Chapter 2
Ecological Significance of Throughfall and Stemflow to the Carbon Cycle in Forest Ecosystems

Siyu Chen, Ruoming Cao, Shinpei Yoshitake, Yasuo Iimura, and Toshiyuki Ohtsuka

Abstract Rainfall enriches the dissolved organic carbon (DOC) after passing through the tree canopy. DOC is exported down stems as stemflow and through leaves, branches, and gaps as throughfall. In this paper, we synthesized the trends and factors that affect the DOC concentrations and fluxes of throughfall and stemflow in a cool-temperate deciduous broad-leaved forest (TDF) and a warm-temperate/subtropical evergreen broad-leaved forest (SEF), and reviewed the literature for various forests in different climatic zones around the world. The DOC concentrations were higher in stemflow (6–332 mg C L^{-1}) than in throughfall (5–29 mg C L^{-1}). The throughfall and stemflow DOC fluxes reported from natural forests in different climate zones range from 1.9 to 48 and 0.01 to 8 g C m^{-2} $year^{-1}$, respectively. The controls on throughfall and stemflow DOC concentrations are diverse, including rainfall characteristics, tree morphology, canopy phenology, and preceding atmospheric deposition. DOC fluxes in the forest carbon cycle act as a pathway, with water being essential to the carbon input of mineral soil. Studies of the fate of DOC in forest ecosystems may provide direct verification of soil C sequestration. Additional research is required to understand the significance of stemflow and throughfall DOC to forest C cycling.

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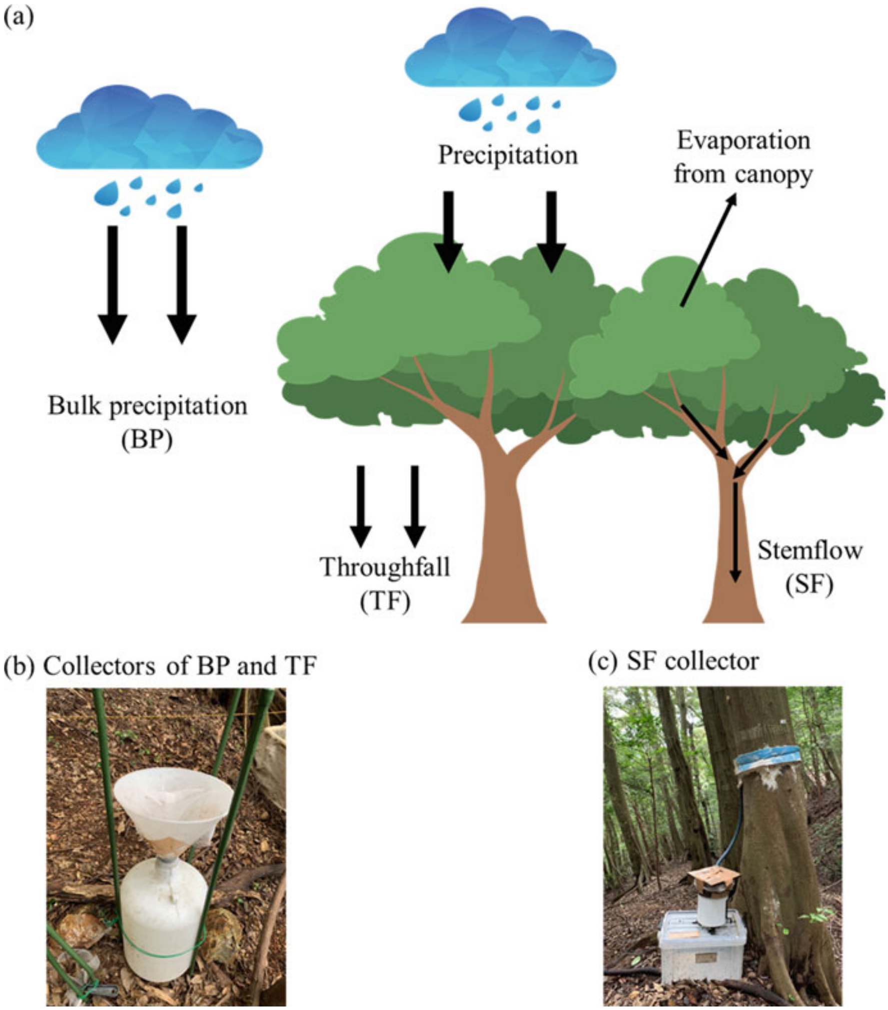

Fig. 2.1 Forest canopy redistributes rainfall into throughfall and stemflow (**a**). Funnel and a collection bottle for assessing bulk precipitation and throughfall (**b**); A stemflow collector attached to a rain gage to detect the volume of stemflow (**c**). Some of the water that passes through the rain gage is collected in a reservoir tank and sampled for analysis

2.1 Introduction

In forest ecosystems, precipitation that falls as rain, snow, or fog must first pass through the canopy before reaching the forest floor. This precipitation is partitioned into three fractions (Fig. 2.1a): (1) the interception that remains on the canopy and is evaporated after or during rainfall; (2) stemflow that flows to the ground via stems and boles; (3) throughfall that may or may not contact the canopy and that falls to the ground between the various components of the vegetation (Crockford and Richardson 2000). In other words, forest canopies redistribute rainfall into throughfall and stemflow, and these water fluxes wash various water-soluble materials out of the forest canopy, stems, and boles, and transfer them to the forest floor. Various nutrients (e.g., sulfur, nitrogen) are added when rain passes through the forest canopy, due to leaf leaching and/or anthropogenic deposition from the atmosphere onto the canopy (Bulter and Likens 1995). For example, dissolved inorganic nitrogen (e.g., NO_3^- and NH_4^+) and dissolved organic nitrogen are enriched by 8.8 and 1.5 kg N ha^{-1} $year^{-1}$, respectively, via throughfall in an urban evergreen broad-leaved forest in central Japan (Cao et al. 2020). The input of water to the forest floor is characterized by the forest composition, canopy structure, stand density, and basal area (Ford and Deans 1978; Crockford and Richardson 2000; Park and Hattori 2002); it is an important part of the material cycle in forest ecosystems.

Dissolved organic carbon (DOC) is operationally defined as organic molecules that pass through a filter, most often 0.45 μm in size. DOC can hydrologically transport carbon between different pools in the ecosystem. The DOC concentrations of rainfall are generally very low, but increase as rainwater passes through the canopy and the forest floor in the form of throughfall and stemflow (Kolka et al. 2008). Generally, the increase in the concentration of DOC due to precipitation is almost certainly a result of leaf and stem leaching, as well as microbial metabolites (biodegradable and hydrophilic neutral carbohydrates) that wash away from the canopy during this process (Guggenberger and Zech 1994; Michalzik et al. 2001; Levia et al. 2012). Thus, throughfall and stemflow are two flow paths by which DOC is removed from the canopy and transferred to the forest floor. Moreover, DOC is the major form of carbon that is transported from the soil solution to streams (Michalzik et al. 2001; Perakis and Hedin 2002).

We investigated the concentrations and fluxes of DOC in precipitation, throughfall, and stemflow in two contrasting forest ecosystems; a cool-temperate deciduous broad-leaved forest (TDF) and a warm-temperate/subtropical evergreen broad-leaved forest (SEF) (Chen 2019). These two types of secondary forests encompass the deciduous forest in a rural deep snow area and the evergreen forest in an urbanized area in the central region of the main island of Japan, where long-term forest monitoring have been intensively investigated. Annual measurements of the forest NPP began in 1998 using a permanent plot (Ohtsuka et al. 2009) beneath a flux tower (Yamamoto et al. 1999; Saigusa et al. 2002) on the site in the TDF, while the measurement of tree growth began in 1989 in the SEF (Chen et al. 2017a). The pattern and process of DOC fluxes in throughfall and stemflow should differ across the contrasting two forests. Although some intensive research has already been conducted, few detailed annual studies have evaluated the contribution of throughfall and stemflow to the annual C budget using the permanent plots.

In this work, we summarized the DOC concentrations and fluxes within the throughfall and stemflow in the two contrasting forests, and reviewed studies of various forests in different climatic zones around the world. Moreover, we evaluated the contribution of DOC fluxes to the ecosystem carbon cycle. The two hydrologic pathways (stemflow and throughfall) in the forest canopy, particularly stemflow, have been rarely investigated within the context of the forest C cycle; this may be partly because DOC fluxes are generally not considered to be critical components of the carbon balance in an ecosystem, being extremely small relative to the carbon fluxes of primary productivity or heterotrophic respiration in terrestrial systems (Hope et al. 1994; Schimel 1995). The objectives of this article were: (1) to compare the dynamics of DOC concentrations and fluxes in throughfall and stemflow using current data, including that from our own studies; (2) to review current knowledge of the processes that influence the dynamics of throughfall and stemflow DOC concentrations and fluxes; and (3) to evaluate all current knowledge to identify major gaps.

2.2 Methodology

2.2.1 Site Description

The TDF used in this study is an experimental forest of the Takayama Field Station, belonging to the River Basin Research Center at Gifu University (36°08′N, 137°25′E, 1420 m a.s.l.). The dominant species are *Quercus crispula, Betula ermanii,* and *B. platyphylla* var. *japonica*, with a basal area of 32.3 m^2 ha^{-1} (Ohtsuka et al. 2005; Saitoh et al. 2012). A permanent plot of 1 ha (100 × 100 m) was set on a west-facing slope. The soil of the study site can be classified as andisol, as well as Japanese volcanic ash soil (Chen et al. 2017b). The annual mean air temperature of the site is 7.3 °C, the average annual precipitation is approximately 2400 mm (2014–2015) distributed throughout the year, and the snow depth is usually 1–2 m in the winter (December–April).

The SEF used in this study is located on Mt. Kinka, central Japan. The topography of the area is hilly with young soil. The bedrock is composed of sedimentary rock on a chert layer. In 1989, a 0.7-ha study plot (70 × 100 m) was established on the lower slopes of Mt. Kinka (ca. 60 m a.s.l., 35°26′ N, 136°47′ E), with a basal area of 46.1 m^2 ha^{-1}. The dominant tree species in this forest is *Castanopsis cuspidata,* which accounts for 87.9% of the basal area (Chen et al. 2017a). The annual mean temperature is 16.1 °C and the average annual precipitation is 1866 mm. It is slightly snowy in the winter.

2.2.2 Experimental Setup and Sample Collection

Nine throughfall collectors were set in each forest, with each throughfall collector consisting of a 21-cm diameter funnel and 12-L collection bottle; samples were collected monthly (Fig. 2.1b). Samples of bulk precipitation were collected using a 12-L bottle set up in a location without a canopy that was near the study area in both sites. Samples were collected from the TDF and SEF from May to November 2015, and from January to December 2017, respectively.

Stemflow collectors (Fig. 2.1c) consisted of a PE film surrounding a tree trunk like a collar, with a tube connecting the collar to a rain gage to measure water volume. Moreover, a reservoir tank (12 L) was set under the rain gage to collect monthly water samples. In the TDF, stemflow collectors were installed on three tree stems in each of the three main species (*Q. crispula, B. ermanii,* and *B. platyphylla* var. *japonica*). In the SEF, stemflow collectors were installed on 12 tree stems of various diameter at breast height classes (20–50 cm) of the dominant species, *C. cuspidata*. The sampled trees were evenly distributed across the both study plots.

During the snowy season in the TDF, snowpack samples were collected in January 2016 and January 2017, when the snowpack had accumulated to its thickest amount. Within the plot, three random locations were selected as sampling points. Snow samples were collected using a 100-mL soil corer from the snow surface to the soil surface (64.3 cm snow depth in January 2016, and 107 cm snow depth in January 2017). Because there was no tree canopy cover, and the understory was also overwhelmed by thick snowpack during the snow season, we assumed that throughfall was the same as bulk precipitation and that there was no stemflow.

2.2.3 Chemical Analysis and Calculation of Fluxes

All water samples were filtered through a 0.45-μm MF-Millipore nitrocellulose membrane. The concentrations of DOC in the solution were measured using a total organic carbon analyzer (TOC-V, Shimadzu, Japan). Additionally, DOC fluxes were calculated based on the average concentration (mg L^{-1}) and water depth (mm) during each sampling time. See Chen et al. (2017b) for further details.

We used the net throughfall (TF) and net stemflow (SF) to identify the DOC fluxes that were influenced by the canopy and trunk. Net TF and net SF were calculated using the following formulas:

$$\text{net TF} = (\text{DOC}_{\text{TF}}—\text{DOC}_{\text{BP}}) \times \text{V}_{\text{TF}};$$

$$\text{net SF} = (\text{DOC}_{\text{SF}}—\text{DOC}_{\text{BP}}) \times \text{V}_{\text{SF}};$$

where DOC_{TF} is the DOC concentration of collected samples of throughfall, DOC_{SF} is the DOC concentration of collected samples of stemflow, DOC_{BP} is the DOC concentration of collected samples of bulk precipitation, V_{TF} is the volume of throughfall, and V_{SF} is the volume of stemflow.

2.3 Dynamics of DOC Concentrations in Forest Ecosystems

2.3.1 DOC Concentration in TDF and SEF

When bulk precipitation entered the forest, the DOC concentration increased in both the TDF and SEF (Table 2.1). During the growing season, in the TDF, the mean DOC concentration in stemflow (15.05 mg C L^{-1}) was much higher than that in throughfall (7.08 mg C L^{-1}) and was more than seven times higher than that in bulk

Table 2.1 Water budget of precipitation, and annual mean dissolved organic carbon (DOC) concentration and fluxes of different hydrological fluxes in a cool-temperate deciduous forest (TDF) and a warm-temperate/subtropical evergreen forest (SEF)

Forest type		Bulk precipitation	Throughfall	Stemflow
Water budget (mm period^{-1})				
	TDF (Growing season)	1592	1122	42.5
	TDF (Snow season)	864	≃864	≃0
	SEF	1864	1436	67.7
Proportion of bulk precipitation (%)				
	TDF (Growing season)	–	70.5	2.7
	TDF (Snow season)	–	≃100	≃0
	SEF	–	77.0	3.6
DOC concentration (mg C L^{-1})				
Mean	TDF (Growing season)	2.98 ± 0.45	7.08 ± 0.42	15.1 ± 0.98
	TDF (Snow season)	0.98 ± 0.10	–	–
	SEF	2.80 ± 0.37	6.62 ± 1.62	11.9 ± 0.96
Range	TDF (Growing season)	1.03 ~ 4.74	1.63 ~ 19.5	3.60 ~ 37.90
	TDF (Snow season)	0.33 ~ 2.20	–	–
	SEF	0.68 ~ 5.32	1.79 ~ 22.2	4.96 ~ 17.25
DOC flux (g C m^{-2} period^{-1})				
	TDF (Growing season)	4.55	7.94	0.62
	TDF (Snow season)	0.27	≃0.27	≃0
	TDF (Annual)	4.82	8.21	0.62
	SEF (Annual)	3.54	7.30	0.90
net DOC flux (g C m^{-2} period^{-1})				
	TDF (Growing season)	–	4.77	0.50
	TDF (Snow season)	–	≃0	≃0
	TDF (Annual)	–	4.77	0.50
	SEF (Annual)	–	4.82	0.62

We assumed no net flux of throughfall (throughfall ≃ bulk precipitation) and no stemflow in the snow season in the TDF. Data from Chen et al. (2017b) and Chen (2019)

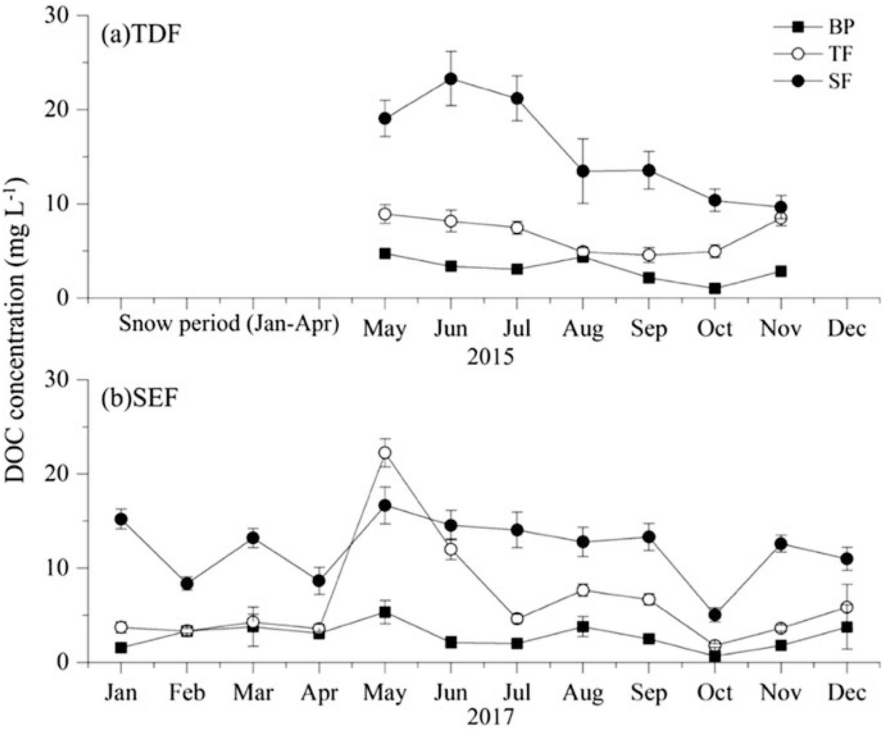

Fig. 2.2 Monthly average dissolved organic carbon (DOC) concentrations of bulk precipitation (BP), throughfall (TF), and stemflow (SF) in a cool-temperate deciduous forest (TDF) in 2015 (**a**), and a warm-temperate/subtropical evergreen forest (SEF) in 2017 (**b**). Data from Chen et al. (2017b) and Chen (2019)

precipitation (2.98 mg C L^{-1}; $p < 0.05$). In the SEF, the annual mean DOC concentrations in throughfall (6.62 mg C L^{-1}) and stemflow (11.87 mg C L^{-1}) were 2.4 and 4.2 times greater than that in precipitation (2.80 mg C L^{-1}), respectively (Table 2.1). The mean concentrations of DOC in bulk precipitation and throughfall were nearly the same in both forests.

There were seasonal changes in the stemflow DOC concentration in the TDF (Fig. 2.2a). The DOC concentration in stemflow was high during the early summer (June or July), then gradually decreased. Compared with stemflow, the DOC concentrations in throughfall and bulk precipitation did not show a distinct monthly variation in the TDF (Fig. 2.2a). Similarly, the DOC concentration in precipitation did not show a distinct monthly variation in the SEF; however, the DOC concentrations in throughfall and stemflow exhibited significant monthly variations (Fig. 2.2b). In May, the DOC concentrations in throughfall and stemflow were 22.24 and 17.24 mg C L^{-1}, respectively, which corresponded to the highest values of the year, before they gradually decreased (Fig. 2.2b).

2.3.2 Factors Affecting DOC Concentration in Throughfall

To date, throughfall has been sampled in most forest ecosystems, including various climatic zones, although research in boreal forests is sparse (Table 2.3). Previous studies have reported that the throughfall DOC concentration in subtropical and temperate forests ranges from 5 to 11 and 7.08 to 29 mg L^{-1}, respectively (Fig. 2.3a). Throughfall DOC concentration ranges are greatest in temperate forests, likely due to their pronounced differences in seasonal leaf states. Conversely, studies of evergreen forest types (subtropical and boreal forests) have noted the lowest variability in throughfall DOC concentrations. The lowest and second-lowest mean throughfall DOC concentrations have been noted in tropical and subtropical forests; this be attributed to their high rainfall conditions, with some studies reporting that large or intense storms are able to wash tree surfaces clean and dilute DOC concentrations (Goller et al. 2006; Levia et al. 2012). In this study, the DOC concentrations of stemflow and throughfall in the TDF and SEF (Table 2.1) were slightly lower than those in previous reports (9–29 mg C L^{-1}), while the DOC concentrations in the precipitation (2.98 and 2.80 mg C L^{-1}) was somewhat higher than those reported in other studies (1.8–2.7 mg C L^{-1}; Currie et al. 1996; Michalzik and Matzner, 1999; Moreno et al. 2001; Solinger et al. 2001).

In the SEF, there was a positive correlation between throughfall DOC concentration and the dry weight of litterfall (Table 2.2). Nitta and Ohsawa (1997) reported that the leaf phenology of *Castanopsis sieboldii* peaked in May, simultaneously with leaf emergence in central Japan. Altogether, we assumed that the amount of litter fall did not directly affect the DOC concentration, but the phenological phenomena on the canopy (e.g., new leaf emergence, florescence) had a great impact on the throughfall DOC concentration. The mean DOC concentration of snowpack (0.98 ± 0.10 mg C L^{-1}) in the TDF was much lower than that in throughfall (7.08 ± 0.42 mg C L^{-1}) during the growing season, due to the leafless conditions (Table 2.1). Comiskey (1978) reported that throughfall DOC concentrations beneath a summer, fully leafed canopy were more than 20 times greater than during the winter, under leafless conditions, in a temperate deciduous forest. Moreover, Solinger et al. (2001) observed obvious changes in throughfall DOC concentrations that significantly correlated with mean seasonal air temperature in a central European deciduous forest.

In both the SEF and TDF, there were no significant correlations between the DOC concentration in the different hydrological fluxes and the precipitation amount (Table 2.2). Rainfall amounts and intensity are uncertain factors with respect to their impact on DOC concentrations; some studies, including our study, have revealed that DOC concentrations are independent of rainfall amount (Solinger et al. 2001; Michalzik et al. 2001), whereas other studies have found that the DOC concentrations in throughfall and stemflow are inversely related to rainfall amount and intensity (Goller et al. 2006; Levia et al. 2012), indicating that large or intense storms may wash tree surfaces clean and dilute tree DOC. The rainfall dilution effect on DOC concentration may be offset by other covarying factors, such as biological

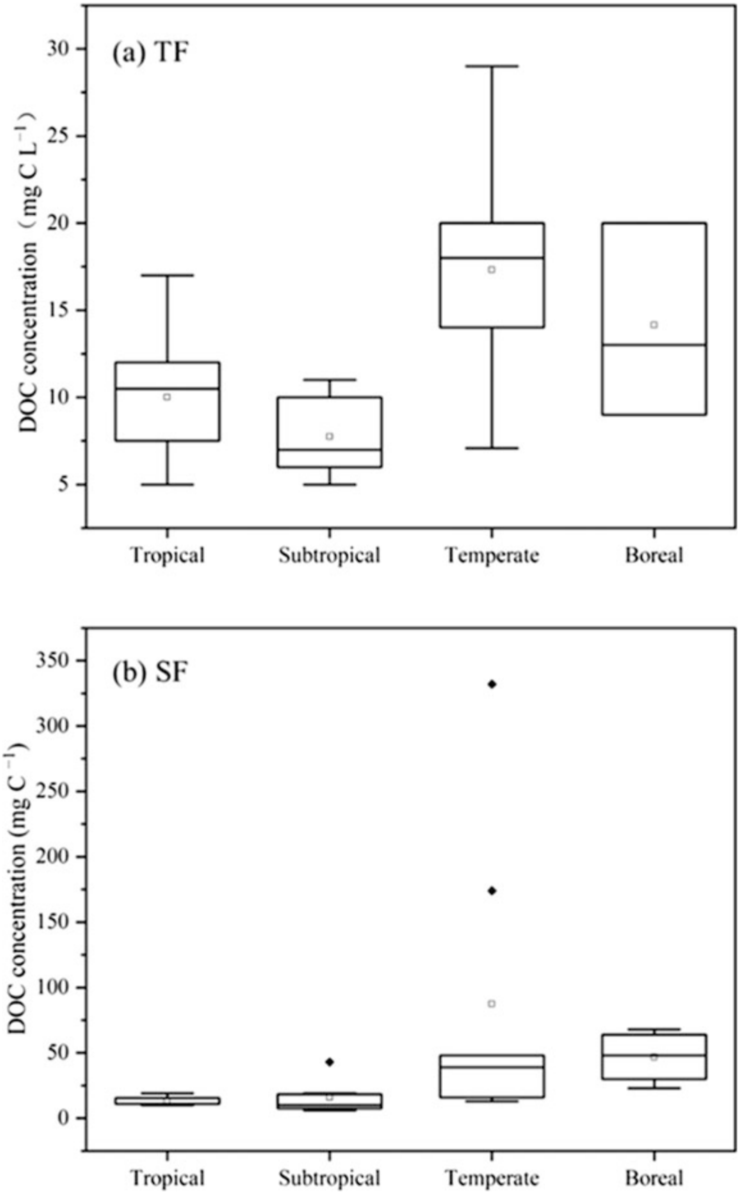

Fig. 2.3 Mean values and ranges of throughfall (**a**) and stemflow (**b**) dissolved organic carbon (DOC) concentrations in different forest types, across climate zones

Table 2.2 Correlation coefficients between the monthly mean DOC concentrations and the monthly DOC fluxes in throughfall and stemflow, with environmental factors such as monthly precipitation, monthly mean temperature, and litter fall in a cool-temperate deciduous forest (TDF, $n = 7$) and a warm-temperate/subtropical evergreen forest (SEF, $n = 12$)

	Monthly mean DOC concentrations		Monthly DOC fluxes				
	Throughfall	Stemflow	Throughfall	Stemflow	Monthly precipitation	Monthly mean temperature	Litter fall
	(mg C L^{-1})		(g C m^{-2} $month^{-1}$)		(mm)	(°C)	(g m^{-2} $month^{-1}$)
Temperate deciduous forest (TDF)							
DOC concentration							
Throughfall (TF)	–	0.842*	0.631	–	−0.109	0.072	−0.067
Stemflow (SF)	0.842*	–	–	0.399	−0.402	0.548	−0.289
DOC flux							
Throughfall (TF)	0.631	–	–	0.210	−0.226	0.211	−0.083
Stemflow (SF)	–	0.399	0.210	–	0.300	−0.077	−0.045
Warm-temperate/subtropical evergreen forest (SEF)							
DOC concentration (mg C L^{-1})							
Throughfall (TF)	–	0.708	0.726**	–	−0.210	0.364	0.716**
Stemflow (SF)	0.708**	–	–	−0.432	−0.475	0.318	0.414*
DOC flux (g C m^{-2} $month^{-1}$)							
Throughfall (TF)	0.726**	–	–	0.329	0.323	0.459	0.516
Stemflow (SF)	–	−0.432	0.329	–	0.917**	0.754*	0.071

Data from Chen et al. (2017a) and Chen (2019)
* indicates significant relationships at $p < 0.05$
** indicates significant relationships at $p < 0.01$

activities and changes in leaf leaching (Yan et al. 2015). Furthermore, variations in DOC concentration are profound between wet and dry seasons, with throughfall and stemflow DOC concentrations being ~10 times higher at the start of the rainy season due to the accumulation of materials during the dry season (Laclau et al. 2003; Ciglasch et al. 2004).

2.3.3 Factors Affecting DOC Concentration in Stemflow

Similarly to throughfall, stemflow DOC concentration ranges are large for most temperate forests and small for evergreen forests (Fig. 2.3b); the DOC concentration of stemflow in subtropical and temperate forests ranges from 6 to 43 and 13 to 332 mg L^{-1}, respectively (Fig. 2.3b). Stemflow DOC concentrations (volume-weighted means) show greater variabilities across forest types (6–332 mg C L^{-1}) than is noted with throughfall concentrations (5–29 mg C L^{-1}). From this study, the DOC concentrations of stemflow in the TDF and SEF were within the lower range of the previous reports, as was the case for throughfall (Table 2.1). The sources of stemflow DOC are dry deposition, canopy and trunk leaching, and incident precipitation. There were significant and positive relationships between the concentrations of DOC in stemflow and the DOC in throughfall in both the SEF and TDF (Table 2.2), with DOC concentration increasing in both forests in the sequence from precipitation to throughfall. Moreover, the stemflow was similar to those reported in other forests (Tesón et al. 2014). Levia et al. (2012) also reported that stemflow DOC concentrations diminished by 50–60% under leafless canopy conditions, compared to fully leafed conditions, likely due to dilution by the enhanced stemflow generation of leafless canopies, but possibly also due to the decrease in leaf surface area and biological activity associated with winter senescence. Phenological phenomena, such as leaf shed during the winter season in the TDF, and leaf and flowering flush in the spring in the SEF, also had indirect impacts on the DOC concentrations of stemflow.

For stemflow, the ability of tree species-specific canopy structures to funnel rainfall to their stem is a factor that affects DOC concentrations (Van Stan and Stubbins 2018). Although increasing rainfall amounts have been similarly shown to dilute throughfall DOC concentrations (Levia et al. 2012), no clear species-specific structural influences over throughfall DOC concentrations have been identified. In the TDF, the stemflow DOC concentration of *Quercus* species was significantly higher than that of either *Betula* species (Chen et al. 2017b); this is owed to the rough and multi-layered fibrous bark of *Quercus*, which retains precipitation longer than the single-layered bark of *Betula*, allowing more DOC to leach. These results match those observed in earlier studies (Inagaki et al. 1995; Levia and Herwitz 2002), in which the DOC concentrations in stemflow were regulated by the retention time of precipitation in the bark, implying that the DOC concentration in stemflow is affected by different bark morphologies.

2.4 Dynamics of DOC Fluxes in Forest Ecosystems

2.4.1 Water Partitioning

The partitioning of gross rainfall into throughfall, stemflow, and intercepted water is controlled by the forest composition, seasonality and canopy foliar status, rainfall characteristics, and meteorological conditions (Siegert and Levia 2014). During the growing season (May–November 2015), the bulk precipitation flux in the TDF was 1592.3 mm, which was partitioned into stemflow (42.5 mm, 2.7% of bulk precipitation) and throughfall (1122.3 mm, 70.5%; Table 2.1). The annual bulk precipitation flux in the SEF was 1864 mm, which was partitioned into stemflow (67.7 mm, 9.0% of bulk precipitation) and throughfall (1436 mm, 77.0%; Table 2.1). Throughfall inputs and canopy interception varied across the different kinds of forests; mean throughfall inputs are reported to range from 27 to 96%, whereas canopy interception loss is reported to range from 9.7 to 19.5% in deciduous forests (Price and Carlyle-Moses 2003). In Japan, the throughfall range has been reported to be from 64 to 97% (Ikawa 2007). In our study, the throughfall (70.5%) and canopy interception (11.6%) measured in the TDF were within the ranges reported from other forests. Conversely, although the proportion of canopy interception (19.4%) in the SEF is slightly lower than that (20.2–48.2%) for a warm-temperate evergreen broad-leaved forest in Kochi, Japan (Fujimoto 1997), it is within the widely reported range of 15–30% for many broad-leaved evergreen forests around the world (Crockford and Richardson 2000; Iroume and Huber 2002).

Stemflow is the smallest fraction of gross rainfall (Helvey and Patric 1965; Levia and Frost 2003). According to Levia and Frost (2003), the mean stemflow inputs range from 0.94 to 20% of the gross rainfall in temperate forests; the average stemflow input in temperate forests is 11.3%. In the TDF and SEF, the stemflow was 2.7 and 3.6% of the gross rainfall, respectively; these are both lower than the average for temperate forests, but are still within the range observed in other forests. Tree size and bark water storage capacity are among the key factors that control stemflow intrastorm generation from deciduous species in the eastern United States (Levia et al. 2010). The lower observed volume of stemflow in the TDF may be attributable to its higher bark water storage capacity. Moreover, González-Martínez et al. (2016) found that understory importantly contributes to stemflow, particularly if the density of the understory vegetation groups is high. Furthermore, this noted difference may be due to variation in the forest structures and rainfall characteristics, as well as the sampling designs (Lloyd 1988; Xu et al. 2005).

2.4.2 DOC Fluxes in Throughfall and Stemflow

Bulk precipitation in the TDF and SEF brought 4.82 and 3.54 g C m^{-2} $year^{-1}$ of DOC into the forest canopy, respectively (Table 2.1). In TDF and SEF, the DOC fluxes in throughfall were 8.21 and 7.30 g C m^{-2} $year^{-1}$, respectively. Canopy and trunks leached 5.27 and 5.44 g C m^{-2} $year^{-1}$ of DOC as net throughfall + stemflow in TDF and SEF, respectively. The throughfall DOC fluxes reported from natural forests in different climate zones range from 1.9 to 48 g C m^{-2} $year^{-1}$ (Table 2.4). Subtropical forests produce the greatest mean and maximum throughfall DOC fluxes (Fig. 2.4a). Additionally, the range in reported throughfall DOC fluxes is greatest for subtropical forests and lowest for boreal forests (Fig. 2.4a). Stemflow DOC fluxes range from 0.01 to 8 g C m^{-2} $year^{-1}$ and vary in response to the species-specific canopy structure (Van Stan and Gordon 2018). The stemflow DOC flux ranges are greatest for tropical forests and lowest for boreal forests (Fig. 2.4b). Although stemflow DOC flux was overlooked in most studies of carbon budgets, Johnson and Lehmann (2006) reported that several large stemflow generating tree species throughout the primary forest ecological zones can generate substantial stemflow DOC to their near-stem soils. All the world's forest types are classified by their temperature and precipitation. DOC fluxes are related to the DOC concentration and water volume, and the drivers that modulate DOC concentration are diverse, including precipitation intensity and frequency, tree morphology, phenoseason, and preceding atmospheric deposition. Therefore, the variation in the DOC fluxes of throughfall and stemflow was attributable to storm duration, storm intensity, and the length of the antecedent dry period, in context with the DOC concentration in the different forest types.

Like the DOC concentrations, the throughfall and stemflow DOC fluxes also demonstrated marked seasonality in the TDF and SEF (Fig. 2.5). In the SEF, the DOC fluxes in throughfall were not significantly correlated with precipitation but were significantly related to its DOC concentration on a monthly scale ($R = 0.726$, $p < 0.01$, Table 2.2). Conversely, in the TDF, there was no significant positive correlation between the DOC fluxes and concentration in throughfall (Table 2.2). Winter is an important season in the TDF; it induces leafed and leafless seasons. As such, we assume that the throughfall DOC concentrations and fluxes were affected by the interaction between precipitation and distinct canopy changes in the TDF.

In the SEF, precipitation was the dominant driver of DOC fluxes in stemflow at a monthly scale ($r = 0.917$, $p < 0.01$, Table 2.2). This effect has also been found in previous studies (Michalzik et al. 2001; Fujii et al. 2009). In contrast, in the TDF, there was no significant correlation between monthly stemflow DOC fluxes and monthly precipitation. Within the leafed or leafless periods in the TDF, precipitation type can affect the stemflow amount. Levia and Underwood (2004) found that winter stemflow generation from leafless deciduous trees is affected by the precipitation event type (e.g., rain, rain-to-snow, and snow-to-rain); even with similar durations, magnitudes, and intensities, different types of precipitation events can produce drastically different stemflow amounts. Furthermore, the canopy state also has a great impact on stemflow amount. Staelens et al. (2007) found that, for various species, stemflow production is greater in a leafless state, which appears to contradict the results of Levia et al. (2012), who noted that stemflow DOC flux diminishes with leaf fall because there is less canopy area to receive dry deposited or organism-derived DOM.

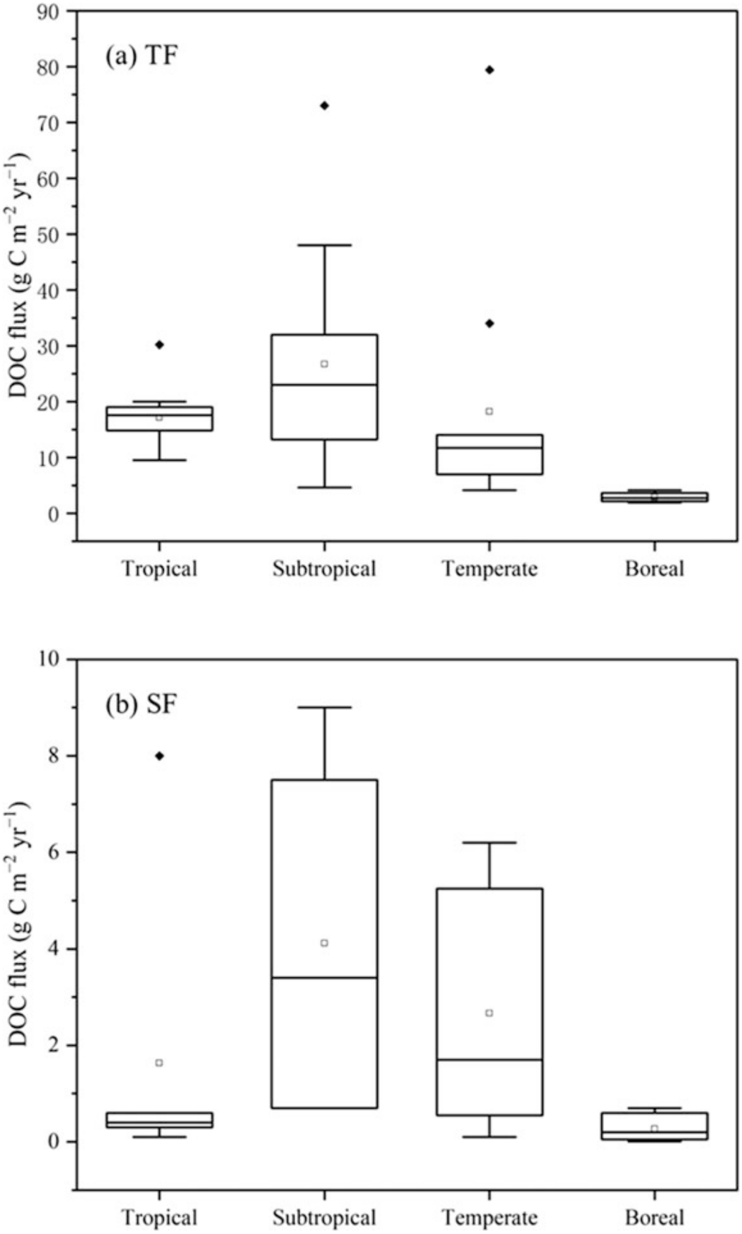

Fig. 2.4 The annual dissolved organic carbon (DOC) flux of throughfall (**a**) and stemflow (**b**) in different forest types, across climate zones

Chen et al. (2019) concluded that tree size is the main factor that controls the stemflow volume and percentage, but only when rainfall intensity is <15 mm h^{-1}.

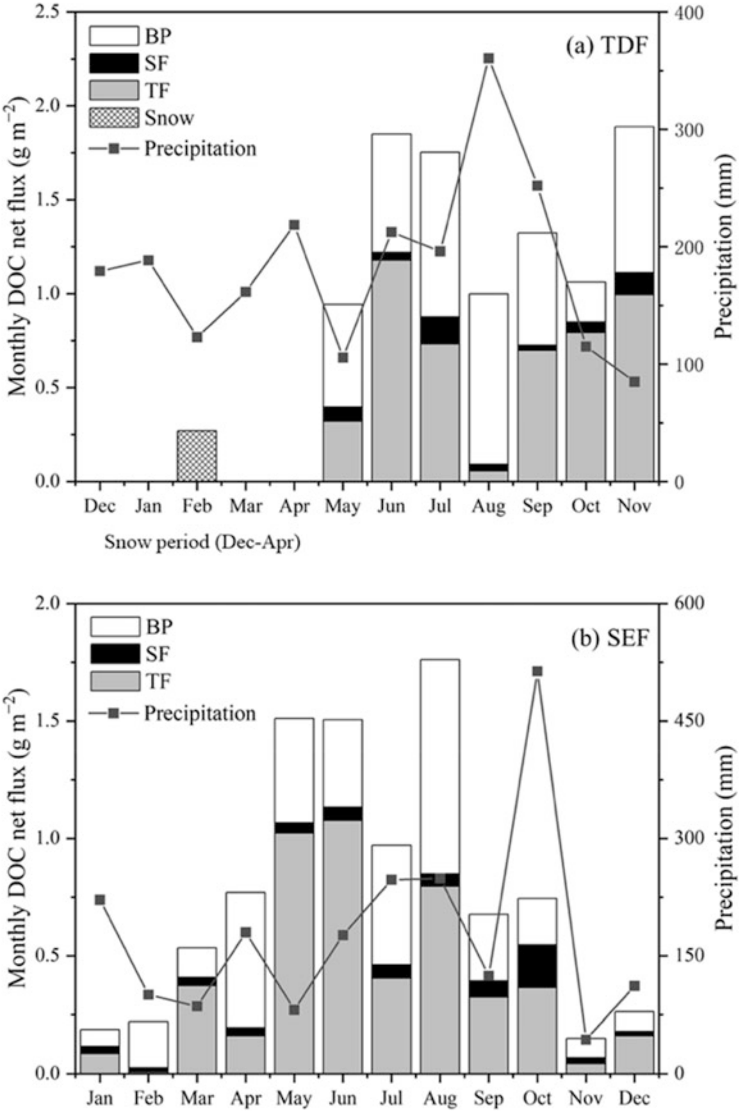

Fig. 2.5 Monthly net DOC flux (bar graph) of bulk precipitation (BP), stemflow (SF), and throughfall (TF), and monthly precipitation (line graph) in (**a**) a cool-temperate deciduous forest (TDF) and (**b**) a warm-temperate/subtropical evergreen forest (SEF). Data from Chen et al. (2017a) and Chen (2019)

The stemflow DOC fluxes were profoundly affected by tree size in the SEF. Furthermore, in the SEF, the monthly DOC fluxes in stemflow were statistically correlated with temperature ($r = 0.754$, $p < 0.05$, Table 2.2); this further supports the supposition that annual mean air temperature may be a main factor influencing annual DOC fluxes, since many biological processes in the production and consumption of DOC depend on temperature (Michalzik and Matzner 1999; Watmough et al. 2004; Schaefer and Alber 2007). Altogether, the factors that drive both the throughfall and stemflow fluxes in the TDF were more complicated than those in the SEF; this is likely due to the profound seasonal canopy change and snow season in the TDF.

2.4.3 DOC Fluxes in the Context of the Carbon Cycle

Forest ecosystems play an important role in absorbing atmospheric CO_2 and temporarily accumulating it as organic matter. The process through which forest ecosystems accumulate organic matter, and their locations, is generally quantified by the biometric method (Ohtsuka et al. 2016). This method determines the balance between NPP, which is the amount of organic matter substantially produced by autotrophs through the absorption of CO_2, and the amount of CO_2 released by heterotrophs by decomposing organic matter, called the net ecosystem production (NEP). In forest ecosystems, the flux of water-mediated carbon (aquatic C), such as DOC, is far less than that of NPP and soil respiration, and has often been neglected in conventional biometric studies (e.g., Ohtsuka et al. 2010).

In recent years, DOC flux from soil has become a crucial component of the net ecosystem carbon budgets at the catchment scale (Webb et al. 2019). For example, in mangrove forests, part of the produced organic matter is released as DOC, but a large part of the decomposed CO_2 is released into the ocean with tidal changes as DIC (Ohtsuka et al. 2020) Furthermore, DOC leakage out of the system has been noted as the cause of differences in NEP estimates calculated using the biometric method, which quantifies organic matter accumulation in the ecosystem, and the eddy-covariance method, which quantifies the CO_2 balance in the forest canopy (Kindler et al. 2011).

In forest ecosystems, if the origin of DOC in throughfall and stemflow is plant leaching, these are part of the organic matter produced by plants. Thus, ignoring these sources is an underestimation of NPP in the biometric method. Ohtsuka (2012) reported 1.07 ± 0.26 ton C ha^{-1} $year^{-1}$ of woody production and 1.83 ± 0.12 ton C ha^{-1} $year^{-1}$ of foliage production in the TDF. In the SEF, woody production is 1.63 ± 0.08 ton C ha^{-1} $year^{-1}$ (Chen et al. 2017a), and the annual litter production of foliage and reproductive organs is 1.99 ± 0.04 and 1.35 ± 0.92 ton C ha^{-1} $year^{-1,}$ respectively (unpublished data, 2017–2019). DOC is also contained in rainfall, and the net DOC fluxes from throughfall and stemflow at the study sites were 52.7 and 54.4 kg C ha^{-1} $year^{-1}$ for the TDF and SEF, respectively (Table 2.1); these values are only 1 to 2% of the above-ground NPPs, thus the issue of underestimation is not very significant. Clark et al. (2001) stated that volatile emissions from plants, which are the source of leaching from the canopy, contribute to about 0–5% of the NPP.

Conversely, DOC flux is an important part of the process by which carbon is stored in the soil (Cotrufo et al. 2015). The DOC in the throughfall and stemflow in forest ecosystems eventually joins with the products of litter decomposition, which is supplied to the soil as litter leachate. For example, Chen (2019) studied the dynamics of litter leachate at these two sites and found that it was 311.5 kg C ha^{-1} within the growing season in the TDF and 309.5 kg C ha^{-1} per year in the SEF. The contribution of net throughfall and stemflow (Table 2.1) to litter leachate reached 16.9% in the TDF and 17.6% in the SEF. Thus, in forest ecosystems, the contribution of throughfall and stemflow to the DOC flux to the soil cannot be ignored. Moreover, the DOC flux of stemflow is often overlooked in water and carbon budgets due to the low contribution of litter leachate, compared to the throughfall; however, it can contribute substantial DOC fluxes to near-stem soils (Johnson and Lehmann 2006) and can be 10–100 times more chemically enriched than rainfall or throughfall (Van Stan and Gordon 2018).

Studies on the fate of supplied DOC to the mineral soil remain limited. Previous studies showed that nearly 50% of the DOC fluxes in throughfall consist of carbohydrates that are dominated by microbial metabolites washed from the canopy, and about 80% of these carbohydrates are easily decomposable. Thus, throughfall provides easily decomposable carbon compounds, which probably act as co-substrates or promoters for the decomposition and mineralization processes of organic carbon on the forest floor (Guggenberger and Zech 1994; Michalzik et al. 2001). Accordingly, although some DOCs are readily degradable, others are adsorbed stably by the soil and play a central role in soil carbon sequestration (Kawahigashi et al. 2006). Furthermore, some DOCs are discharged out of the system through groundwater at the watershed scale, but this does not occur to a large extent in forest ecosystems, except in mangrove forests (Webb et al. 2019). In general, the CO_2 absorbed in forest ecosystems accumulates either in the woody biomass pool of trees or in the soil carbon pool as NEP; however, biometric methods induce a great deal of uncertainty in estimates of the latter compared to the former, which can be directly quantified by allometry (Ohtsuka et al. 2013). Future studies of detailed dynamics, including input by DOC flux, as well as its short-term decomposition and DOC output at the watershed scale, may provide direct verification of soil carbon sequestration in forest ecosystems.

2.5 Conclusion

Although DOC fluxes in throughfall and stemflow are quantitatively significant fluxes of carbon, they remain poorly integrated into models, budgets, and conceptualizations of terrestrial and aquatic ecosystem biogeochemistry. Most studies have investigated the factors that control the amount and quality of throughfall and stemflow. The factors that affect the throughfall and stemflow DOC concentrations are diverse, including rainfall chemistry, precipitation intensity and frequency, tree morphology, phenology, canopy change, and preceding atmospheric deposition.

Our results from two forest stands indicate that canopy phenological patterns (e.g., leafless snowy season, leaf and/or flowering flush) are the direct and indirect reasons for variability in throughfall and stemflow DOC concentrations. Moreover, the DOC concentrations in stemflow were regulated by species-specific retention time in the bark. The DOC flux is a result of DOC concentration and water budget. Current research suggests that rainfall frequency, rainfall amount, and rainfall partitioning all influence the throughfall and stemflow DOC fluxes. In addition to these hydrological drivers, biological drivers should also be assessed, such as tree morphology, canopy phenology, and the presence and type of epiflora and epifauna. In time, these assessments should improve our understanding and predictions of the quantity and quality of throughfall and stemflow DOC generation and export. Furthermore, stemflow brings abundant water and nutrients to the soils near stems, suggesting that stemflow may have an important influence on the ecological processes of near-stem soils, few rare studies have investigated this influence.

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Appendix Tables

Table 2.3 Annual volume-weighted mean concentrations of dissolved organic carbon (DOC) in throughfall (TF) and stemflow (SF) in various forest ecosystems across climate zones

Forest type	Mean TF (mg C L^{-1})	Mean SF (mg C L^{-1})	Study site description	References
Tropical	6 ± 3	–	Tabonuco (*Dacryodes excelsa*) forest type	McDowell (1998)
	9 ± 42	54 ± 270	Eucalypt	Laclau et al. (2003)
	10 ± 8	–	Savanna	
	12 ± 6	11 ± 12	Sedimentary plain (mature pristine rain forest)	Tobon et al. (2004)
	13 ± 12	11 ± 16	High Terrace (mature pristine rain forest)	
	11 ± 8	10 ± 14	Low Terrace (mature pristine rain forest)	
	8 ± 7	19 ±32	Floodplain (mature pristine rain forest)	
	5 ± 1	–	*Pinus kesiya*	Moller et al. (2005)
	12	15	Microcatchment 1 (evergreen montane forest)	Goller et al. (2006)
	11	14	Microcatchment 2.1 (evergreen montane forest)	
	12	–	Microcatchment 2.2 (evergreen montane forest)	
	15	–	Microcatchment 2.3 (evergreen montane forest)	
	17	19	Microcatchment 3 (evergreen montane forest)	
	9 ± 2	–	Mature forest	Schrumpf et al. (2006)
	12 ± 2	–	Secondary forest	
	7 ± 5	–	Tropical rainforest, Brazil	Germer et al. (2007)
	11 ± 4	16 ± 12	Fringe *Rhizophora mangle*	Wanek et al. (2007)
	6 ± 2	11 ± 11	Dwarf *R. mangle*	
	9 ± 0.7	–	*Shorea laevis* and *Dipterocarpus cornutus* (BS)	Fujii et al. (2009)
	5 ± 0.3	–	*Shorea laevis* and *Dipterocarpus cornutus* (BB)	
	–	40	Primary ridge forest	Hofhansl et al. (2012)
	–	16	Primary ravine forest	
	–	26	Secondary ravine forest	

(continued)

Table 2.3 (continued)

Forest type	Mean TF (mg C L^{-1})	Mean SF (mg C L^{-1})	Study site description	References
Subtropical				
	10 ± 4	10 ± 5	Secondary hardwood	Liu and Sheu (2003)
	8 ± 3	7 ± 4	Natural hardwood	
	5 ± 1	43 ± 28	*Cunninghamia lanceolate*	Wang et al. (2004)
	7 ± 3	8 ± 5	Secondary hardwood	
	6 ± 2	6 ± 2	Natural hardwood	
	11 ± 8	18 ± 14	*Schima superba*	Guo et al. (2005)
	10 ± 7	19 ± 17	*Cunninghamia lanceolata*	
	6 ± 24	–	Subtropical wet forest	Heartsill-Scalley et al. (2007)
	6.6 ± 1.3	12 ± 3.3		Present study
Temperate				
	17 ± 13	332 ± 820	Maimai (*Pinus radiata*)	Moore (1987)
	22 ± 13	43 ± 23	Larry river (*Leptospermum scoparium, P. radiata*)	
	9 ± 2	–	Deciduous forest	Qualls et al. (1991)
	25 ± 19	–	Pine forest	Currie et al. (1996)
	29 ± 44	–	Hardwood forest	
	20 ± 7	28 ± 17	*Populus tremuloides*	Kolka et al. (1999)
	20 ± 7	35 ± 32	*Betula papyrifera-Acer rubrum*	
	18 ± 4	39 ± 7	*Abies balsamea*	
	18 ± 4	174 ± 98	*Picea mariana*	
	16	16	Beech and oak	Chang and Matzner (2000)
	10	–	*Picea abies*	Frank et al. (2000)
	14	–	European deciduous forest	Solinger et al. (2001)
	–	13 ± 8	*Fagus grandifolia*	Levia et al. (2012)
	–	48 ± 35	*Liriodendron tulipifera*	
	7.08 ± 0.42	15.05 ± 0.98	Deciduous forest	Chen et al. (2017a)
Boreal				
	9	30	Broadleaved upland forest	Dalva (1991)
	13	23	Swamp forest	
	15	68	Needleleaved upland forest	
	20 ± 7	64 ± 26	*Pinus banksiana*	Moore (2003)
	20 ± 14	37 ± 19	*P. tremuloides*	
	13 ± 4	59 ± 25	*P. mariana*	
	9 ± 10	–	*Acer saccharum, Fagus grandifolia*	Turgeon and Courchesne (2008)

Table 2.4 Annual mean dissolved organic carbon (DOC) fluxes of throughfall (TF) and stemflow (SF) in various forest ecosystems across climate zones

Forest type	Mean TF (g C m^{-2} $year^{-1}$)	Mean SF (g C m^{-2} $year^{-1}$)	Study site description	References
Tropical		8	*Cyrilla racemiflora*	Frangi and Lugo (1985)
	15.1	–	Mature forest	Schrumpf et al. (2006)
	20	–	Secondary forest	
	14.8	0.3	Sedimentary plain	Tobon et al. (2004)
	19	0.3	High terrace	
	17.5	0.5	Low terrace	
	17.6	0.6	Floodplain	
	30.2	–	Tropical rainforest, Brazil	Germer et al. (2007)
	18.2		*Shorea laevis* and *Dipterocarpus cornutus* (BS)	Fujii et al. (2009)
	9.7		*Shorea laevis* and *Dipterocarpus cornutus* (BB)	
	9.5	0.1		Hofhansl et al. (2012)
Subtropical	4.6		Eucalypt	Laclau et al. (2003)
	4.8		Savanna	
	23.1	1.5	Secondary hardwood	Liu and Sheu (2003)
	18.9	0.7	Natural hardwood	
	13.2	–	Subtropical wet forest	Heartsill-Scalley et al. (2007)
	23	0.7	Oak with epiphytes	Van Stan and Stubbins (2018)
	48	5.3	Cedar with epiphytes	
	32	7.5	Bare cedar	
	73	9		Present study
Temperate	4.1	–	*Fagus grandifolia, Betula alleghaniensis, Acer saccharum*	McDowell and Likens (1988)
	34	5.6		Moore and Jackson (1989)
	13.1	–	Deciduous forest	Qualls et al. (1991)
	13.9	–	Pine forest	Currie et al. (1996)

(continued)

Table 2.4 (continued)

Forest type	Mean TF (g C m^{-2} $year^{-1}$)	Mean SF (g C m^{-2} $year^{-1}$)	Study site description	References
	11.7	–	Hardwood forest	
	6.8	0.8	*Populus tremuloides*	Kolka et al. (1999)
	14	0.5	*Betula papyrifera*	
	7.7	0.6	*Abies balsamea*	
	8.4	0.1	*Picea mariana*	
	7	–	European deciduous forest	Solinger et al. (2001)
	–	4.9	*Fagus grandifolia*	Levia et al. (2012)
	–	2.6	*Liriodendron tulipifera*	
	79.4	6.2	Deciduous forest	Chen et al. (2017a)
Boreal				
	1.9	0.1	Broadleaved upland forest	Dalva (1991)
	2.2	0.05	Swamp forest	
	2.1	0.2	Needleleaved upland forest	
	4.1	0.01	Woodland	Koprivnjak and Moore (1992)
	3.3	–	Forest	
	4	0.6	*Pinus banksiana*	Moore (2003)
	3.2	0.7	*P. tremuloides*	
	2.3	0.2	*P. mariana*	

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