Cycles, 19(4), doi:10.1029/2005GB002606, 2005.

Subke, J.A., Reichstein, M., and Tenhunen, J.D.: Explaining temporal variation in soil CO_2 efflux in a mature spruce forest in Southern Germany, Soil Biology & Biochemistry, 35(11), 1467–1483, 2003.

Tian, Y.Q., Yu, Q., Feig, A.D., Ye, C., and Blunden, A.: Effects of climate and land-surface processes on terrestrial dissolved organic carbon export to major U.S. coastal rivers, Ecological Engineering, 54, 192-201, 2013.

Tu, J.Y., and Chou, C.: Changes in precipitation frequency and intensity in the vicinity of Taiwan: typhoon versus non-typhoon events, Environmental Research Letters, 8(1), 71–80, 2013.

van den Berg, L.J.L., Shotbolt, L., and Ashmore, M.R.: Dissolved organic carbon (DOC) concentrations in UK soils and the influence of soil, vegetation type and seasonality, Science of the Total Environment, 427, 269–276, 2012.

Wang, H.C., Wang, S.F., Lin, K.C., Shaner, P.J., and Lin, T.C.: Litterfall and Element Fluxes in a Natural Hardwood Forest and a Chinese-fir Plantation Experiencing Frequent Typhoon Disturbance in Central Taiwan, Biotropica, 45(5), 541–548, 2013.

Worrall, F., and Burt, T.P.: Trends in DOC concentration in Great Britain, Journal of Hydrology, 346(3–4), 81–92, 2007.

Yano, Y., Lajtha, K., Sollins, P., and Caldwell, B.A.: Chemical and seasonal controls on the dynamics of dissolved organic matter in a coniferous old-growth stand in the Pacific Northwest, USA, Biogeochemistry, 71(2), 197–223, 2004.

Zaman, M., and Chang, S.X.: Substrate type, temperature, and moisture content affect gross and net N mineralization and nitrification rates in agroforestry systems, Biology and Fertility of Soils, 39(4), 269–279, 2004.

Zhang, Z., Fukushima, T., Onda, Y., Gomi, T., Fukuyama, T., Sidle, R., Kosugi, K., and Matsushige, K.: Nutrient runoff from forested watersheds in central Japan during typhoon storms: implications for understanding runoff mechanisms during storm events, Hydrological Processes, 21(9), 1167–1178, 2007.

Ziegler, S.E., and Lyon, D.R.: Factors regulating epilithic biofilm carbon cycling and release with nutrient enrichment in headwater streams, Hydrobiologia, 657, 71–88, 2010.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Biogeosciences Discussions
Open Access

Table 1. The mean and standard deviation (SD) of DOC concentrations [mg L^{-1}], water discharge [m^3 s^{-1}] and air temperature [℃] at PL, DYK and GGL stations in dry (Nov – Apr) and wet (May – Oct) seasons and for whole calendar years during the observation period. The number in parentheses stands for sample size.

Station	Season	2002	2003	2004	2005	2012	2013	2014	All
					DOC (mg L^{-1}, Mean±SD)				
PL	Dry	0.76±0.19 (22)	0.72±0.25 (51)	0.62±0.18 (54)	0.51±0.10 (34)	0.50±0.17 (62)	0.75±0.36 (48)	0.59±0.31 (42)	0.63±0.26 (313)
	Wet	0.76±0.25 (52)	0.94±0.22 (53)	0.96±0.34 (51)	0.72±0.23 (27)	0.78±0.37 (62)	1.20±0.46 (41)	0.69±0.21 (29)	0.86±0.35 (315)
	All	0.76±0.23 (74)	0.83±0.26 (104)	0.78±0.32 (105)	0.60±0.20 (61)	0.64±0.32 (124)	0.95±0.47 (89)	0.63±0.27 (71)	0.75±0.33 (628)
DYK	Dry	0.76±0.26 (22)	0.87±0.30 (51)	0.78±0.21 (54)	0.58±0.13 (34)	0.66±0.56 (62)	0.71±0.24 (46)	0.62±0.22 (43)	0.72±0.34 (312)
	Wet	1.06±0.36 (52)	1.28±0.32 (54)	0.99±0.23 (52)	0.73±0.46 (27)	0.87±0.44 (62)	1.11±0.38 (42)	0.72±0.30 (31)	0.95±0.40 (320)
	All	0.97±0.36 (74)	1.08±0.37 (105)	0.88±0.24 (106)	0.65±0.33 (61)	0.71±0.51 (124)	0.90±0.37 (88)	0.67±0.26 (74)	0.85±0.40 (632)
GGL	Dry	0.72±0.27 (21)	0.72±0.24 (51)	0.70±0.11 (54)	0.64±0.13 (34)	0.57±0.18 (61)	0.86±0.34 (49)	0.59±0.21 (43)	0.68±0.24 (313)
	Wet	1.01±0.25 (52)	0.98±0.33 (54)	0.76±0.37 (52)	0.69±0.30 (27)	0.83±0.49 (61)	1.18±0.30 (42)	0.75±0.43 (31)	0.88±0.40 (319)
	All	0.92±0.39 (73)	0.85±0.32 (105)	0.73±0.27 (106)	0.66±0.22 (61)	0.70±0.39 (122)	1.00±0.36 (91)	0.66±0.33 (74)	0.79±0.35 (632)
					Water discharge (m^3 s^{-1}, Mean±SD)				
PL	Dry	6.12±6.73 (181)	11.21±19.53 (180)	11.85±13.50 (182)	13.81±12.64 (181)	15.12±11.56 (182)	11.45±12.91 (181)	12.77±11.61 (181)	11.76±13.35 (1268)
	Wet	9.37±21.83 (184)	9.90±17.55 (184)	14.17±23.16 (182)	21.94±37.84 (184)	15.30±25.85 (184)	10.93±20.24 (184)	13.85±14.04 (184)	13.64±24.26 (1286)
	All	7.75±16.27 (365)	10.55±18.55 (364)	13.02±18.99 (364)	17.91±28.56 (365)	15.21±10.04 (366)	11.19±16.98 (365)	13.31±12.89 (365)	12.68±19.70 (2554)
DYK	Dry	2.29±3.25 (181)	3.71±6.17 (181)	3.55±6.71 (182)	7.61±10.14 (181)	9.50±6.92 (182)	7.03±6.89 (181)	7.19±5.66 (181)	5.88±7.69 (1269)
	Wet	4.67±12.61 (184)	4.84±8.29 (184)	6.45±11.61 (179)	19.65±40.90 (184)	13.10±26.16 (184)	8.60±16.72 (184)	9.41±10.90 (184)	9.53±21.72 (1283)
	All	3.49±9.31 (365)	4.28±8.26 (365)	5.01±9.60 (361)	13.68±30.46 (365)	11.31±19.24 (366)	7.82±12.83 (365)	8.31±8.77 (365)	7.70±16.42 (2552)
GGL	Dry	0.57±1.00 (167)	1.34±1.64 (181)	1.70±2.25 (182)	2.85±2.84 (181)	1.29±1.33 (182)	1.36±1.82 (181)	0.75±1.16 (179)	1.40±2.09 (1253)
	Wet	1.07±2.82 (171)	1.75±2.48 (184)	2.27±3.71 (184)	5.93±10.80 (184)	2.16±5.46 (184)	1.81±4.97 (184)	3.12±5.68 (184)	2.59±5.92 (1275)
	All	0.82±2.13 (338)	1.55±2.11 (365)	1.99±3.08 (366)	4.40±8.06 (365)	1.73±4.00 (366)	1.59±3.83 (365)	1.95±4.28 (363)	2.01±4.49 (2528)
					Air temperature (℃, Mean±SD)				
Weather station	Dry	17.85±4.06 (181)	17.47±4.35 (180)	16.69±3.78 (182)	17.08±4.79 (181)	16.70±3.96 (182)	16.88±3.44 (156)	15.84±3.83 (181)	16.25±4.00 (1243)
	Wet	24.48±2.35 (184)	24.34±2.69 (184)	23.71±2.96 (184)	24.60±2.49 (184)	23.48±2.71 (184)	24.54±2.76 (184)	24.55±2.71 (184)	24.24±2.77 (1288)
	All	20.70±4.97 (365)	20.41±5.47 (364)	19.99±5.07 (366)	20.17±5.78 (365)	19.74±5.04 (366)	21.02±4.91 (340)	20.23±5.47 (365)	20.39±5.24 (2531)

Table 2. The observed minimum, maximum and mean ± standard deviation (SD) of DOC concentrations [mg L^{-1}] and the maximum water discharge [m^3 s^{-1}] for four sampled typhoon events at PL, DYK and GGL stations.

Station	Year	Typhoon	Water Discharge (m^3 s^{-1})	DOC (mg L^{-1})		
			Max	Min	Max	Mean±SD
PL	2012	Saola	641.3	0.68	2.36	1.33±0.49
	2013	Soulik	381.9	0.57	2.79	1.53±0.81
	2013	Tarmi	365.3	0.64	2.40	1.21±0.69
	2014	Matmo	203.8	0.76	1.93	1.40±0.40
DYK	2012	Saola	592.8	0.65	2.17	1.14±0.38
	2013	Soulik	468.7	0.52	4.11	1.37±1.08
	2013	Tarmi	291.2	0.63	2.68	1.07±0.64
	2014	Matmo	201.3	0.69	1.92	1.31±0.51
GGL	2012	Saola	135.1	0.59	2.73	1.32±0.55
	2013	Soulik	130.6	0.50	2.89	1.33±0.85
	2013	Tarmi	76.3	0.52	2.70	1.03±0.70
	2014	Matmo	97.5	0.62	2.19	1.21±0.57

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Table 3. Non-typhoon and typhoon rating curves derived from the observed DOC flux [g s^{-1}] against water discharge Q [m^3 s^{-1}] at PL, DYK and GGL stations.

	Typhoon period			Non-Typhoon period		
	DOC flux [g s^{-1}]	R^2	Sample size	DOC flux [g s^{-1}]	R^2	Sample size
PL	$1.22\ Q^{0.99}$	0.92	71	$0.92\ Q^{0.86}$	0.83	634
DYK	$1.03\ Q^{1.01}$	0.98	68	$0.87\ Q^{0.89}$	0.91	636
GGL	$1.11\ Q^{0.98}$	0.92	64	$0.71\ Q^{0.97}$	0.94	632

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Biogeosciences Discussions Open Access EGU

Table 4. DOC yield [kg ha^{-1} y^{-1}] at PL, DYK and GGL stations during typhoon and non-typhoon periods. The percentage of typhoon contribution to the annual total DOC flux and water discharge are also shown. SD stands for standard deviation.

Station	Year	Number of typhoon events	Duration [Days]	DOC yield [kg ha^{-1} y^{-1}]			Contribution of Typhoon (%)	
				Typhoon	Non-Typhoon	Sum	DOC flux	Water discharge
PL	2002	3	9	6.88	12.98	19.86	34.7	25.6
	2003	5	9	2.57	22.08	24.65	10.4	7.0
	2004	7	19	14.06	20.24	34.30	41.0	31.1
	2005	7	23	16.99	29.27	46.26	36.7	27.4
	2012	3	8	6.26	30.29	36.55	17.1	11.8
	2013	4	9	6.46	20.98	27.44	23.5	16.7
	2014	2	3	1.69	28.87	30.56	5.5	3.7
	Mean±SD	4.25±1.91	11±6.57	7.44±5.38	26.04±9.18	33.48±9.99	22.3±13.7	16.2±10.6
DYK	2002	3	9	4.52	7.46	11.98	37.7	31.2
	2003	5	9	2.16	11.67	13.83	15.6	12.1
	2004	7	19	8.17	72.30	80.47	10.2	7.8
	2005	7	23	21.63	26.27	47.90	45.2	38.1
	2012	3	8	7.29	29.74	37.03	19.7	15.5
	2013	4	9	6.30	19.55	25.85	24.4	19.4
	2014	2	3	1.92	24.34	26.26	7.3	5.6
	Mean±SD	4.25±1.91	11±6.57	7.21±6.24	29.87±21.04	37.08±22.92	21.3±13.7	17.2±11.8
GGL	2002	3	9	3.97	5.49	9.46	42.0	31.4
	2003	5	9	2.35	13.57	15.92	14.8	9.9
	2004	7	19	9.90	13.10	23.00	43.1	32.4
	2005	7	23	22.00	28.90	50.90	43.2	32.6
	2012	3	8	5.22	13.56	18.78	27.8	19.6
	2013	4	9	6.07	11.59	17.66	34.4	24.9
	2014	2	3	2.79	17.18	19.97	14.0	9.4
	Mean±SD	4.25±1.91	11±6.57	7.37±6.38	14.82±6.63	22.19±12.33	31.2±11.9	22.8±9.5

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

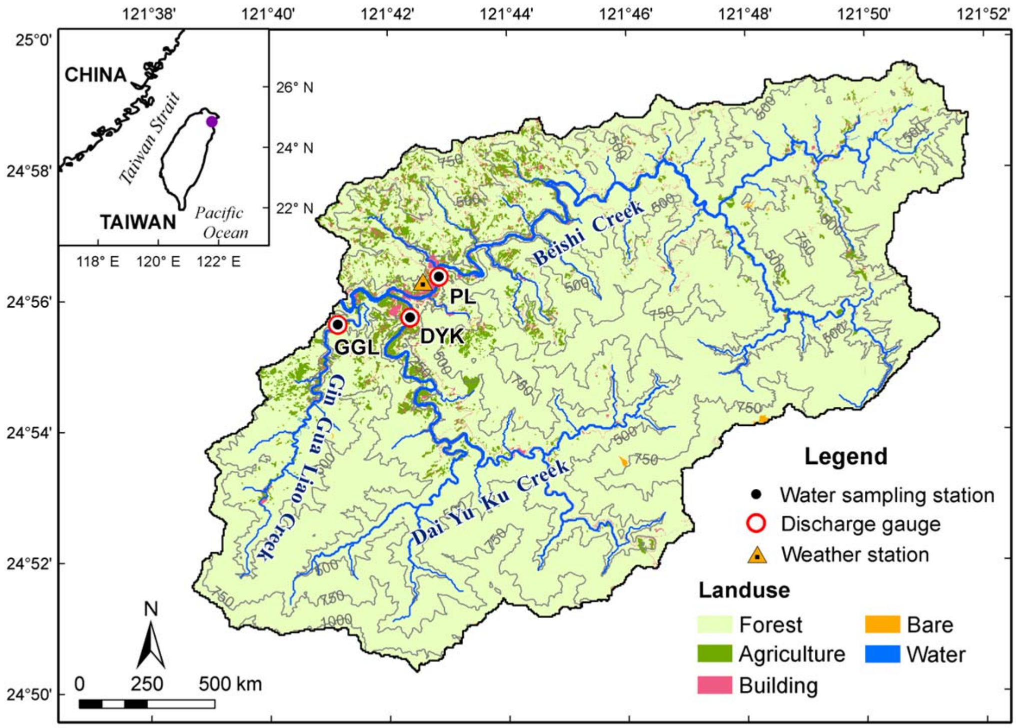

Figure 1. The study watershed, including water sampling sites, discharge gauges, weather station and land use patterns. Water samples were taken from PL, DYK, and GGL watersheds.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

Biogeosciences
Discussions
Open Access
EGU

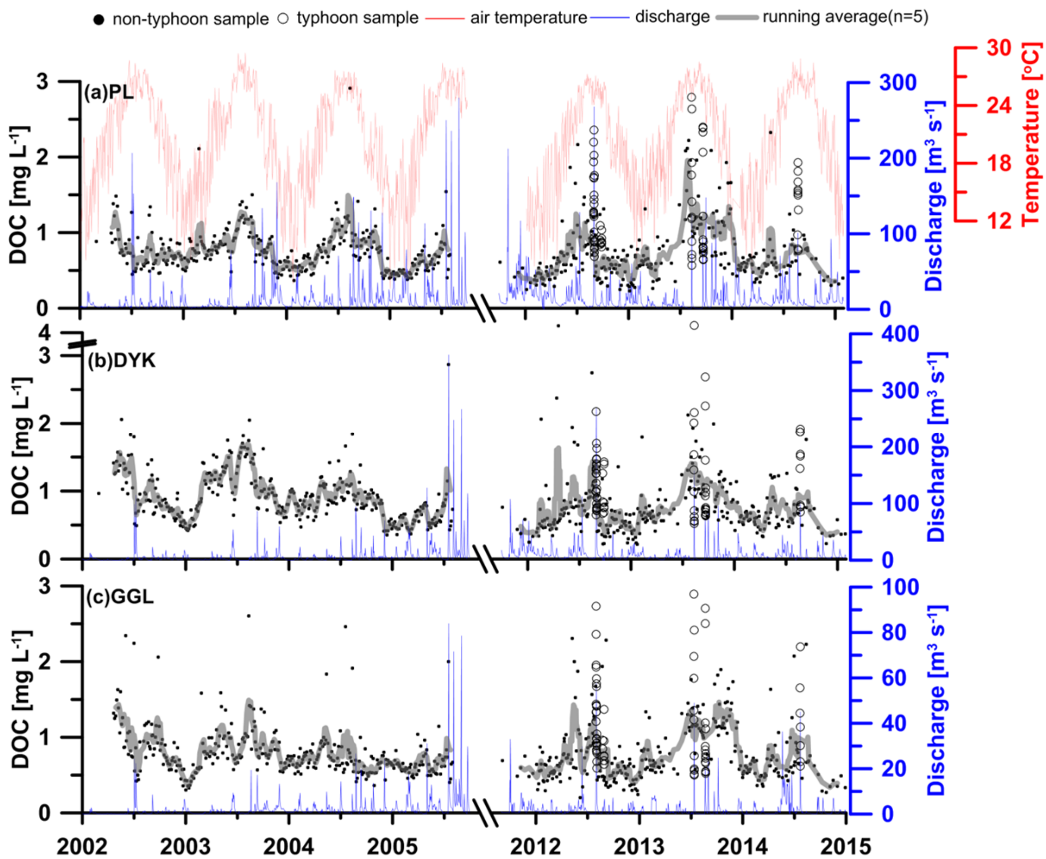

Figure 2. The monitored air temperature [℃] (red line), water discharge [m^3 s^{-1}] (blue line), and DOC concentration [mg L^{-1}] in the (a) PL, (b) DYK and (c) GGL watersheds. The three watersheds share the same air temperature data shown in panel (a). Water samples include typhoon (open circle) and non-typhoon (black dot) samples. The running average of 5 adjacent DOC samples is illustrated by a thick grey line.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

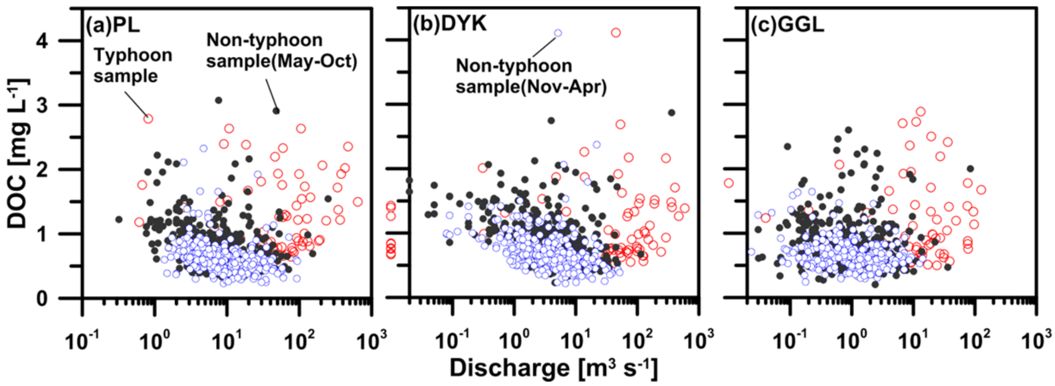

Figure 3. The relation of observed DOC concentration [mg L^{-1}] against water discharge [m^3 s^{-1}] in (a) PL, (b) DYK, and (c) GGL watersheds. Blue circles and black dots indicate non-typhoon samples taken in dry (cool) and wet (warm) season, respectively. Red circles stand for typhoon samples.

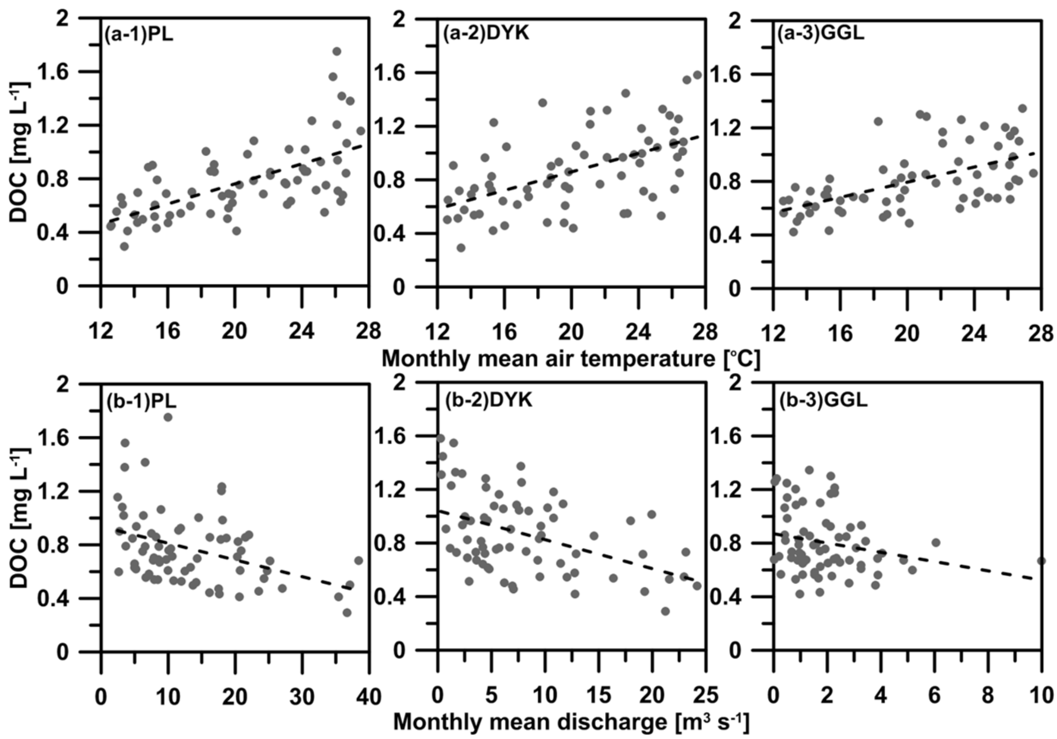

Figure 4. The relations of monthly mean DOC concentration [mg L^{-1}] against (a) monthly mean air temperature [℃] and (b) monthly mean water discharge [m^3 s^{-1}] observed at PL (-1), DYK (-2) and GGL (-3) watersheds during the observation period. All the fitted linear regression lines are statistically significant with *p-value* < 0.05.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

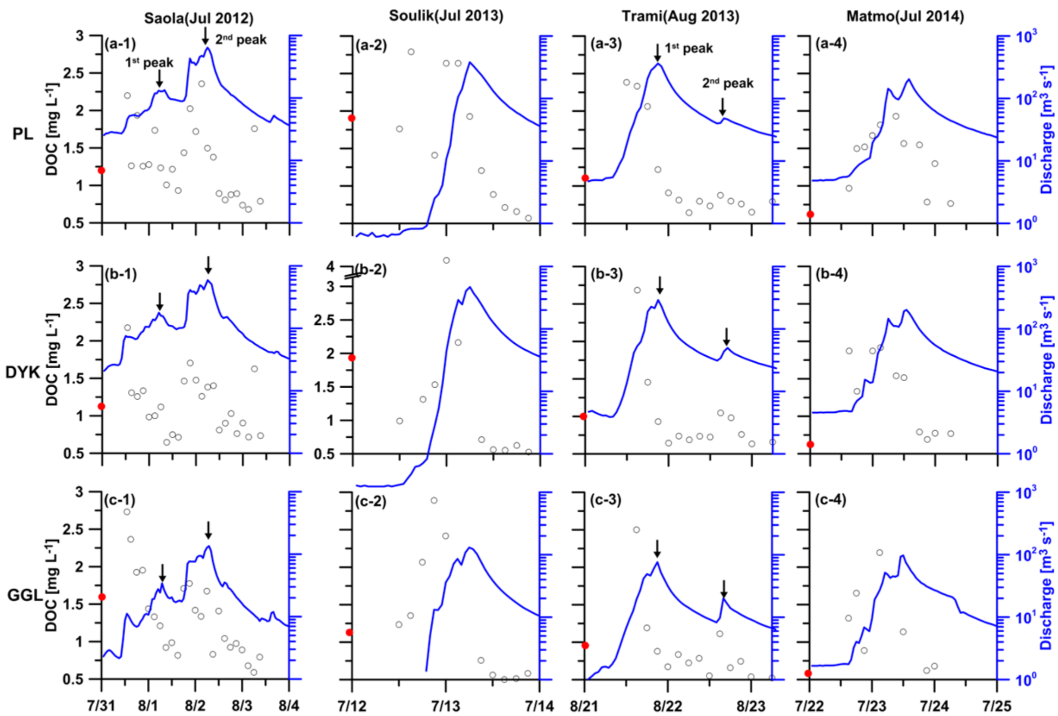

Figure 5. DOC concentrations [mg L^{-1}] (black circle) and water discharge [m^3 s^{-1}] (blue line) observed at (a) PL, (b) DYK, and (c) GGL watersheds during the typhoons Saola (-1), Soulik (-2), Trami (-3), and Matmo (-4). The last non-typhoon sample taken before the invasion of the respective typhoon is illustrated as red dot.

Biogeosciences Discuss., doi:10.5194/bg-2017-105, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 5 April 2017

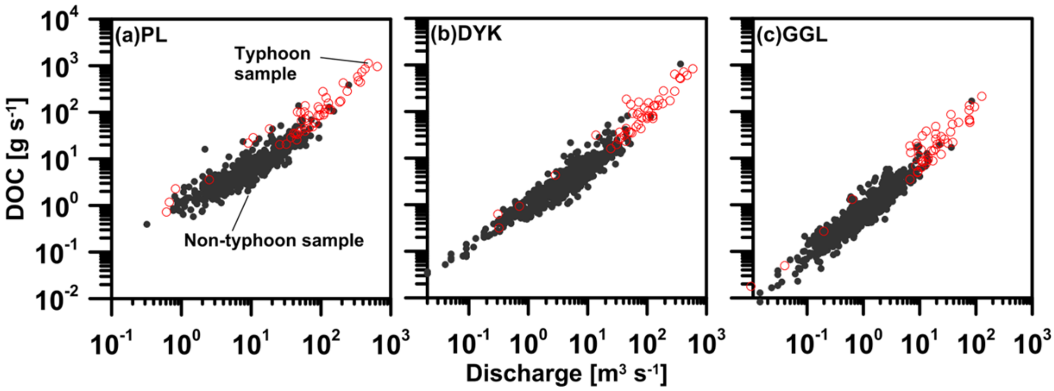

Figure 6. The log-log graphs of observed DOC fluxes [g s^{-1}] against water discharge [m^3 s^{-1}] at (a) PL, (b) DYK and (c) GGL watersheds for both typhoon (red circle) and non-typhoon (black dot) samples.