Controls on the Dynamics of Dissolved Organic Carbon in Litter Leachate in Contrasting Two Forest Ecosystems

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(対照的な二つの森林生態系におけるリター浸出液中の溶存有機炭素動態の制御要因)

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Abstract

Dissolved organic carbon (DOC) can hydrologically transport carbon between different pools in the ecosystem, and it is also the major form of carbon transported with soil solution and in streams. Despite growing attention to the role of DOC in forest carbon cycling, to date, most of studies about DOC dynamics were focus on forested catchment or in the soil profile. Less information is available on comparing the effects of vegetation type, forest structure and canopy phenology on DOC of throughfall, stemflow and litter leachate at different forests. Considering deciduous and evergreen forests are the two main type of forests in the world, which has different vegetation types with different leaf emergence patterns and life spans. The previous studies indicated canopy structure is an important controlling factor on water partitioning in the forest, and throughfall patterns have been reported a great variability between leafed and leafless seasons in the broadleaved deciduous forest. Hence, given the importance of DOC fluxes in the forest carbon balance, and the forest floor is the primary source of DOC, it is essential to analyze controlling factors of DOC concentrations and fluxes from the forest floor in related to throughfall, stemflow and litter leachate in different forest ecosystems.

Our researches were established on two study plots at a cool-temperate deciduous broad-leaved and a warm-temperate evergreen broad-leaved forest in Central Japan, respectively. The main objective of this research is to evaluate the controls on the dynamics of DOC in litter leachate in these two forests. The deciduous broad-leaved forest contained 35 species, while evergreen forest contained 26 species. Stand density in

the deciduous forest was 581 stems ha^{-1} comparing 379 stems 0.7 ha^{-1} in the evergreen forest. However, the basal area of evergreen forest (46.08 m^2 ha^{-1}) was higher than that of deciduous forest (29.37 m^2 ha^{-1}), moreover, Shannon's diversity index in the evergreen and the deciduous forest was 1.19 and 2.74, respectively. In the evergreen forest, *C. cuspidata* occupied 90.24% and 91.70% in the number, and the BA of the whole living tree stems in 2017 (DBH ≥10 cm), respectively. Nevertheless, the compositions of BA and stem number were more involved in deciduous forest, the dominant five species in the number and BA were *Quercus crispula, Betula ermanii, Betula platyphylla, Magnolia obovate,* and *Tilia japonica*, which occupied 54.12% in stem number and 78.41% in BA (DBH ≥ 5 cm). Beyond that, the forest floor of the deciduous forest is covered 100% (ca. 40 stems m^{-2}) by a very dense evergreen dwarf bamboo *Sasa senanensis* with the height of 1—1.5 m.

Mean DOC concentration during the study period increased in the sequence from bulk precipitation, throughfall, stemflow, and litter leachate at both study forests. The monthly variations of DOC concentrations were very similar in throughfall and stemflow at the deciduous and evergreen forests, which were highest in the leaf emergence season (May or June), then gradually decreased. Moreover, litter leachate DOC concentration in the evergreen forest was also highest in May, and it positively and significantly correlated to DOC concentration of throughfall and temperature. Interestingly, litter leachate DOC concentration in the deciduous forest has two peaks, being high in spring and autumn, which was reasonably correlated with the amount of litterfall of bamboo and trees, and positively significant correlation was found between dry weight of previous monthly litterfall and litter leachate DOC concentration. The different litter leachate DOC concentration dynamics in evergreen and deciduous forests may mainly attribute to the different season of litter inputs. Considering the litterfall was more or less synchronized with the leaf emergence of evergreen forest occurred in spring, and the temperature was generally increasing after litterfall, while litterfall of deciduous forest mainly occurred in autumn and the temperature was decreasing; thus the litterfall in the deciduous forest may be decomposed slowly than it in the evergreen forest. These results indicating that canopy phenology (leaf emergence, florescence, and leaf fall) was an essential factor control the throughfall DOC concentration in both evergreen and deciduous forests and indirectly affected the DOC concentrations in litter leachate.

DOC flux is a result of DOC concentration and water budget. Water partitioning in the forest was regulated by forest structure, including tree species composition, tree density and basal area. Litter leachate DOC fluxes were positively related to rainfall amount and throughfall DOC fluxes at monthly scale in both forests. The litter leachate DOC fluxes were 311.5 kg ha^{-1} 7month^{-1} and 309.5 kg ha^{-1} yr^{-1} for deciduous and evergreen forest during the study period, which were comparable to the highest values recorded for temperate forests (100–398 kg ha^{-1} yr^{-1}). The difference of DOC fluxes between two forests might be due to the different rainfall amount, the different canopy phenology, and the species composition (litter input, lignin concentration of foliar litter) of two forests. However, the net contribution of DOC fluxes from throughfall, stemflow, and litter leachate were similar in the two forests. The most significant contribution was from litter leachate while stemflow contributed least.

This study has identified that the different canopy phenology patterns and forest structures are the main factors controlling the variability of DOC in the evergreen and deciduous forests. In the evergreen forest, almost synchronized periods of leaf emergence, florescence and leaf fall resulted in the DOC concentrations of throughfall, stemflow and litter leachate were highest in May. In the deciduous forest, two peaks of litter leachate DOC concentration reflected the different leaf fall patterns, because of the evergreen understory-dwarf bamboo. Beyond that, despite DOC fluxes of precipitation, throughfall, stemflow, and litter leachate exhibited variabilities among different forests, the proportions of DOC fluxes from precipitation, throughfall, stemflow and litter leachate in the total DOC fluxes input to the soil were comparable in different forests.

1. General Introduction

1.1 Deciduous Broad-Leaved Forest and Evergreen Broad-Leaved Forest

Deciduous broad-leaved forests occur in the temperate climate zone of mid-latitudes with a distinct winter, but not one that is too cold or long to support broad-leaved angiosperms (hardwoods). They are mainly dominated by deciduous broad-leaved trees, including the forests of eastern North America, northeastern Asia, and western and central Europe (not including higher mountains)(Perry et al., 2008). These regions have long growing seasons (four to six frost-free months) and precipitation either distributed evenly throughout the year or peaking in the summer. The characteristic dominant broad-leaved trees include oaks (*Quercus* spp.), beeches (*Fagus* spp.), maples (*Acer* spp.), or birches (*Betula* spp.)(Stephen et al., 2017).

Although most temperate forests are characterized by the dominance (or potential dominance) of deciduous broad-leaved trees, where precipitation is concentrated in the winter, temperate forests tend to be dominated by either conifers or evergreen broad-leaved species rather than deciduous broad-leaved species. Temperate evergreen broad-leaved forests occur in the temperate areas with mild, frost-free winters and relatively high precipitation (greater than about 1,500 mm) that is well distributed throughout the year. Evergreen broad-leaved (Lucidophyllous) forests are distributed widely in the subtropical and warm-temperate regions of East Asia (Ohsawa et al., 1990). They are mainly dominated by evergreen species of *Fagaceae, Lauraceae, Theaceae, Magnoliaceae, and Hamamelidaceae*; beyond that, *Castanopsis cuspidata* is one of the typical dominant species from the coastal area of central Japan to southwestern Japan (Tagawa et al., 1995). Ohsawa (1993) suggested that the tropical lower montane forests that are mainly dominated by evergreen *Fagaceae* (especially *Castanopsis*) can be correlated to the horizontal subtropical/warm-temperate zone of East Asia as lucidophyllous forests, and the northern latitudinal limit reaches sea level at 35° N of central Japan.

1.2 Hydrology Cycle in Forest Ecosystem

The hydrologic cycle is an essential feature of all ecosystems, and particularly forests. Precipitation which falls as rain, snow, or fog must first pass through the forest canopy before it reaches the soil. It is partitioned into three fractions: first is interception that remains on the vegetation and is evaporated after or during rainfall; second is stemflow that flows to the ground via trunks or stems; third is throughfall that may or may not contact the canopy and which falls to the ground between the various components of the vegetation (Crockford and Richardson 2000). After precipitation reaches the ground surface by throughfall and stemflow, it may wet the litter, run off, or infiltrate into the soil where it may percolate to the water table. Some water in the soil is extracted by plant roots, and the part of water taken up by plants may be stored within the stem, branches, and foliage temporarily, but most are transpired quite rapidly from the leaves into the atmosphere. Beyond that, evaporation of water also occurs from plant and soil surfaces when they are wet (Richard et al., 2007).

Forest canopies modify both the amount and the horizontal distribution of throughfall and stemflow. As a result of this redistribution, the input of water to the forest floor is characterized by forest structure and tree characteristics. Previous studies reported that the larger trunk diameter (DBH, diameter at breast height) leads to greater the potential for stemflow yield. Herwitz and Landforms (1986) found that steep branches have a greater potential for contributing to stemflow than more horizontal or below horizontal branches. Bark type is also an essential factor affects stemflow yield, due to the considerable variation in thickness and bark type within and between species for trees of similar size. Wettability and thickness have substantial effects on stemflow yield (Crockford and Richardson, 1987). Smooth, easily wetted bark has the potential for high stemflow yields, whereas thick absorptive bark results in small yields because the bark has to be saturated before stemflow commences. Moreover, gaps in the canopy will certainly increase throughfall and its spatial variability. Gaps in the canopy also can affect stemflow because the rain may have greater direct access to the trunk. However, access may or may not be greater, depending on the leaf area index (LAI) and the leaf shape and orientation (Crockford and Richardson, 2000) although stemflow contributes little to net precipitation but is a spatially concentrated water flux across a small area around the boles.

Beyond that, climate conditions also affect forest hydrology, including continuity and proportion of dry periods, rainfall intensity and wind conditions (Carlyle-Moses and Price 2006).

1.3 Carbon Cycle in Forest Ecosystem

Carbon begins its cycle through forest ecosystems when plants assimilate atmospheric

CO_2 through photosynthesis. Terrestrial ecosystem production has been defined regarding gross primary production (GPP), net primary production (NPP), net ecosystem production (NEP) and net ecosystem exchange (NEE). NEP represents the net gain of forest ecosystems in carbon exchange with the atmosphere. Soil humus represents the primary accumulation of carbon in most ecosystems because it remains unoxidized for centuries. It is the most critical long-term carbon storage site in ecosystems. The effort to increase our understanding of the carbon balance has resulted in a global network of eddy covariance towers (Baldocchi, 2008; Baldocchi and Meyers, 1998). GPP and NPP were the most commonly reported measure of terrestrial production in ecosystems (Ohtsuka et al., 2007; Hyvonen et al. 2007; Webb et al. 2018). In recent years, it was realized that the functional link between terrestrial and aquatic ecosystems occurs in the form of lateral fluxes of organic carbon. A review of Webb et al., (2018) reported that the total aquatic carbon flux was positively correlated with terrestrial NEP, suggesting highly productive ecosystems will have greater aquatic carbon offsets. Considering the great difference in the range of terrestrial NEP (~ 1000 g C m^{-2} y^{-1}) compared to aquatic fluxes (~ 100 g C m^{-2} y^{-1}), ecosystems with small NEP's had greater relative aquatic carbon offsets overall in their NECB's (net ecosystem carbon budget). Moreover, earlier studies supposed that omission of dissolved organic carbon (DOC) fluxes as a possible explanation for the gap between atmosphere-based and land-based estimates of the continental carbon balance of Europe (Siemens et al., 2003; Janssens et al., 2003). Indeed, Schulze et al., (2009) reported that the gap decreased when the European carbon balance accounted for DOC losses. However, the role of aquatic pathways contribute to the NECB of different ecosystems remains poorly understood, more site-specific investigations need to be undertaken across a broader range of climatic regions and ecosystem types.

1.4 Reviews of DOC in Forest Ecosystems

Dissolved organic carbon (DOC) is operationally defined as organic molecules that pass through a filter, most often 0.45 μm. DOC can hydrologically transport carbon between different pools in the ecosystem; it is also the major form of carbon transported with soil solution and in streams. DOC concentrations of rainfall are generally very low but increase as the rainwater passes through the canopy and forest floor (Kolka et al. 2008). Throughfall and stemflow are two flow paths of DOC removed from the canopy and transferred to the forest floor. As mentioned before, throughfall is the portion of precipitation that passes directly through the forest canopy or initially intercepted by the surfaces of aboveground plants and subsequently drips from the canopy, and stemflow is intercepted rainfall that moves down the stems or trunks of trees (Levia and Frost 2003; Staelens et al. 2008; Levia et al. 2011). Of these two hydrologic pathways in the forest canopy, stemflow has been much less thoroughly investigated than throughfall concerning its role as a pathway for DOC and its contribution to the DOC in the soil. Numerous recent investigations have highlighted that DOC plays a vital role in C cycling in natural ecosystems (e.g., Kindler et al. 2011). The amount of DOC in soil solution is the balance of inputs and outputs of organic carbon to the soil water.

Since (Gosz et al. 1976) reported that the nutrient and organic matter content of the forest floor of the Hubbard Brook Experimental Forest during different seasons and attempted to correlated results from studies of vegetation, litter, decomposition, stemflow, throughfall, and soil. DOC dynamics through soils and groundwater have been thoroughly investigated, and the results have shown that the quantity of DOC and character of DOM (dissolved organic matter) influence the soil and soil solution chemistry (Moore 2003; Kalbitz et al., 2007; Ramirez et al., 2010; Inamdar et al., 2011; Levia et al., 2012). DOC is also a significant source of organic carbon in the mineral soil, which originates from biological decomposition, throughfall or litter leaching, root exudates (Bolan et al., 2011, Neff and Asner 2001). Additionally, soil adsorption, microbial degradation, or export via seepage and near-surface runoff are considered to be the major sinks or losses of DOC (Qualls et al., 1991; Hinton et al., 1997; Kalbitz et al., 2000).

In forest ecosystems, the forest floor has been identified as a primary source for DOM (Cronan & Aiken 1985; Qualls et al., 1991; Currie et al., 1996). The origin of DOC in forest floors has often been attributed to the biological degradation of plant residues (Guggenberger and Zech 1994; Dai et al., 1996) and leaching from litterfall (Qualls et al., 1991). Beyond that, vegetation types have influences on DOC concentrations in litter leachate under temperate and tropical forests, for example, with higher DOC concentrations in coniferous forests than in broad-leaved deciduous forests (Ciglasch et al., 2004; Dittman et al., 2007). According to Michalzik et al., (2001), DOC fluxes in throughfall of temperate forests range from 4 to16 g m^{-2} $year^{-1}$, whereas the flux in the forest floor is usually is in the range 10–40 g m^{-2} $year^{-1}$. The soluble fluxes of organic compounds from throughfall and out of the litter layer can amount to 1%–19% of the total litterfall C flux and 1%–5% of NPP (Gosz et al., 1973; McDowell and Likens 1988; Qualls et al., 1991). However, DOC concentrations and fluxes of mineral soil decrease with depth and under the B horizon the flux is usually below 10 g m^{-2} $year^{-1}$. The difference between O and B horizons is widely thought to be mainly due to physical and chemical retention rather than rapid mineralization (Kalbitz et al., 2000).

A growing number of studies focus on the controlling factors of variability in soil DOC concentrations at local, regional, or national scale (Kindler et al., 2011; Borken et al., 2011; Buckingham et al., 2008; van den Berg et al., 2012). However, much less information is available on the proportions of DOC that are contributed through precipitation, throughfall, stemflow and litter leachate to the DOC input to the soil, and stemflow has been particularly overlooked. These may be partly because DOC fluxes are generally not considered to be critical components of carbon balance in the ecosystem, being extremely small relative to the carbon fluxes of primary productivity or heterotrophic respiration in terrestrial systems (Hope et al., 1994; Schimel 1995). Moreover, according to a review of 42 DOC studies by Michalzik et al., (2001), these studies have been performed mainly on ecosystems in Europe and North America. In Asia, the unique climatic and other environmental characteristics that distinguish the region from the relatively well-studied forests of Europe and the USA (Fujii et al., 2011a), several studies about DOC flux have been conducted in subtropical forest (Liu and Sheu

2003; Xu et al., 2005) or tropical forest (Fujii et al., 2011b). To date, most of studies about DOC dynamics were focus on forested catchment or in the soil profile (Kawasaki et al., 2002, 2005; Kawahigashi 2011; Fujii et al., 2011a). The investigations of linking the DOC fluxes in temperate forest ecosystems to the soil organic carbon in Japan were limited (Shibata et al., 2001). Much less information is available on comparing the effects of vegetation type, forest structure and canopy phenology on DOC variability at different forests. Deciduous and evergreen forests are the two primary type of forests in the world, which has different vegetation types with different leaf emergence patterns and life spans. Previous studies showed canopy structure is an important controlling factor on throughfall patterns; broadleaved deciduous canopies have been reported to influence throughfall patterns during the leafed season (Keim et al., 2005; Staelens et al., 2006b). Some study assumed that the multiple layers within the forest canopy and differences in canopy phenology might complicate throughfall patterns in tropical forests (e.g., Germer et al., 2006; Zimmermann et al., 2009; Zimmermann and lsenbeer 2008). Hence, given the importance of DOC fluxes in the forest carbon balance, and the forest floor is the primary source of DOC, it is essential to analyze controlling factors of DOC concentrations and fluxes from the forest floor in related to throughfall, stemflow and litter leachate in different forest ecosystems.

Taken together, the main objectives of this study were: 1) to compare the concentration and flux patterns of DOC in the different ecosystem strata (bulk precipitation, throughfall, stemflow, litter leachate) of deciduous and evergreen broad-leaved forests in Central

Japan; 2) to identify the controlling factors on the DOC concentrations and fluxes in the forest ecosystems, differentiating between deciduous and evergreen broad-leaved forests. We assumed that the variation of canopy phenology change is the main reason causing the difference of DOC concentration in throughfall, stemflow and litter leachate in these two study forests.

2. Forest Structure

2.1 Study Area

2.1.1 Site Description of Deciduous Broad-Leaved Forest

The study forest (Takayama Forest), a cool-temperate deciduous broad-leaved forest, is an experimental forest of Takayama Field Station belonging to the River Basin Research Center at Gifu University, Japan. It is located in the central region of the main island of Japan (36°08'N, 137°25'E, 1420 m a.s.l.) (Fig. 2.1). The dominant species are *Quercus crispula*, *Betula ermanii*, and *Betula platyphylla* var. *japonica*. A few evergreen conifer species were also present, the height of the dominant forest canopy ranges from 13 to 20 m. The forest floor is covered 100% (ca. 40 stems m^{-2}) by a very dense evergreen dwarf bamboo *Sasa senanensis* with height of 1—1.5 m (Ohtsuka et al., 2005, Saitoh et al., 2012). A permanent plot of 1 ha (100 m × 100 m) was set on a west-facing slope. The study area has a seasonal cool-temperate climate. The annual mean air temperature of the site is 7.3ºC, the average annual precipitation is about 2,400 mm (2014–2015) distributed throughout the year, and snow depth is usually 1–2 m in winter (December–April). Average monthly precipitation and air temperatures over nine years (2007–2015) are shown in Fig. 2.2. The precipitation and temperature data were recorded by the meteorological station at the Takayama Study Site (http://sateco-archive.green.gifu-u.ac.jp/AWS1/).

2.1.2 Site Description of Evergreen Broad-Leaved Forest

The study site is located on Mt. Kinka, central Japan (Fig. 2.3). The topography of the area is hilly with young soil. The bedrock is composed of sedimentary rock on a chert layer. A 0.7 ha study plot (70 m × 100 m) was established on the lower slopes of Mt.

Kinka (ca. 60 ma.s.l., 35°26′ N, 136°47′ E) in 1989 (Fig. 2.3). The study area is in the subtropical monsoon climate zone. The studied forest is an evergreen broad-leaved forest, which has a basal area of 46.1 $m^2\ ha^{-1}$. The dominant tree species in this forest is *Castanopsis cuspidata,* which accounts for 87.86% of the basal area, and it is also the dominant canopy tree species in the study plot (Chen et al., 2017). The annual mean temperature is 16.1 °C, and the mean temperature in the coldest month, January, and the hottest month, August, are 4.4 °C, and 28.0 °C, respectively (Fig. 2.4). The average annual precipitation is 1866 mm. The climatic data were collected at a weather station situated approximately 4 km from the study plot.

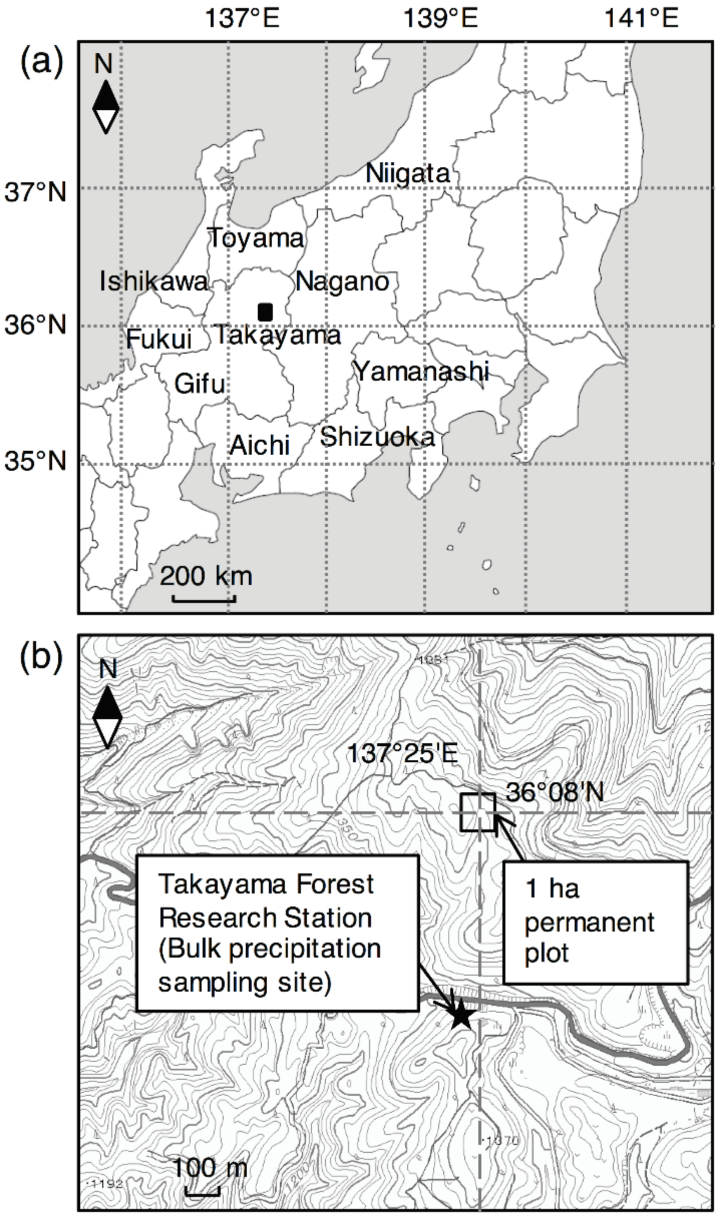

Fig. 2.1 Location of the deciduous forets study site at the Takayama Forest Research Station of River Basin Research Center, Gifu University, central Japan (a). Square indicates a permanent quadrant of 100 m×100 m (map (b) from http://maps.gsi.go.jp/#16/36. 142709/137.422228)

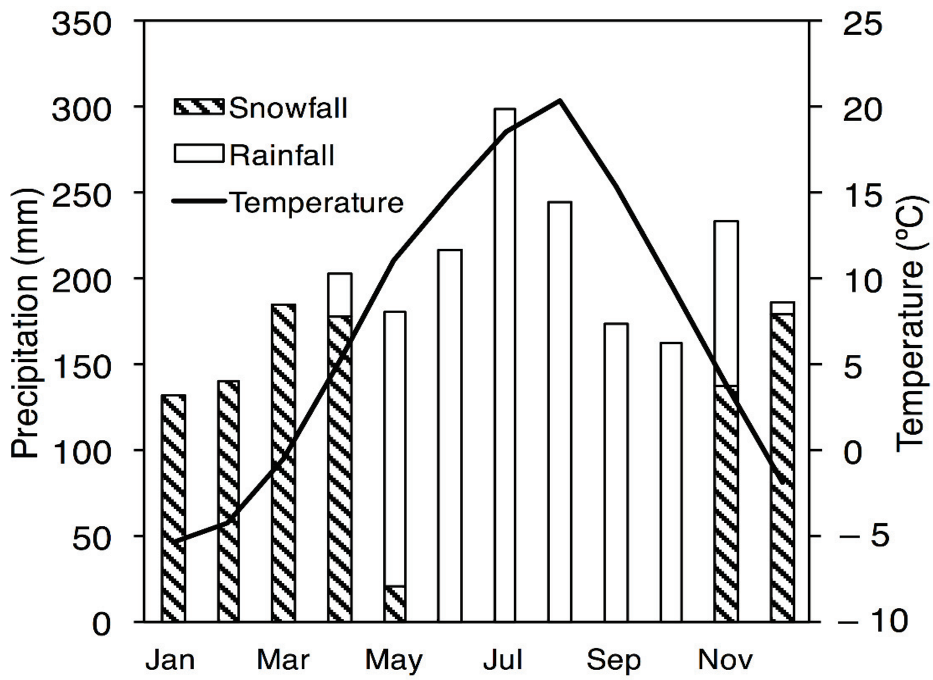

Fig. 2.2 Average monthly precipitation and temperature of deciduous forest over nine years (2007–2015).

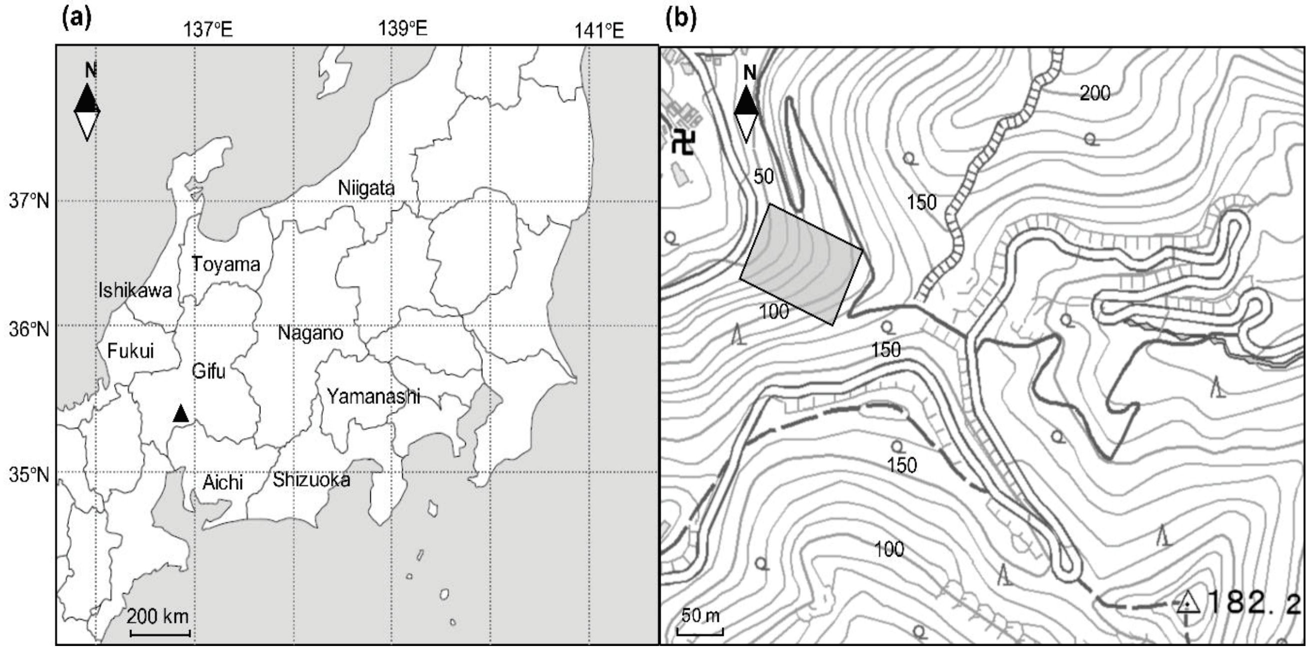

Fig. 2.3 (a) location of the evergreen forest study site at Mt. Kinka (▲), central Japan; (b) the square indicates the permanent plot of 70 m × 100 m at the lower slope of Mt. Kinka. The contours signify elevation (m a.s.l.).

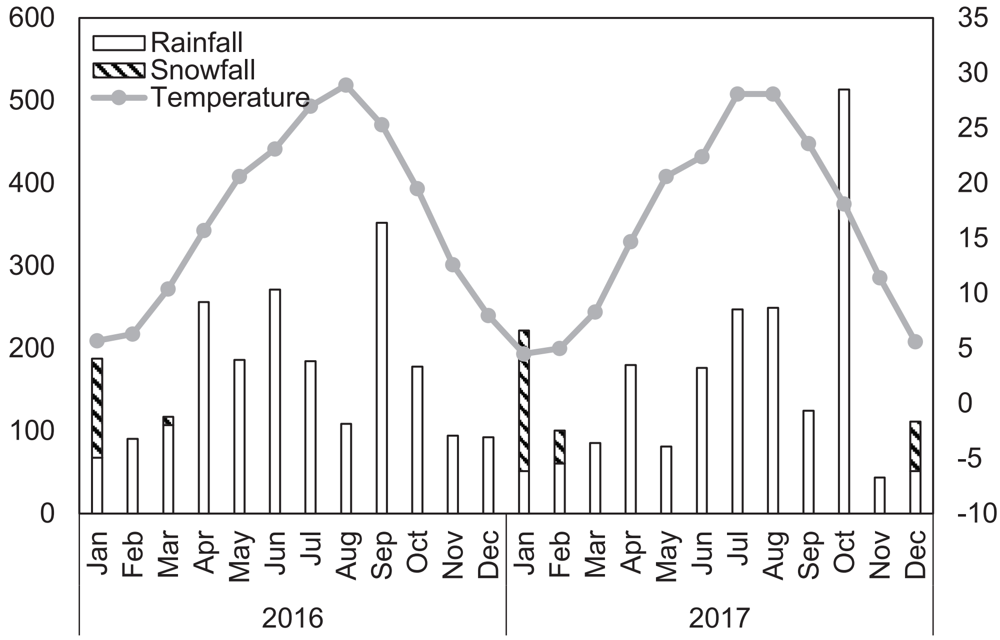

Fig 2.4. Monthly average temperature and precipitation of evergreen forest study site in 2016 and 2017.

2.2 Forest Structure of Deciduous Forest

2.2.1 Field Methods

The 1-ha study plot was divided into 100 subplots of 100 m^2 using a compass survey, all live stems ≥ 5.0 cm in the permanent plot were tagged and painted at the measuring position of the DBH. The DBH was measured in April 1999 before the growing season. In late fall (November or December) each year from 2000 to 2017 (except for 1999 and 2004), all tagged live stems were re-measured at the same painted position and any stems that had reached 5.0 cm DBH since the last measurement was tagged.

Relative growth rate of DBH (RGRD) was calculated as shown in Equation:

$$RGRD = (\ln D_2 - \ln D_1)/(t_2 - t_1),$$

where D_1 and D_2 is the DBH (cm) at the beginning (t_1) and the end (t_2) of the year of measuring interval, respectively.

2.2.2 Structure and Species Composition

The plot contained 35 woody plant species, and 785 living stems ≥ 5 cm of DBH, with a BA (basal area) of 29.4 m^2 ha^{-1} (Table 2.1). There were 35 species in total, including 33 species of deciduous broad-leaved trees, such as *Quercus crispula, Betula ermanii, Betula platyphylla, Magnolia obovate, and Tilia japonica*, and two species of coniferous trees (*Abies homolepis, Pinus parviflora,* Table 2.1). Deciduous broad-leaved tree species occupied 98.85% and 96.61% in the number and the BA of the total living tree stems, respectively. *Quercus crispula* was the most abundant overstory tree species in both number (24.20%) and BA (32.70%). While *Betula ermanii* consisted of 14.27% in total tree number and 25.82% in BA. Moreover, *Quercus crispula, Betula ermanii* and *Betula platyphylla* comprised 68.15% in BA and 44.46% in stem number; they were the three main species in the plot (Table 2.1).

2.2.3 Temporal Changes of Forest Structure

We summarized the forest structure from 2002 to 2017 at an interval of 5 years in Table 2.2. The results showed that the stem density of deciduous trees significantly decreased during the 15-years from 1068 stems ha^{-1} to 780 stems ha^{-1}, while the evergreen trees were almost unchanged. At first, BAs of the deciduous trees increased gradually from 29.12 in 2002 to 30.30 m^2 ha^{-1} in 2012. However, BAs of deciduous trees decreased to 28.38 m^2 ha^{-1} in 2017 (Table 2.2). In contrast, the BAs of evergreen trees increasing steadily (Table 2.2). Moreover, the numbers of deciduous species of over 5 cm DBH decreased from 37 in 2002 to 33 in 2017 (Table 2.2). Comparing the numbers of trees in different DBH class, the number of trees at 10–30cm continuously decreased from 2002 to 2017 (Fig. 2.5)

The mean annual relative growth rate of DBH (RGRD) of trees in 2002–2007, 2007–2012, and 2012–2017 was 0.007 ± 0.0003, 0.013 ± 0.0005, and 0.007 ± 0.0003, respectively, which was highest during the second interval of 2007 to 2012. Comparing the RGRD of trees in each DBH class, RGRD of 30–40 cm was highest during the three survey periods (Fig. 2.6).

Table 2.1 Species composition of trees (DBH ≥ 5 cm) in the 1-ha permanent plot of evergreen forest in October, 2017.

	Basal area		DBH (cm)		No. of stems	
	$cm^2\ ha^{-1}$	%	Mean	Maximum	ha^{-1}	%
Deciduous trees						
Quercus crispula	96067	32.70	23.50	66.86	190	24.08
Betula ermanii	75841	25.82	28.13	56.79	112	14.20
Betula platyphylla	28292	9.63	25.58	50.85	47	5.96
Magnolia obovata	19482	6.63	20.46	41.65	48	6.08
Tilia japonica	10651	3.63	19.78	38.82	30	3.80
Acer rufinerve	9461	3.22	18.15	40.52	31	3.93
Acanthopanax sciadophylloides	6297	2.14	20.40	40.70	15	1.90
Acer sidboldianum	6118	2.08	9.85	28.69	69	8.75
Ilex macropoda	4335	1.48	12.14	24.16	32	4.06
Acer pictum	2804	0.95	12.52	28.73	18	2.28
Prunus grayana	2572	0.88	11.40	19.36	22	2.79
Betula maximowicziana	2355	0.80	31.26	37.98	3	0.38
Acer distylum	2321	0.79	10.09	19.10	26	3.30
Hydrangea paniculata	2145	0.73	8.69	19.55	32	4.06
Chamaecyparis pisifera	1856	0.63	48.62	48.62	1	0.13
Fagus crenata	1767	0.60	21.91	31.31	4	0.51
Sorbus alnifolia	1572	0.54	12.30	20.24	12	1.52
Phellodendron amurense	1410	0.48	20.59	27.75	4	0.51
Prunus jamasakura	1453	0.49	12.15	25.92	10	1.27
Castanea crenata	975	0.33	35.25	35.25	1	0.13
Prunus sargentii	938	0.32	18.87	27.50	3	0.38
Fraxinus lanuginosa	931	0.32	7.96	11.63	18	2.28
Acer japonicum	872	0.30	7.68	15.14	17	2.15
Populus sieboldii	808	0.28	32.08	32.08	1	0.13
Acer micranthum	676	0.23	11.42	15.08	6	0.76
Carpinus japonica	486	0.17	15.37	23.93	1	0.13
Symplocos coreana	384	0.13	6.30	7.54	12	1.52
Kalopanax pictus	255	0.09	18.04	18.04	1	0.13
Acer argutum	281	0.10	10.83	12.70	3	0.38
Viburnum furcatum	173	0.06	5.58	6.66	7	0.89
Swida controversa	114	0.04	12.07	12.07	1	0.13
Benthamidia Japonica	56	0.02	8.45	8.45	1	0.13
Euonymus oxyphyllus	42	0.01	5.14	5.28	2	0.25
Subtotal	283789	96.62			780	98.86
Evergreen trees						
Abies homolepis	6568	2.24	27.15	57.09	8	1.01
Pinus parviflora	3402	1.16	65.83	65.83	1	0.13
Subtotal	9969	3.40			9	1.14
Total	293759	100			789	100

Table 2.2 Dynamics of basal area (BA) and number of stems in the 1-ha permanent plot of deciduous forest.

DBH > 5 cm	2002 (Dec)		2007(Nov)		2012 (Oct)		2017 (Oct)	
	stems/ha^{-1}	BA(m^{-2}/ha)	stems/ha^{-1}	BA(m^{-2}/ha)	stems/ha^{-1}	BA(m^{-2}/ha)	stems/ha^{-1}	BA(m^{-2}/ha)
Deciduous trees								
Quercus crispula	258	86076	224	88942	210	93801	190	96067
Betula ermanii	167	73275	145	75588	138	80213	112	75841
Betula platyphylla	77	34105	58	29862	51	28710	47	28292
Magnolia obovata	72	20066	72	21917	67	23435	48	19482
Tilia japonica	47	12899	41	12942	40	13503	30	10651
Acer rufinerve	52	14004	46	13656	39	12144	31	9461
Acanthopanax sciadophylloides	17	5825	17	6099	18	6643	15	6297
Acer sidboldianum	67	5128	67	5592	71	6148	69	6118
Prunus sargentii	18	4140	10	2272	7	1873	3	938
Ilex macropoda	29	3630	30	3879	31	4103	32	4335
Acer pictum	22	3436	24	2793	24	2836	18	2804
Prunus grayana	32	3282	29	3177	27	3227	22	2572
Hydrangea paniculata	45	2478	42	2675	39	2380	32	2145
Phellodendron amurense	6	2438	5	2453	5	2535	4	1410
Betula maximowicziana	4	2259	4	2472	4	2608	3	2355
Fagus crenata	5	2154	5	2350	5	2570	4	1767
Acer distylum	28	1909	29	2144	29	2417	26	2321
Populus sieboldii	2	1705	2	1757	2	1849	1	808
Prunus jamasakura	14	1521	13	1615	12	1673	10	1453
Chamaecyparis pisifera	1	1476	1	1590	1	1706	1	1856
Sorbus alnifolia	12	1299	12	1381	12	1473	12	1572
Swida controversa	4	942	3	918	3	942	1	114
Fraxinus lanuginosa	22	869	20	905	19	921	18	931
Prunus maximowiczii	2	835	0	0	0	0	0	0
Kalopanax pictus	5	821	4	855	4	928	1	255
Acer japonicum	18	793	19	832	20	917	17	872
Castanea crenata	1	745	1	807	1	885	1	975
Magnolia salicifolia	2	695	2	688	0	0	0	0
Acer micranthum	4	467	4	508	6	608	6	676
Symplocos coreana	17	486	17	498	12	369	12	384
Carpinus japonica	2	443	2	465	2	482	1	486
Aesculus turbinata	3	311	3	343	3	365	0	0
Acer argutum	3	253	3	264	3	275	3	281
Viburnum furcatum	6	207	6	177	5	148	7	173
Euonymus oxyphyllus	2	170	2	172	2	175	2	42
Benthamidia Japonica	1	61	1	56	1	57	1	56
Sorbus commixta	1	27	1	30	1	31	0	0
Subtotal	1068	291230	964	292674	914	302950	780	283789
Evergreen trees								
Abies homolepis	9	5203	8	5665	8	6114	8	6568
Pinus parviflora	1	2946	1	3154	1	3273	1	3402
Subtotal	10	8149	9	8819	9	9387	9	9969
Total	1078	299380	973	301493	923	312337	789	293759

2.3 Forest Structure of Evergreen Forest

2.3.1 Field Methods

A 0.7 ha study plot (70 m × 100 m) was established on the lower slopes of Mt. Kinka (ca. 60 ma.s.l., 35°26′ N, 136°47′ E) in 1989 (Fig.2.1). The study plot was divided into 70 subplots of 100 m^2 using a compass survey. In May 1989, all stems of tree species with a diameter at breast height (DBH) greater than or equal to 10 cm were mapped as x–y coordinates, identified to the species level and measured for DBH. A number tag was attached to each trunk at 1.3 m height using a stapler, and the measuring position was marked using paint. The DBH of these stems were re-measured in May 1995 (six growing seasons after 1989) and October 2004 (10 growing seasons after 1995) at the same painted position of the trunks together with those of newly recruited stems over 10 cm and dead stems during the intervals. In January 2017 (12 growing seasons after 2004), this 0.7 ha plot was reconstructed using the tree map, and the remaining numbered of tags on trunks, and we had identified all tree stems over 10 cm in 2004. Then, all tree stems taller than 1.3 m high were re-tagged and their DBH measured together with the dead stems greater than 10 cm in 2004.

Relative growth rate of DBH (RGRD) was calculated as shown in Equation:

$$RGRD = (\ln D_2 - \ln D_1)/(t_2 - t_1),$$

where D_1 and D_2 is the DBH (cm) at the beginning (t_1) and the end (t_2) of the year of measuring interval, respectively.

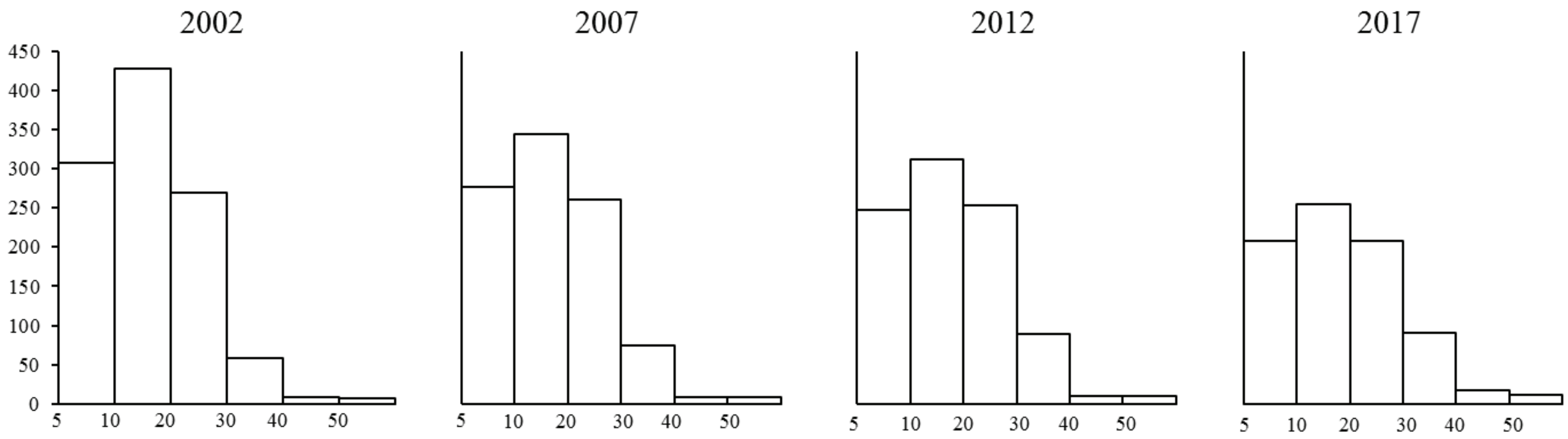

Fig. 2.5 Change of diameter at breast height (DBH) class distributions in the permanent plot of evergreen forest during measuring period.

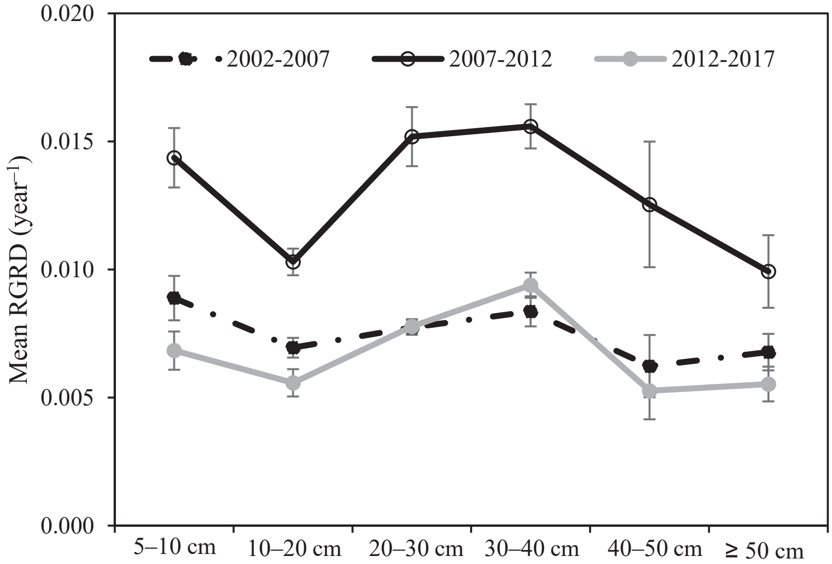

Fig. 2.6 Mean relative growth rate of DBH (RGRD) of trees at different DBH class in each measuring interval of evergreen forest.

Annual recruitment rate (R) and annual mortality (M) of tree stems were calculated as follows:

$R = N_R/N_1 \times (t_2 - t_1)$,

$M = N_M/N_1 \times (t_2 - t_1)$,

where N_R is the number of recruitment tree stems at the end of the year (t_2) of measuring interval, N_1 is the number of the whole tree stems at the beginning of the year (t_1) of measuring interval, and N_M is the number of dead tree stems in the year t_2.

2.3.2 Structure and Species Composition

The plot contained 26 woody plant species, and 1301 living stems ≥ 1.3 m of height, with a BA of 46.08 m^2 ha^{-1} (Table 2.3), including evergreen broad-leaved trees (13 species) and deciduous broad-leaved trees (13 species). Evergreen broad-leaved tree species occupied 94.51% and 91.70% in the number and the BA of the total living tree stems, respectively. *Castanopsis cuspidata* was the most abundant overstory tree species in BA (87.76%), while *Cleyera japonica* was the most dominant understory subtree species based on stem number followed by *Eurya japonica* (Table 2.3). The plot also contained some deciduous broad-leaved species (e.g., *Ilex micrococca, I. macropoda and Magnolia obovata*), which only comprised 5.49% in BA and 8.30% in stem number.

2.3.3 Temporal Changes of Forest Structure

The stem density of evergreen trees significantly decreased during the 28-years from 684 ± 15 stems ha^{-1} to 460 ± 7 stems ha^{-1}, while the BAs of the evergreen trees increased significantly from 29.51 ± 1.80 to 39.54 ± 2.24 m^2 ha^{-1} (Table 2.4). In contrast, the stem density of deciduous trees tended to decrease at a corresponding rate to the decrease of BA, but the changes were not significant (Table 2.4). Moreover, the numbers of deciduous species of over 10 cm DBH decreased from 12 in 1989 to 7 in 2017 (Table 2.5). Overall, recruitment of tree stems was less than the mortality; the total stems decreased significantly from 1989 (779 ± 37 stems ha^{-1}) to 2017 (510 ± 16 stems ha^{-1}, Table 2.4). In contrast to decreasing stem number, the BA of the stand increased due to the growth of *C. cuspidata*, from 29.18 ± 1.84 (87.81% of total) to 38.71 ± 2.22 (91.88%). In this case, the stem density of *C. cuspidata* decreased in proportion to accumulating biomass of individual, and the slope of the regression lines on the log density to log tree biomass was −1.67 during the 28 years (Fig. 2.7).

The mean annual relative growth rate of DBH (RGRD) of *C. cuspidata* in each survey interval was 0.007 ± 0.0009, 0.012 ± 0.0010, and 0.008 ± 0.0012, respectively, which was highest during the second interval of 1995 to 2004. However, comparing the RGRD of *C. cuspidate* in each DBH class, there were no significant changes in RGRD with DBH size during the first interval of 1989 to 1995 (Fig. 2.8a). Conversely, RGRD of individuals larger than 30 cm DBH size were significantly higher for the 2004–2017 period (Fig. 2.8a). Annual mortality of *C. cuspidata* showed a similar pattern during the three survey periods, and the mortality reduced significantly from the 10–20 cm class to the 20–30 cm class; then, the mortality did not show significant differences. Because of different growth and mortality pattern of *C. cuspidata*, with decreasing deciduous trees, the DBH class distribution changed from L shape to unimodal during the study period (Fig. 2.9). In this case, the study forest was close to being a pure stand of *C. cuspidata* during the 28 years due to the large DBH size and its predominance of BA (Table 2.4 and 2.5).

Table 2.3 Species composition of trees (stems ≥ 1.3 m of height) in the permanent plot (0.7 ha) of evergreen forest in January 2017.

	Basal area		DBH (cm)		No. of stems	
	$cm^2\ ha^{-1}$	%	Mean	Maximum	Per plot	%
Evergreen trees						
Castanopsis cuspidata	404424	87.76	28.0	63.9	359	27.6
Cleyera japonica	20592	4.47	5.6	23.0	458	35.2
Eurya japonica	6580	1.43	5.0	12.6	206	15.8
Quercus glauca	3321	0.72	3.3	37.4	118	9.1
Ilex rotunda	350	0.08	3.2	9.7	23	1.8
Prunus spinulosa	78	0.02	3.0	4.8	6	0.5
Illicium anisatum	56	0.01	4.9	6.1	2	0.2
Aucuba japonica	54	0.01	1.9	3.7	10	0.8
Ilex latifolia	18	0	2.2	3.0	3	0.2
Cinnamomum tenuifolium	16	0	3.8	3.8	1	0.08
Gardenia jasminoides	13	0	1.9	2.2	3	0.2
Photinia glabra	6	0	1.3	1.8	3	0.2
Ligustrum japonicum	5	0	2.2	2.2	1	0.08
Subtotal	435514	94.51	-	-	1193	91.7
Deciduous trees						
Ilex micrococca	6213	1.35	42.7	48.4	3	0.2
Ilex macropoda	5974	1.30	7.2	25.0	71	5.5
Magnolia obovata	4716	1.02	22.9	38.7	7	0.5
Eleutherococcus sciadophylloides	3585	0.78	10.2	46.2	11	0.8
Rhus sylvestris	2283	0.50	15.8	22.6	7	0.5
Quercus serrata	1618	0.35	38.0	38.0	1	0.08
Padus grayana	696	0.15	24.9	24.9	1	0.08
Clethra barbinervis	95	0.02	5.5	9.0	2	0.2
Diospyros kaki	45	0.01	6.3	6.3	1	0.08
Hamamelis japonica	25	0.01	4.7	4.7	1	0.08
Carpinus laxiflora	22	0	4.4	4.4	1	0.08
Aphananthe aspera	9	0	2.9	2.9	1	0.08
Styrax japonica	8	0	2.6	2.6	1	0.08
Subtotal	25290	5.49	-	-	108	8.3
Total	460804	100	11.7	63.9	1301	100

Table 2.4 Dynamics of basal area (BA; m^2 ha^{-1}) and number of stems (stems ha^{-1}) of each species (DBH ≥ 10 cm) in the permanent plot of evergreen forest during the 28-year period.

	Number of stems (ha^{-1})				BA (m^2 ha^{-1})			
	1989 (May)	1995 (May)	2004 (Oct)	2017 (Jan)	1989 (May)	1995 (May)	2004 (Oct)	2017 (Jan)
Evergreen trees								
Castanopsis cuspidata	666 ± 13 a	626 ± 13 a	519 ± 14 b	404 ± 10 c	29.18 ± 1.84 a	31.42 ± 2.46 ab	35.70 ± 2.06 ab	38.71 ± 2.22 b
Other species	19 ± 5 a	30 ± 6 a	20 ± 5 a	56 ± 7 b	0.33 ± 0.10 a	0.40 ± 0.11 ab	0.43 ± 0.10 ab	0.84 ± 0.14 b
Subtotal	684 ± 15 a	656 ± 18 a	539 ± 11 b	460 ± 7 c	29.51 ± 1.80 a	31.81 ± 2.41 a	36.13 ± 2.03 b	39.54 ± 2.24 c
Deciduous trees	91 ± 30 a	79 ± 34 a	56 ± 19 a	46 ± 14 a	2.76 ± 0.85 a	2.90 ± 0.94 a	2.45 ± 0.59 a	2.21 ± 0.77 a
Total	779 ± 37 a	733 ± 38 a	591 ± 21 b	510 ± 16 b	33.23 ± 1.88 a	34.99 ± 2.04 ab	38.31 ± 1.83 ab	42.13 ± 1.82 b

[a] Different letters within each variable indicate significant differences among the different survey year ($p < 0.05$).

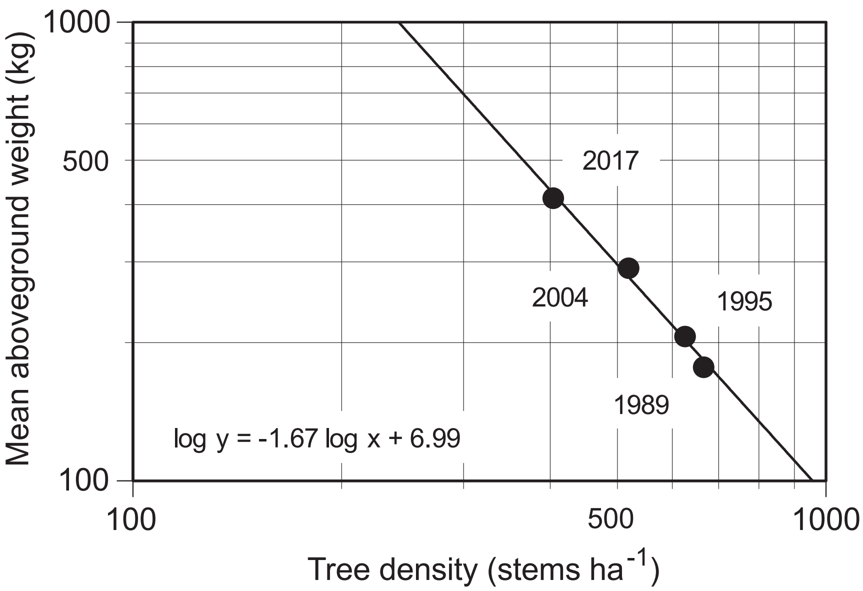

Fig. 2.7 Relationships between tree density (stems ha^{-1}) and mean aboveground weight (kg) of *Castanopsis cuspidata* in the permanent plot of evergreen forest during the study period. The number shows the measuring year of the forest biomass.

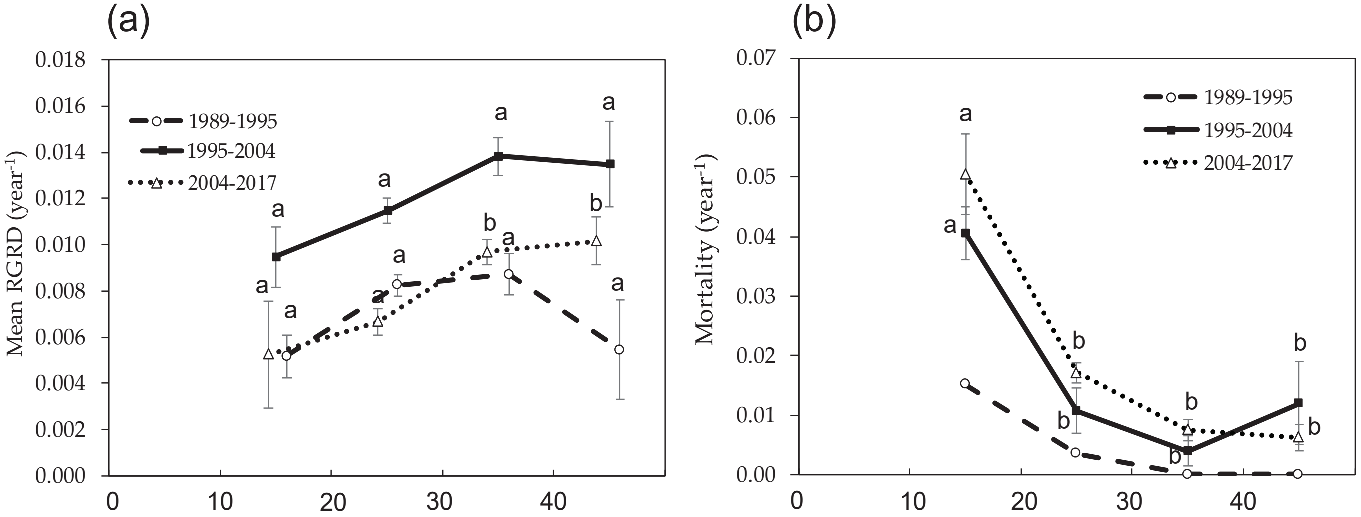

Fig. 2.8 (a) Mean relative growth rate of DBH (RGRD) of *Castanopsis cuspidata* in each measuring interval. (b) Mortality of each DBH class of *C. cuspidata* in each measuring interval of evergreen forest. The DBH class of the stems is the beginning of each measuring interval (The DBH ≥ 40 cm class includes several stems of DBH ≥ 50 cm). Error bars indicate SE of the means and the letters indicate significant differences among DBH classes in each measuring interval ($p < 0.05$). Because the tree map was made during 1995, we could not check the location of some trees that dies during 1989–1995; therefore, the statistical difference of mortality during the 1989–1995 period was not assessed.

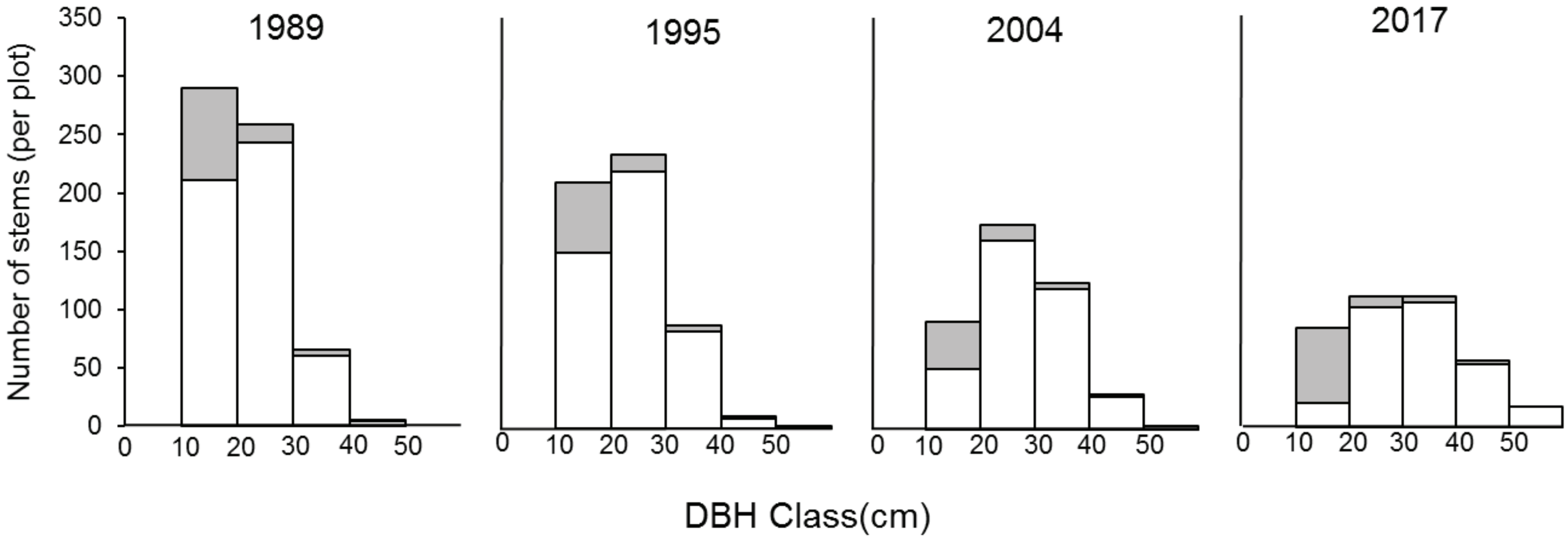

Fig. 2.9 Change of diameter at breast height (DBH) class distributions in the permanent plot during the measuring period. Open bars represent stems of *Castanopsis cuspidata*, and shaded area stems of other tree species in the evergreen forest. (The area of per plot was 0.7 ha).

Table 2.5 Dynamics of species and stems number in the permanent plot of evergreen forest (0.7 ha) during the 28-year period (DBH ≥ 10 cm).

		1989 (May)	1995 (May)	2004 (Oct)	2017 (Jan)
Evergreen species					
1	*Castanopsis cuspidata*	518	463	361	298
2	*Cleyera japonica*	12	14	15	39
3	*Quercus glauca*	2	2	2	1
4	*Eurya japonica*	1	1	1	4
5	*Ilex pedunculosa*	1	1	0	0
Subtotal		534	481	379	342
Deciduous species					
1	*Magnolia obovata*	15	13	10	6
2	*Eleutherococcus sciadophylloides*	24	14	5	3
3	*Ilex micrococca*	7	7	5	3
4	*Ilex macropoda*	16	16	16	17
5	*Rhus sylvestris*	14	9	6	6
6	*Quercus serrata*	2	2	1	1
7	*Padus grayana*	2	1	1	1
8	*Cerasus jamasakura*	1	1	0	0
9	*Hamamelis japonica*	1	1	0	0
10	*Gamblea innovans*	1	0	0	0
11	*Carpinus laxiflora*	1	0	0	0
12	*Styrax japonica*	1	0	0	0
Subtotal		85	64	44	37
Total		619	545	423	379
Number of species		17	14	11	11

3. DOC in the Cool-Temperate Broad-Leaved Deciduous Forest

3.1 Introduction

Takayama Forest, is a part of the Asia Flux network, the carbon fluxes and budgets within it have been measured regularly since October 1993 (Yamamoto et al., 1999; Saigusa et al., 2002). Biometric-based carbon flux measurements have been conducted intensively in the Takayama Forest, so that where and how the forest stores C is well known (Ohtsuka et al., 2005). Total NPP at the site was 6.5 ± 1.07 t C ha^{-1} $year^{-1}$, including biomass increment (0.3 t C ha^{-1} $year^{-1}$), tree mortality (1.0 t C ha^{-1} $year^{-1}$), aboveground detritus production (2.3 t C ha^{-1} $year^{-1}$), fine root production (1.8 t C ha^{-1} $year^{-1}$) and forest floor community of dwarf bamboo (1.1 t C ha^{-1} $year^{-1}$). The mean estimated annual soil respiration amounted to 7.1 ± 0.44 t C ha^{-1} $year^{-1}$ (Mo et al., 2005), and heterotrophic respiration was estimated at 4.4 t C ha^{-1} $year^{-1}$, which included decomposition of soil organic matter (SOM) and coarse woody debris (Ohtsuka et al., 2014). Ohtsuka et al., (2005) concluded that the woody portion did not dominate C uptake, and that the contribution of the SOM pool to the carbon sink in the Takayama Forest might be large (0.8 t C ha^{-1} $year^{-1}$). The same researchers also suggested that the dense forest floor of dwarf bamboo might play a critical role in soil carbon sequestration. Yet there are no previous studies about the contribution of DOC fluxes from throughfall, stemflow, or litter leachate to the carbon cycling in the soil of this study site, and the contribution of DOC fluxes to the large SOC (soil organic carbon) pool remains unknown. DOC flux measurements should clarify the role of soluble carbon input to the mineral soils that contribute to SOM accumulation directly, and the roles of trees and dwarf bamboos in the input to litter leachate. In consideration of the heavy snow regularly occurs in the cool-temperate regions of Japan during winter season, especially at the side of Japan Sea, there are two contrasting seasons at the Takayama Forest: growing season (May– November) and snow season (December–April), that is, DOC dynamics are completely different within the two seasons. In the snow season, evergreen understory dwarf bamboos are buried under the snow and the trees almost without leaves [number of evergreen trees only accounted for 1% at Takayama forest (Ohtsuka et al., 2005)]. As Siegert and Levia (2014) reported that stemflow and throughfall were related to canopy foliar status, hence, the canopy has little impact on the DOC dynamic of stemflow and throughfall during the snow season at the study site, that is to say, there is almost no stemflow, and the throughfall is nearly equal to the snowfall. Nevertheless, the DOC proceed to leaching from litter, because the litter layer remained slightly above 0 ℃, litter was still decomposed by microorganisms (Uchida et al., 2005). Although, the 1–2 m depth snow generally has melted at the end of April, the study of meltwater draining dynamics during the snowmelt period was insufficient.

Therefore, this study focuses on the investigation of DOC dynamics during the growing season and the objectives are: (1) to evaluate the variation in DOC concentration in throughfall, stemflow, and litter leachate of this deciduous forest, (2) to estimate the role of dense understory dwarf bamboo in the DOC dynamics in this ecosystem, and (3) to quantify the contribution of DOC from different forest water flux conditions to the DOC input to the soil during the growing season.

3.2 Materials and Methods

3.2.1 Experimental Setup and Sample Collection

The stemflow collector consisted of two pieces of formed polyethylene with aluminized film (thickness 8 mm) which were cut into rectangles (width 6 cm and 10 cm). First, the tree bole was wrapped with the smaller mat (6 cm in width), and the mat was sealed to the bark with silicone sealant to ensure that there was no leak between the bark and the mat. This purpose of this mat was to make a space to let stemflow flow into the tube without leakage. Then we attached the second mat, which was wider than the first (10 cm in width), on top of the first mat. The bottoms of the two mats were aligned and sealed with silicone. A tube was connected to a sample reservoir tank. Stemflow collectors were set up on examples of each of the three main species, *Quercus crispula, Betula ermanii,* and *Betula platyphylla* var. *japonica* (Fig. 3.1). Three trees of each species were examined for a total of nine samples. According to the topography, the sampled trees were evenly distributed on the valley bottom, the north slope and the south slope within the permanent plot. The volume of stemflow was measured using a rain gauge with a reservoir tank.

Each throughfall collector consisted of a 21 cm diameter funnel and a collection bottle (volume 12 L). A draining mesh bag covered the top of the funnel, and a plug of glass wool was placed in the funnel neck to exclude particulate matter from the collection bottle. A pair of throughfall collectors was set near each stemflow sample site for a total of nine pairs of throughfall collectors. One throughfall collector in each pair was used to collect throughfall above the dwarf bamboo while the other was used to collect throughfall below the dwarf bamboo in the same location.

The litter leachate was collected using zero tension lysimeter; each zero tension lysimeter was also set near each stemflow sample for a total of nine litter leachate samplers. These lysimeters of 144cm^2 area containing a glass wool plug and draining into a 12 L plastic bottle through a flexible tube were installed directly underneath the litter layer.

Samples of bulk precipitation were collected using a collector (20 L) set up in a location without a canopy that was near the study area. The bulk precipitation collector was almost identical to the throughfall collector except for the volume of the collection bottle. Samples of precipitation were collected at the same time and in the same manner as samples of throughfall, about once a month. The soil solution was sampled using porous cup ceramic tension lysimeters (Model DIK-8390-11 soil water sampler with a DIK-3900-51 cup, Daiki Rika Kogyo Co., Ltd, Japan), which were installed at a depth of 20 cm in three replicate plots near the stemflow samplers (Fig. 3.1).

Litterfall was collected in 14 replicates using litter traps (1 m^2 area) that were set higher than the dwarf bamboo, enabling us to separate measurements of detritus production from the dwarf bamboo community in the permanent plot. Dwarf bamboo litter was collected in four replicate measurements using litter traps (1 m^2 area) which were set up on the ground. Both samples were collected monthly from May 2015 to

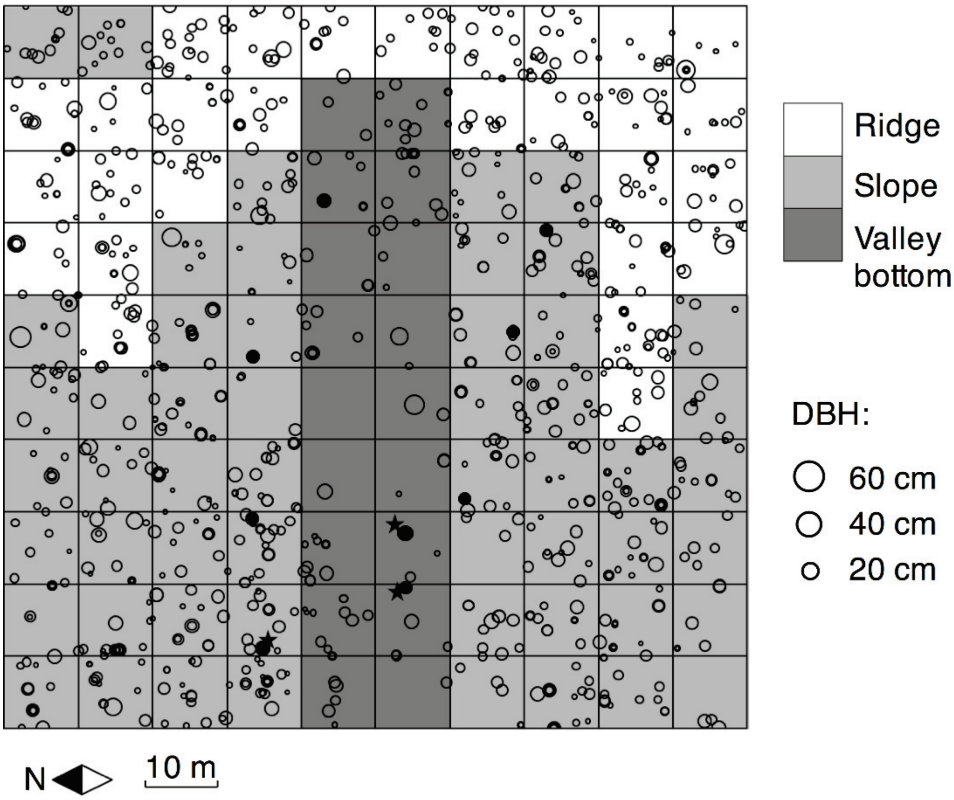

Fig. 3.1 Distribution of all tree stems in the 1-ha plot of deciduous forest, which has been divided into three topographical types (Jia et al. 2003). Open circles indicate living trees, solid circles indicate sample trees for stemflow collection, and the size of each circle indicates the DBH size of the tree. The DBH size of each stem is superimposed on the distribution diagram. Throughfall collectors and litter leachate collectors were set near the sample trees. Stars indicate the locations of soil solution collectors

December 2015 (litter traps also set during snow period, the samples collected in May including the samples from January to May, therefore, it was annual amount of litterfall).

A basic soil profile was obtained and some characteristics of the soils collected from representative areas within the study site were noted. The moist color of each horizon was determined according to standard soil color charts. Soil samples were taken in each horizon. These samples were used for measurements of soil pH and gravimetric soil carbon and nitrogen contents after being air-dried and passed through a 2-mm mesh sieve; plant debris and roots were removed from soil with tweezers, and the absence of debris and roots from the soil samples was confirmed through visual assessment.

3.2.2 Chemical Analysis

The water volume of throughfall, litter leachate, and bulk precipitation was measured monthly from May 2015 to November 2015 using a measuring cylinder (5 L) in the field. The water volume of the stemflow was read out from a rain gauge once per month. Subsamples of stemflow, throughfall, litter leachate, bulk precipitation, soil solution for chemical analysis were taken in clean 100 ml polyethylene bottles at the same time.

After pH and electrical conductivity were measured with a pH and EC meter (Horiba, D-54), all water samples were filtered through a 0.45 μm MF-Millipore nitrocellulose membrane and stored at −18 °C in the dark until analysis. The concentrations of DOC in solution were measured with a total organic carbon analyzer (TOC-V, Shimadzu, Japan). To obtain the NPOC (Non-Purgeable Organic Carbon) measurement (TOC by acidification/sparging method), each sample is acidified with a small amount of hydrochloric acid, then sparged with sparge gas. This processing removes all inorganic carbon (IC) from the sample by converting it to carbon dioxide. The TOC concentration is determined by measuring the TC of the sample after the IC is eliminated.

Litterfall dried at 70ºC to measure dry matter weight. The dry biomass was converted to C mass using compartment-specific C content as determined for samples by a CN analyzer (SUMIGRAPH NC-800, Sumika Chemical Analysis Service, Ltd).

The soil pH for H_2O and NaF was measured with a pH meter with a glass electrode. Total carbon and nitrogen contents of soil (dry weight base) were measured with a CN-analyzer (SUMIGRAPH NC-22F) according to the dry combustion method.

3.2.3 Calculation of Fluxes

When we use the term *DOC flux* in this study, we are referring to the DOC flux that was the quantity of DOC from precipitation, stemflow, throughfall and litter leachate input to the soil per stand area during the growing season (May to November). The monthly amount of DOC (kg ha^{-1} $month^{-1}$) calculated by monthly water volume (L $month^{-1}$) multiplied by the monthly mean DOC concentration (kg L^{-1}). The DOC flux (kg ha^{-1} 7 $month^{-1}$) per growing season is cumulative monthly amount of DOC from May to November 2015.

The stemflow per unit stand area was estimated using the basal area of each sample tree and the total basal area of all trees in the stand (Deutscher and Kulturbau, 1992). The formula was as follows:

$h_{ns} = (V_{ns}/b)\ (B/S)$,

where h_{ns} is the stemflow (mm), V_{ns} is the volume of stemflow of the tree measured (dm^3), b is the basal area of the sample tree (m^2), B is the total basal area of all trees in the measuring area (m^2), and S is the plot area (m^2).

The flux in throughfall and litter leachates were calculated using the measured water volumes and concentrations in each sample on each sampling day. The formula were as follows:

$F = VC/100S_1$,

where F is the monthly flux in a 1 ha plot (kg ha^{-1}), V is the monthly volume (L), C is the monthly concentration of each element (mg L^{-1}), and S_1 (m^2) is the area of the funnel ($0.0441m^2$) or lysimeter plate ($0.0144m^2$) used to collect the sample.

The flux in stemflow and precipitation were calculated using the formula as follows:

$F = hC/100$,

where F is the monthly flux in 1 ha plot (kg ha^{-1}), h is the monthly volume (mm), and C is the monthly concentration (mg L^{-1}).

$F_s = \Sigma F_m$,

where F_s is the sum of growing season flux in a 1 ha plot (kg ha^{-1}) and F_m is the monthly flux (kg ha^{-1}).

3.2.4 Statistical Analyses

Concentrations of DOC are presented as arithmetic means. One-way ANOVA was used to detect significant differences in DOC concentration in different water flux conditions and different species, and in pH and EC in different water flux conditions. Correlation analysis was carried out using linear regression analysis. Significant effects were identified at $P < 0.05$. All statistical analyses were performed with IBM SPSS STATISTICA 22.0.

3.3 Results

3.3.1 Chemical Characteristics of Soil Profile

The soil at the study site has a very thick and dark-colored A horizon with high C content, particularly in the 2A horizon, and a very high pH (NaF) ranging from 9.4 to 11.2 (Table 3.1). pH (NaF) greater than 9.4 (Wada, 1986) or 9.5 (FAO, 2014) is used as a criterion for andisol (Soil Survey Stuff, 2014), a soil order that is rich in soil carbon and allophane and/or organo-aluminum complexes. Therefore, the soil at the study site can be classified as an andisol along with Japanese volcanic ash soils (Kuroboku).

3.3.2 Concentration of DOC

When bulk precipitation entered the forest, the DOC concentration showed an appreciable increase (Table 3.2). During the growing season, mean DOC concentration in litter leachate (21.33 ± 1.01 mg L^{-1}) was much higher than in stemflow (15.05 ± 0.98 mg L^{-1}) or in throughfall (6.84 ± 0.45 mg L^{-1} above the dwarf bamboo and 7.08 ± 0.42 mg L^{-1} below it), and was more than seven times the mean DOC in bulk precipitation (2.98 ± 0.45 mg L^{-1}) ($P < 0.05$). Unlike in litter leachate, the mean DOC concentration in soil solute at a depth of 20 cm (5.89 ± 0.56 mg L^{-1}) decreased considerably to only 27.6% of that in litter leachate (Table 3.2). EC decreased significantly with DOC concentration, and low DOC concentrations were associated with low EC.

There were seasonal changes in DOC concentration, especially for litter leachate and stemflow (Fig. 3.2). DOC concentration in stemflow was high during early summer (June or July) and gradually decreased from that time. Figure 5 shows monthly changes of litter fall, precipitation and litter leachate DOC concentration. Monthly mean DOC concentration was independent of the monthly amount of precipitation. Moreover, litter leachate DOC concentration was high in spring and autumn, and thus, there were no clear correlation with temperature. In contrast, litter leachate DOC concentration was fairly correlated with the amount of litterfall of bamboo and trees. The annual amount (dry weight) of total litterfall was 548.8 g m^{-2}, consist of dwarf bamboo litter (199.7 g m^{-2}) mainly occurred in spring and canopy tree litter occurred in autumn (349.1 g m^{-2}) (Fig. 3.3). The C content in dwarf bamboo and canopy tree was 41.4% and 49.5%, respectively, thus, the C fluxes in dwarf bamboo and canopy trees were 826.8 and 1728.0 kg C $ha^{-1}yr^{-1}$, respectively. Then the C flux in the total litterfall was 2554.8 kg C $ha^{-1}yr^{-1}$.

The most striking result to emerge from the data is the interspecific differences in DOC concentration in stemflow on a monthly scale: the DOC concentration of *Quercus* was significantly higher than that of either *Betula* species in every month (Fig. 3.4). In litter leachate, the DOC concentration was also higher during early summer and gradually decreased from that point; the concentration was also extremely high in November (Fig. 3.2). Compared with litter leachate and stemflow, DOC concentrations in precipitation, and throughfall did not show a distinct monthly variation (Fig. 3.2). Mean DOC concentration of throughfall above the bamboo and that below the bamboo did not differ significantly on either a monthly or a yearly scale (Fig. 3.2, Table 3.2).

3.3.3 Water Budgets and Flux of DOC During the Growing Season

The bulk precipitation flux during the growing season (May–November 2015) was 1592.3 mm. The bulk precipitation was partitioned into stemflow (42.5 mm, 2.7% of bulk precipitation) and throughfall above bamboo (1407.0 mm, 88.4%). Interception of precipitation by bamboo leaves decreased the flux of throughfall below the bamboo (1122.3 mm, 70.5%). Litter leachate (1452.9 mm) attained up to 91.2% of bulk precipitation (Fig. 3.5).

During the growing season, bulk precipitation brought 45.4 kg ha^{-1} 7 $months^{-1}$ of DOC into the forest (Fig. 3.5). Canopy and trunks leached 56.4 kg ha^{-1} 7 $months^{-1}$ of DOC, while stemflow and throughfall above bamboo accounted for 5.0 kg ha^{-1} 7 $months^{-1}$ and 51.4 kg ha^{-1} 7 $months^{-1}$, respectively. The difference in DOC flux between throughfall above bamboo and throughfall below bamboo was 11.7 kg ha^{-1} 7 $months^{-1}$. The aboveground DOC input to the mineral soil was up to 311.5 kg ha^{-1} 7 $months^{-1}$, of which litterfall contributed 225.9 kg ha^{-1} 7 $months^{-1}$to the mineral soil (Fig. 3.5).

Monthly mean DOC fluxes in stemflow (R = 0.828, P < 0.01) and litter leachate (R = 0.661, P < 0.05) were positively correlated with the monthly amount of precipitation. The monthly mean DOC fluxes in throughfall above the dwarf bamboo (R = 0.605, P < 0.05) and throughfall below the dwarf bamboo (R = 0.618, P < 0.05) were positively correlated with the monthly mean DOC concentration.

3.4. Discussion

3.4.1 Variations and Regulation of DOC Concentration

The trend observed at the study site by which DOC concentration increases in the sequence from precipitation to throughfall, stemflow and litter leachate was similar to those reported in other forests (Tesón et al., 2014). In general terms, the increase in DOC concentration from precipitation to throughfall is almost certainly due to leaf leaching and microbial metabolites (biodegradable and hydrophilic neutral carbohydrates) that wash from the canopy during this process (Guggenberger and Zech 1994; Michalzik et al., 2001; Levia et al., 2012). In this study site, the mean concentration of DOC in throughfall (6.84 ± 0.45 mg C L−1) consistent with previous reports (3—35 mg C L−1, Michalzik et al., 2001; Fujii et al., 2011a), while the mean concentration of DOC in the precipitation (2.98 ± 0.45 mg C L−1) was a little higher than that reported in other studies (1.8—2.7 mg C L^{-1}; Currie et al., 1996, Michalzik et al., 1999, Moreno et al., 2001 and Solinger et al., 2001). Contrary to expectations, the DOC concentration in throughfall below the dwarf bamboo (7.08 ± 0.42 mg C L^{-1}) was not notably different from that in throughfall above the dwarf bamboo (6.84 ± 0.45 mg C L^{-1}) (Table 3.2), which indicates that the bamboo canopy had little effect on the DOC concentration. There are two likely causes for this finding: one is that bamboo with fibrous foliage becomes wet slowly and does not easily leach DOC; another is that the bamboo canopy is becoming sparse because of artificial damage at sampling times.

Table 3.1 Description of soil profile at the deciduous forest.

Horizon	Depth (cm)	Moist color	pH (H_2O)	pH (NaF)	Total C (g kg^{-1})	Total N (g kg^{-1})	C:N ratio
O	+ 7						
A1	0-21	10YR2/3	4.6	9.4	125.1	7.2	17
2A	21-48	10YR2/1	5.0	11.0	132.5	5.5	24
2A/B	48-60	10YR4/3	5.0	11.2	60.4	3.2	19
Bw1	60-100+	10YR5/6	5.1	10.7	27.8	1.9	15

Table 3.2 Average DOC concentration, pH and EC in different water flux of deciduous forest in 2015.

Flux	n	DOC mean ($mg\ L^{-1}$)	DOC range ($mg\ L^{-1}$)	pH	EC ($mS\ m^{-1}$)
Bulk precipitation	8	2.98 ± 0.45ab	1.03 - 4.74	5.54 ± 0.31a	0.89 ± 0.12a
Stemflow	72	15.05 ± 0.98c	3.60 - 37.90	5.56 ± 0.11a	2.72 ± 0.41bc
Throughfall above bamboo	72	6.84 ± 0.45b	1.18 - 20.57	5.61 ± 0.11a	2.39 ± 0.66abc
Throughfall below bamboo	72	7.08 ± 0.42b	1.63 - 19.45	5.72 ± 0.12a	2.21 ± 0.50abc
Litter leachate	70	21.33 ± 1.01d	7.91 - 43.76	5.42 ± 0.09a	3.34 ± 0.28c
Soil solution （20cm）	15	5.89 ± 0.56ab	1.68 - 10.77	5.59 ± 0.26a	1.51 ± 0.32ab

Different letters within each variable indicate significant differences among the water flux conditions ($P < 0.05$)

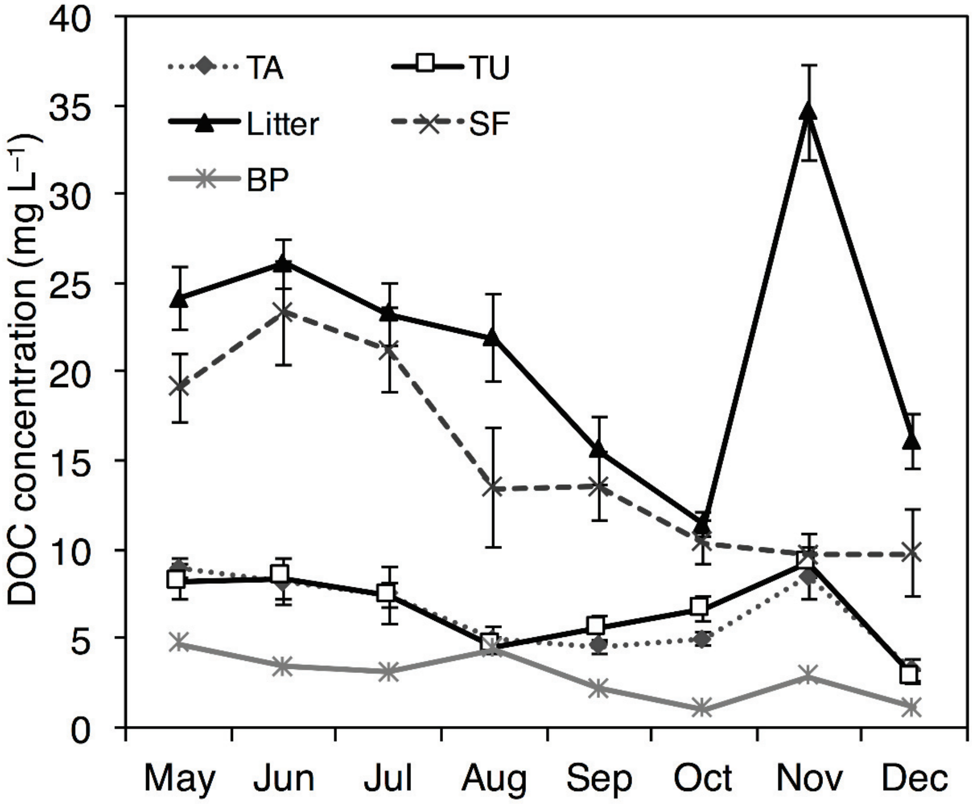

Fig. 3.2 Monthly average DOC concentrations in different water flux conditions of deciduous forest in 2015. Error bars indicate standard errors (n =9) (TA: throughfall above the dwarf bamboo, TU: throughfall below the dwarf bamboo, SF: stemflow, BP: bulk precipitation, DOC: dissolved organic carbon)

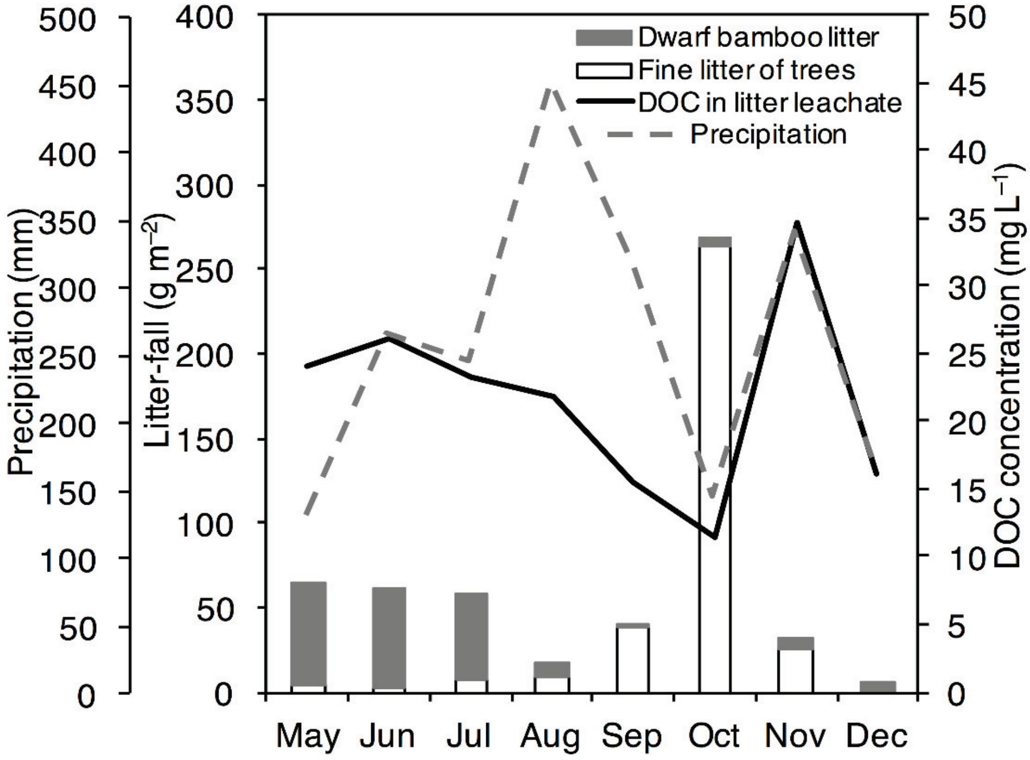

Fig. 3.3 Monthly mean litter leachate DOC concentrations, monthly precipitation and monthly mean weights of litterfall in the deciduous forest in 2015. Note: the weight of litterfall showed in May also incuding snow period (Jan–Apr), not just in May (DOC dissolved organic carbon).

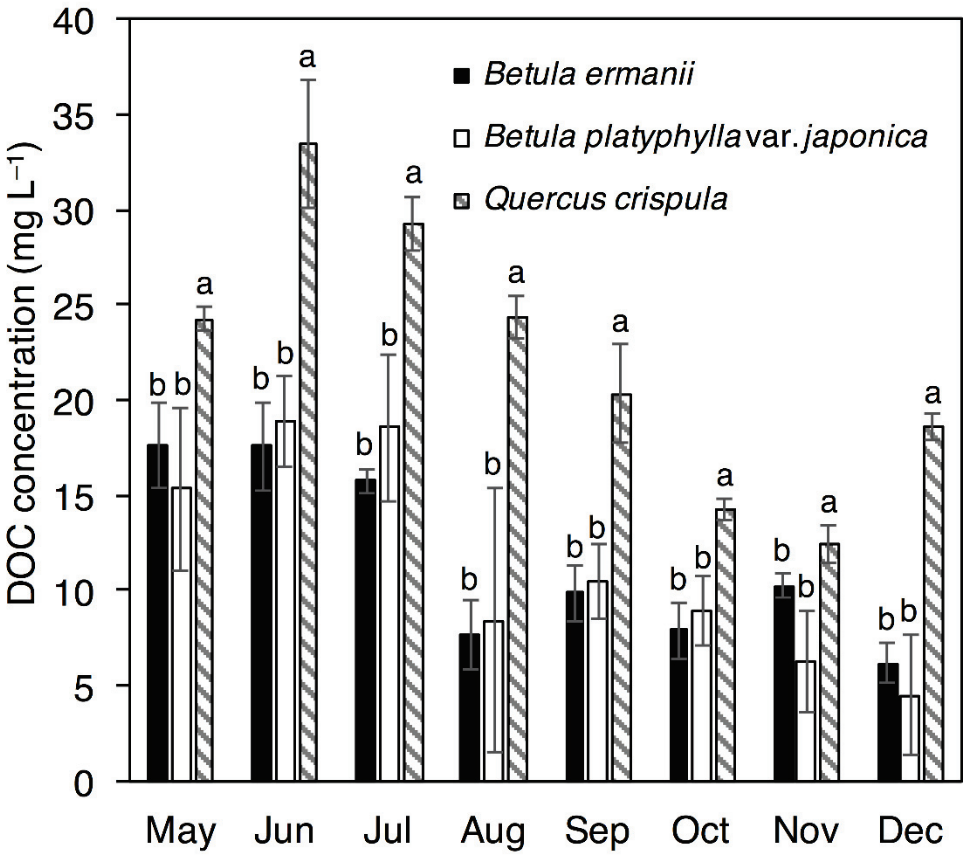

Fig. 3.4 Monthly mean stemflow DOC concentration among different species of deciduous forest in 2015, error bars indicate standard errors (n = 3), different letters within each month indicate significant differences among the different species (DOC: dissolved organic carbon)

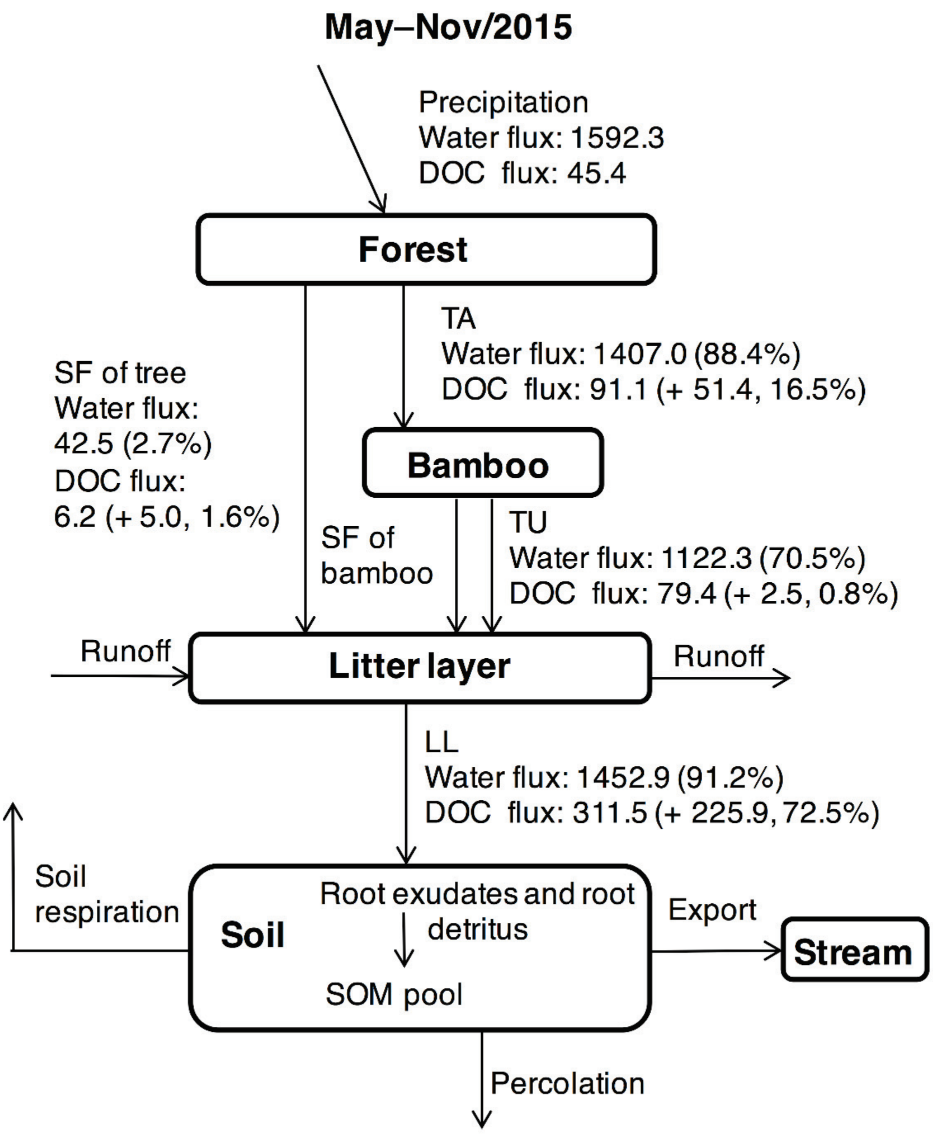

Fig. 3.5 Water fluxes and dissolved organic carbon (DOC) fluxes in the study site during the growing season in the deciduous forest from May to November 2015. Water flux is in mm, DOC flux is in kg ha1 7 months1 (SF stemflow, TA throughfall above the dwarf bamboo, TU throughfall below the dwarf bamboo, LL litter leachate, BP bulk precipitation, SOC soil organic carbon, data in brackets indicate ratio of water flux to gross rainfall, net release of DOC fluxes, and the ratio of net contribution from each component to the total DOC flux during the growing season, respectively

As previously stated, clear interspecific differences were observed in the DOC concentrations in stemflow (Fig. 3.4). These results match those observed in earlier studies (Inagaki et al., 1995; Levia and Herwitz 2002), in which DOC concentrations in stemflow were regulated by retention time when precipitation was retained in the bark, which implies that the DOC concentration in the stemflow is affected by different bark morphologies. DOC concentration was higher in *Quercus* stemflow than in *Betula* stemflow, owing to the rough and multi-layered fibrous bark of *Quercus*, which thus retains precipitation longer than the single-layered bark of *Betula* does allowing more DOC to leach.

With respect to the DOC concentration in litter leachate, Michalzik and Matzner (1999) found a positive correlation between temperature and the DOC concentration in the forest floor, which was in line with the higher DOC concentration observed in warmer seasons, owing to the effect of temperature on microbial activity (Cronan and Aiken 1985; McDowell and Likens 1988; Dai et al., 1996; Kalbitz et al., 2000). In addition, some studies reported recent litter as the primary source of DOC in forest floor leachates, and the litter leachate DOC concentration showed a positive response to the litterfall dynamics (Qualls et al., 1991; Casals et al., 1995; Currie et al., 1996; Michalzik and Matzner 1999). Apart from this, Solinger et al., (2001) investigated a significant correlation between DOC concentrations in throughfall vs. litter leachate.

However, in Takayama Forest, higher DOC concentration in litter leachate observed in

June and November but not in summer season (July and August) (Fig. 3.3), and thus, the correlation of DOC concentration and temperature was not found. One reason for this can be related to the litter inputs, DOC concentration in litter leachate continuously decreased from June to October, then dramatically increased in November, showing a positive response to the litterfall dynamics (Fig. 3.3), which owing to the seasonal leaf phenology in the deciduous forest occurs not only in canopy trees in autumn, but also in the understory of dwarf bamboo in the spring. The other reason was the seasonal characteristic of precipitation in the study site, the heavy rainfall currently occurred in July and August (Fig. 2.2), with more water passing through the forest floor and less contact time, DOC concentrations are lower, which matched the results showing a dilution effect of increasing water fluxes on DOC concentration (McDowell and Wood 1984; Easthouse et al., 1992). Within one year limited data, we can't confirm the relationship between litter leachate DOC concentration vs. temperature or litter input, however, the results suggest that the control on DOC concentration in the forest floor was not a single factor, but was a complex interaction among litterfall input, microbial activities and water flux. Further research would be needed to determine the relative importance of each.

3.4.2 Water budgets and dissolved organic carbon flux during the growing season

The partitioning of gross rainfall into throughfall, stemflow, and intercepted water is controlled by forest composition, seasonality and canopy foliar status, rainfall characteristics and meteorological conditions (Siegert and Levia 2014). Mean throughfall inputs are reported to range from 27 to 96%, while canopy interception loss is reported to range from 9.7 to 19.5% in various deciduous forests (Price and Carlyle-Moses 2003). In Japan, the range of throughfall has been reported at 64 to 97% (Ikawa 2007). Throughfall above bamboo (88.4%) and canopy interception (11.6%) measured at this study site were within the ranges reported from other forests.

Stemflow is considered to be the smallest fraction of gross rainfall (Helvey and Patric 1965; Levia and Frost 2003). According to Levia and Frost (2003), mean stemflow inputs ranged from 0.94 to 20% of the gross rainfall in temperate forests; the average stemflow input in temperate forests was 11.3%. Stemflow at our study site was 2.7% of the gross rainfall, which was lower than the average for temperate forests, but still within the range observed in other forests. Moreover, González-Martínez et al., (2016) found that understory contributed importantly to stemflow, particularly if the density of understory vegetation groups is high. Regarding the considerable difference between litter leachate (1452.9mm) and throughfall below the bamboo combined with stemflow (1164.8mm) (Fig. 7), and the dense dwarf bamboo in the study plot, we assumed that a quite part of water may be transported by stemflow of dwarf bamboo.

The growing season DOC flux was 311.5 kg ha^{-1} 7 $months^{-1}$ at the study site, which was in the upper range of those reported in other temperate forest ecosystems (100–400 kg C $ha^{-1}yr^{-1}$, Michalzik et al., 2001) and much higher than that reported in another deciduous forest in Steigerwald, Germany (85.9–208.2 kg C $ha^{-1}yr^{-1}$; Solinger et. al 2001) and in Japan (52.6–343.6 kg C $ha^{-1}yr^{-1}$; Fujii et al., 2011a). The magnitude of the DOC flux might be explained by several factors. First of all, precipitation plays a crucial role because of the DOC fluxes are directly related to the amount of precipitation (Schmidt et al., 2009), as remarkable correlation was shown between monthly DOC flux in litter leachate and bulk precipitation in the Takayama Forest. Second, litterfall contributes significantly to DOC production in forest floors, and while DOC fluxes leaching from the forest floor typically range from 10% to 12.5% of the C fluxes in the litterfall (Qualls et al., 1991; Solinger et al., 2001; Park and Matzner, 2003), the carbon input from canopy tree litter at our study site was up to 1728.0 kg C $ha^{-1}yr^{-1}$. Additionally, fresh litter contributes significantly to DOC production in forest floors (Kalbitz et al., 2000), and the input of litter is large which occurred not only in autumn but also in spring, due to the dense understory of dwarf bamboo at our study site (Fig. 3.3). The litter production by dwarf bamboo alone estimated at 826.8 kg C $ha^{-1}yr^{-1}$ in 2015; thus the total litter production was 2554.8 kg C $ha^{-1}yr^{-1}$, which was much higher than those at other study sites (920–1530 kg C $ha^{-1}yr^{-1}$, Leppälammi-Kujansuu et al., 2014).

As regard the net contribution of different water flux conditions to the total DOC flux, the largest DOC input to mineral soil during the growing season was provided by litter leachate (225.9 kg ha^{-1} 7 $months^{-1}$), which contributed 72.5% of the DOC input flux (311.5 kg ha^{-1} 7 $months^{-1}$, Fig. 3.5), and about 8.8% of the C flux in the litterfall (2554.8 kg C $ha^{-1}yr^{-1}$). Interestingly, the total precipitation DOC flux was up to 45.4 kg ha^{-1}, which was abundant compared to those at other sites (Table 3.3), implying that atmospheric deposition was a non-negligible source of DOC at the study site. Moreover, 43.6% (39.7 kg ha^{-1} 7 $months^{-1}$) of DOC flux in the form of throughfall above the bamboo (91.1 kg ha^{-1} 7 $months^{-1}$) came from rainfall, while 56.4% (51.4 kg ha^{-1} 7 $months^{-1}$) originated from dry deposition and canopy exchange.

3.4.3 Implications for Takayama Forest

As previously stated, DOC fluxes have been thought to be minor compared to NPP, and thus DOC fluxes have been considered to be minor components of the ecosystem carbon balance. For example, Gosz et al., (1976) reported that the quantity of organic matter transported to the forest floor via throughfall and stemflow was equivalent to only 1% of the NPP of trees at the Hubbard Brook Experimental Forest. In the Takayama Forest, the estimated DOC flux of the throughfall and stemflow during the growing season was 97.3 kg C ha^{-1}7 $months^{-1}$, only 1.5% of the NPP (6.5 t C ha^{-1} yr^{-1}, Ohtsuka et al., 2005). In contrast, the estimated litter leachate DOC flux during the growing season including leaching from the litter amounted to 311.5 kg C ha^{-1} 7 $months^{-1}$. Ohtsuka et al., (2009) reported that the SOM pool plays an important role relative to that of biomass pools in the carbon sink in the Takayama Forest. They estimated a high accumulation rate of 0.8 t C ha^{-1} yr^{-1}, although their estimate of ΔSOM, based solely on the balance between the carbon fluxes that enter via plant litter and depart via heterotrophic respiration, was tenuous. The estimated litter leachate DOC flux during the growing season was as high as 38.9% of the estimated annual soil carbon accumulation.

Moreover, although stemflow is considered to be the smallest fraction of the gross rainfall in general (Helvey and Patric 1965; Levia and Frost 2003), and the contribution at our study site was only 2.7% of gross rainfall, our measurement method might have resulted in an underestimate of the contribution of DOC flux from stemflow due to localized inputs around trunk bases. For example, Herwitz (1986) reported that stemflow delivered a quantity of water to the bases of plants that was on average 21 times greater than the gross precipitation equivalent. Moreover, Laclau et al., (2010) demonstrated that there were variations in fine root densities and soil chemistry around trunk bases due to higher concentrations of nutrients from stemflow. Furthermore, another source of input to the SOM pool consists of below-ground DOC fluxes, including leaching from below-ground litter (dead roots and rhizome of dwarf bamboo) and root exudates. Although few studies have included estimates of root exudates or leached organic carbon from below-ground sources in forest ecosystems, Bekku et al., (1997) found that root exudates accounted for 3–13% of NPP in temperate weed communities. Thus, the potential impact of below-ground DOC fluxes is not negligible compared to that of above-ground litter leachate.

In addition, DOC flux from litter leachate may continue during the snow season, because microbial activity and litter decomposition don't halt under the snow in the Takayama Forest. According to the study of Uchida et al., (2005), the mass loss rate of litter during snow season accounted for 26% of the annual mass loss using litter bag method. Therefore, more than a quarter of annual litter leachate DOC flux may occur under the snow (ca. 79 kg ha^{-1}). Beyond that, the average annual snowfall amounted to 34% of annual precipitation, thus, the snowfall may also bring a considerable DOC flux (ca. 23 kg ha^{-1}) into the forest as precipitation during growing season. Combining DOC flux from litter leachate under snow and snowfall, approximately 33% of DOC flux was underestimated. Despite the data need further investigation to confirm, we supposed that the unevaluated litter leachate and snowfall during the snow period have a vital contribution to annual DOC flux.

In the Takayama Forest, the DOC concentration in the soil solution (20 cm depth) decreased dramatically compared to the different soil type in the other forests (Table 3.4). This is probably due to the chemical and physical properties of the andisols in the Takayama Forest, and particularly to the presence of labile and active metals (especially Al and Fe) that originated from volcanic materials, which can be inferred from the higher pH values of NaF (Inoue 1986). Moreover, Kawahigashi (2008) reported that andisols had the highest capacity for DOC adsorption, adsorbing more than 90% of DOC, and that DOC rarely leaches from andisols to stream. Taken together, these results suggest that DOC fluxes are the main carbon input to the mineral soil, and that the surface mineral horizon of andisols is the major sink for DOC in the Takayama Forest. The annual dwarf bamboo litter (199.7 g m^{-2}) comprised 36.4% of the total litter carbon production (548.8

g m^{-2}), suggesting the importance of a dense dwarf bamboo understory for stable and continuous production of DOC, especially in spring.

Table 3.3 DOC concentration and flux of bulk precipitation in different sites.

Study site	Precipitation (mm)	DOC concentration (mg L^{-1})	DOC flux (kg ha^{-1} yr^{-1})	Reference
Eucalyptus grandis plantations of South-Africa	1388	2.0	27.1	Tesón et al., 2014
Hubbard Brook Valley	1278	1.1	16.0	McDowell and Likens, 1988
Steigerwald Nature Park(Northern Bavaria, Germany)	665	1.8	11.9	Solinger et al., 2001
	838	2.3	22.0	
PROTOS experimentalsite： Coulissenhieb, Waldstein, Bavaria, Germany	1100	2.7	17.8	Michalzik et al., 1999
10-sites- average in Northern China	635	3.0	19.0	Pan et al., 2010
Seoul, Korea	1727	1.1	19.0	Yan et al., 2015
Matsuzawa catchment, central Japan	1658	1.4	20.6	Kawasaki et al., 2005
Takayama site, Japan	1592	2.98	45.4	Present study, the growing season

Table 3.4 Comparing the DOC concentration in litter leachate, 20 cm depth and the decrease percentage from litter leachate (O horizon) to upper B (20 cm) to the other sites

Study site	Soil type	Litter leachate (O horizon) (mg L^{-1})	Upper B (20cm) (mg L^{-1})	Decrease percentage (%)	Reference
BITEOK research site: Steigerwald National Park, Bavaria, Germany	Dystric Cambisol	26.90	16.20	39.8	Park and Matzner, 2003
Nagano site: Mt. Yatsugakate, Nagano, Japan	Andisols	6.80	1.40	79.4	
Tango site: Tango Peninsula, Kyoto, Japan	Spodosol	13.00	2.30	82.3	Fujii et al, 2011a
Kyoto site: Mt. Yoshida, Kyoto, Japan	Inceptisol	15.40	4.30	72.1	
Matsuzawa catchment, central Japan: PW plot		27.85	8.33	70.1	
Matsuzawa catchment, central Japan: UZ plot	Brown forest soil	28.07	10.50	62.6	Kawasaki et al., 2002
Matsuzawa catchment, central Japan: SZ plot		20.88	4.99	76.1	
Takayama site: Takayama, Japan	Andisols	21.33	5.89	72.4	Present study

4. DOC in the Warm-Temperate Broad-Leaved Evergreen Forest (Lucidophyllous Forest)

4.1 Introduction

The study site Mt. Kinka (35°26′ N, 136°47′ E, the peak is 329 m) is located in Gifu Prefecture, central Japan. Almost all areas (597 ha) of Mt. Kinka consist of secondary natural forests (93%) and artificial coniferous forests (2%). In particular, the lower slopes of Mt. Kinka are covered by secondary evergreen broad-leaved forests that predominated by *Castanopsis cuspidata*, which were mainly recovered after the World War II. As mentioned before, evergreen broad-leaved (Lucidophyllous) forests are distributed widely in the subtropical and warm-temperate regions of East Asia. Numerous studies have quantified and characterized fluxes of DOC in the forest ecosystems at local, regional, or national scale (Borken et al., 2011; Buckingham et al., 2008b; van den Berget al., 2012), but most studies were established in deciduous and coniferous forests (Michalzik et al., 2001, Kindler et al., 2011, Camino-Serrano et al., 2014), little is known about the origin, composition, and fate of DOC in the evergreen broad-leaved forest ecosystems. Considering the highest average NPP has been reported for evergreen broad-leaved species occupying mesic temperate environments in Japan (Perry et al., 2008), it may also be a large contributor of DOC flux inputs to the soil. Beyond that, previous studies found that canopy structure is an important controlling factor on throughfall patterns, broad-leaved deciduous canopies have been shown to influence throughfall patterns during the leafed season (Keim et al., 2005; Staelens et al., 2006b). Moreover, some study assumed that the multiple layers within the forest canopy and differences in canopy phenology might complicate throughfall patterns in tropical forests (e.g., Germer et al., 2006; Zimmermann et al., 2009; Zimmermann and lsenbeer 2008). Although there is no clear leafed and leafless season in evergreen forest, the changes of canopy phenology still have impacts on the dynamics of DOC concentration in throughfall, stemflow and litter leachate. To test the hypothesis, we evaluated the variation in DOC concentration in throughfall, stemflow, and litter leachate of this evergreen forest, and quantified the annual contribution of DOC from different forest water flux conditions to the DOC input to the soil, aims to figure out the seasonal change patterns of DOC.

4.2 Materials and Methods

4.2.1 Experimental Setup and Sample Collection

The stemflow collector consisted of two pieces of formed polyethylene with aluminized film (thickness 8 mm) which were cut into rectangles (width 6 cm and 10 cm). First, the tree bole was wrapped with the smaller mat (6 cm in width), and the mat was sealed to the bark with silicone sealant to ensure that there was no leak between the bark and the mat. This purpose of this mat was to make a space to let stemflow flow into the tube without leakage. Then we attached the second mat, which was wider than the first (10 cm in width), on top of the first mat. The bottoms of the two mats were aligned and sealed with silicone. A tube was connected to a sample reservoir tank. Stemflow collectors were set up on the dominant species *C. cuspidata*, including four DBH classes (20–30 cm, 30–40 cm, 40–50 cm, >50 cm) with three individual trees in each DBH class. The sampled trees were evenly distributed on the study plot. The volume of stemflow was measured using a rain gauge with a reservoir tank.

Each throughfall collector consisted of a 21 cm diameter funnel and a collection bottle (volume 12 L). A draining mesh bag covered the top of the funnel, and a plug of glass wool was placed in the funnel neck to exclude particulate matter from the collection bottle. Nine throughfall collectors were randomly distributed within the study plot.

The litter leachate was collected using zero tension lysimeter; each zero tension lysimeter was set near each throughfall collector for a total of nine litter leachate samplers. These lysimeters of 161cm^2 area containing a glass wool plug and draining into a 12 L plastic bottle through a flexible tube were installed directly underneath the litter layer.

Samples of bulk precipitation were collected using a collector (20 L) set up in a location without a canopy that was near the study area. The bulk precipitation collector was almost identical to the throughfall collector except for the volume of the collection bottle. Samples of precipitation were collected at the same time and in the same manner as samples of throughfall, about twice a month.

Litterfall and flower were collected in using litter traps (1 m^2 area) that was set near each throughfall collector for a total of nine litter traps. Litterfall and flower were collected once a month.

4.2.2 Chemical Analysis

The water volume of throughfall, litter leachate, and bulk precipitation was measured twice a month from January 2017 to December 2017 using a measuring cylinder (5 L) in the field. The water volume of the stemflow was read out from a rain gauge twice per month. Subsamples of stemflow, throughfall, litter leachate, bulk precipitation for chemical analysis were taken in clean 100 ml polyethylene bottles at the same time.

After pH and electrical conductivity were measured with a pH and EC meter (Horiba, D-54), all water samples were filtered through a 0.45 μm MF-Millipore nitrocellulose membrane and stored at −18 °C in the dark until analysis. The concentrations of DOC in solution were measured with a total organic carbon analyzer (TOC-V, Shimadzu, Japan). To obtain the NPOC (Non-Purgeable Organic Carbon) measurement (TOC by acidification/sparging method), each sample is acidified with a small amount of hydrochloric acid, then sparged with sparge gas. This processing removes all inorganic carbon (IC) from the sample by converting it to carbon dioxide. The TOC concentration is determined by measuring the TC of the sample after the IC is eliminated.

Litterfall and flower were separated in the laboratory, then dried at 70ºC to measure dry matter weight.

4.2.3 Calculation of Fluxes

When we use the term *DOC flux* in this study, we are referring to the DOC flux that was the quantity of DOC from precipitation, stemflow, throughfall and litter leachate input to the soil per stand area during the whole year (January to December 2017). The monthly amount of DOC (kg ha^{-1} $month^{-1}$) calculated by monthly water volume (L $month^{-1}$) multiplied by the monthly mean DOC concentration (kg L^{-1}). The annual DOC flux (kg ha^{-1} yr^{-1}) is a cumulative monthly amount of DOC from January to December 2017.

The stemflow per unit stand area was estimated using the basal area of each sample tree and the total basal area of all trees in the stand (Deutscher and Kulturbau, 1992). The formula was as follows:

$h_{ns} = (V_{ns}/b)$ (B/S),

where h_{ns} is the stemflow (mm), V_{ns} is the volume of stemflow of the tree measured (dm^3), b is the basal area of the sample tree (m^2), B is the total basal area of all trees in the measuring area (m^2), and S is the plot area (m^2).

The flux in throughfall and litter leachates were calculated using the measured water volumes and concentrations in each sample on each sampling day. The formula was as follows:

$F = VC /100S_1$,

where F is the monthly flux in a 1 ha plot (kg ha^{-1}), V is the monthly volume (L), C is the monthly concentration of each element (mg L^{-1}), and S_1 (m^2) is the area of the funnel ($0.0346m^2$) or lysimeter plate ($0.0144m^2$) used to collect the sample.

The flux in stemflow and precipitation were calculated using the formula as follows:

$F = hC/100$,

where F is the monthly flux in 1 ha plot (kg ha^{-1}), h is the monthly volume (mm), and C is the monthly concentration (mg L^{-1}).

$F_s = \Sigma\ F_m$,

where F_s is the annual flux in a 1 ha plot (kg ha^{-1} yr^{-1}) and F_m is the monthly flux (kg ha^{-1}).

4.2.4 Statistical Analyses

Concentrations of DOC are presented as arithmetic means. One-way ANOVA was used to detect significant differences in DOC concentration in different water flux conditions and different species, and in pH and EC in different water flux conditions. Correlation analysis was carried out using linear regression analysis. Significant effects were identified at $P < 0.05$. All statistical analyses were performed with IBM SPSS STATISTICA 22.0.

4.3 Results

4.3.1 Dynamics of DOC Concentration

Annual mean DOC concentration in bulk precipitation was 2.80 ± 0.37 mg L^{-1} and increased as precipitation passed through forest canopies. DOC concentrations in throughfall (6.62 ± 1.62 mg L^{-1}) and stemflow (11.87 ± 0.96 mg L^{-1}) were 2.4 times and 4.2 times as much as that in precipitation, respectively. Moreover, DOC concentration was highest in litter leachate (19.78 ± 3.23 mg L^{-1}) (Table 4.1). Stemflow pH (5.00 ± 0.11) was lowest compared to the pH of other water fluxes. However, there was no significant difference among EC of different water flux (Table 4.1).

DOC concentrations of throughfall, stemflow and litter leachate in every month were higher than those in precipitation. DOC concentration in precipitation did not show a distinct monthly variation, while DOC concentrations in throughfall, stemflow and litter leachate exhibited significant monthly variations. DOC concentrations in throughfall, stemflow and litter leachate in May was 22.24, 17.24 and 39.97 mg L^{-1}, respectively, which were highest during the whole year, then gradually decreased (Fig. 4.1). Moreover, the amounts of litterfall (133.9 g m^{-2}) and flower (69.3 g m^{-2}) were also extremely high in May (Fig. 4.2). Beyond that, seasonal changes of DOC concentrations were very similar in throughfall and stemflow, which were highest in summer and there was no obvious difference in the other seasons (Fig. 4.3). However, in litter leachate, the highest DOC concentration was also observed in summer, and relatively higher DOC concentrations were found in autumn and winter, lowest DOC concentration was in spring.

Correlation analysis showed that DOC concentrations in stemflow and litter leachate were significantly positive related to throughfall DOC concentration (Table 4.2), while a positive correlation was found between throughfall DOC concentration and dry weight of litterfall and flower. Moreover, DOC concentration in litter leachate also positive related to the dry weight of flower and temperature. The correlation between the DOC concentration of different water flux and the rainfall amount was not significant, although the correlation values indicated some negative relationships (Table 4.2)

4.3.2 Water Partitioning and DOC Flux

The annual precipitation flux was 1864 mm at the study site. The precipitation was partitioned into stemflow (67.7 mm, 3.6% of precipitation) and throughfall (1436 mm, 77.0%). Litter leachate (1506.9 mm) attained up to 80.8% of precipitation (Fig 4.4).

Clear monthly DOC fluxes changes were observed in different water fluxes, especially for DOC fluxes in litter leachate and throughfall (Fig. 4.5). Significant correlations were found between monthly DOC fluxes in stemflow vs. precipitation amount ($r = 0.917$, $p < 0.01$) and litter leachate vs. monthly precipitation amount ($r = 0.637$, $p < 0.05$), whereas monthly DOC fluxes in throughfall was positively correlated to monthly DOC concentration in throughfall ($r = 0.726$, $p < 0.01$).

Although precipitation brought only 35.4 kg^{-1} ha^{-1} yr^{-1} of DOC into the forest, the annual DOC flux input to soil was up to 309.5 kg^{-1} ha^{-1} yr^{-1}. Net contribution of stemflow (6.6 kg^{-1} ha^{-1} yr^{-1}), throughfall (42.2 kg^{-1} ha^{-1} yr^{-1}) and litter leachate (227.5 kg^{-1} ha^{-1} yr^{-1}) to the total DOC flux was 2.1%, 13.6% and 73.5%, respectively (Fig 4.4).

4.4 Discussion

4.4.1 Dynamics of DOC Concentration

There was a definite difference in DOC concentration among precipitation, throughfall, stemflow and litter leachate at both annual and monthly scale (Table 4.1, Fig. 4.1), and the order of the DOC concentrations in this study was always: litter leachate > stemflow > throughfall > precipitation. The results are similar to those reported in other forest ecosystems (Michalzik et al., 2001, Solinger et al., 2001, Chen et al., 2017). It is generally assumed that the wash-off from the canopy, including branches and trunks and leaching from the leaves are the two mayor sources of DOC in throughfall and stemflow. Previous studies in subtropical forests reported that DOC concentration in throughfall and stemflow ranged in 5–11 mg L^{-1} and 6–43mg L^{-1}, respectively (Van Stan and Stubbins 2018), the annual mean DOC concentration in throughfall (6.62 ± 1.62 mg L^{-1}) and stemflow (11.87 ± 0.96 mg L^{-1}) in this study consistent with previous reports. There was rare research investigated the DOC concentration in litter leachate in the subtropical evergreen broadleaved forest. However, the annual mean DOC concentration in litter leachate (19.78 ± 3.23 mg L^{-1}) was lower than the range of those investigated in the temperate forest ecosystems (20–40 mg L^{-1}, Michalzik et al., 2001).

Significant and positive relationships were found in concentrations of DOC in stemflow vs. in throughfall and litter leachate vs. in throughfall. Whereas throughfall DOC concentration was positively correlated to dry weight of litterfall and flower. These results explained the same patterns of monthly changes in both DOC concentrations and dry weight of litterfall and flower found in this study. Additionally, Nitta and Ohsawa (1997) reported that leaf fall of *Castanopsis* had a high peak in May simultaneously with leaf emergence. Taken together, we supposed that the canopy exchanges (leaf emergence, leaf fall and florescence) had a great impact on throughfall DOC concentration and had indirect impacts on DOC concentrations in stemflow and litter leachate. DOC concentration in litter leachate was also positively correlated to temperature (Table 4.2 $p < 0.05$), suggesting a significant biological control on the DOC leaching from litter, which confirming the results in previous studies in both laboratory experiments and field studies (Andersson et al., 2000; Kalbitz et al., 2000; Solinger et al., 2001). Beyond that, numerous studies found that litter leachate DOC concentration showed a positive response to the litterfall dynamics in temperate forests (Casals et al., 1995; Currie et al., 1996; Michalzik and Matzner 1999). Interestingly, in this study, no statistically significant correlation was found between litter leachate DOC concentration and litterfall, nevertheless, the statistically significant correlation found between litter leachate DOC concentration and flower. As we know, there was no previous research reported the correlation between litter leachate DOC concentration and flower, we supposed that the amount of flower might also be an essential source of DOC on the forest floor during the flower season. Moreover, the correlations of DOC concentration in different water fluxes and precipitation amount were not significant, especially for DOC concentration in litter leachate (Table 4.2), this result was in consensus with other studies that DOC concentration was not independent to precipitation amount (Songler et al., 2001, Michalzik et al., 2001). These may due to the rainfall dilution effect on DOC concentration was offset by other covarying factors, such as biological activities and changes in leaf leaching (Yan et al., 2015).

4.4.2 Water Partitioning and DOC Flux

Forest canopies redistributed rainfall into throughfall and stemflow, as a result of this redistribution, the input of water to the forest floor is characterized by forest composition, canopy structure, stand density, and basal area (Ford and Deans 1978; Crockford and Richardson 2000; Park and Hattori 2002). Throughfall and stemflow inputs are reported to range 47–91%, 0.3–9.5%, respectively, in deciduous, coniferous, tropical and eucalyptus forest around the global (Levia et al., 2011). In Japan, the range of throughfall has been reported at 64–97% (Ikawa 2007). Throughfall (77.0%) and stemflow (3.6%) investigated in this study were within the ranges reported from other forests. The proportion of canopy interception (19.4%) in this study is a little lower than the result

(20.2–48.2%) from a temperate evergreen broad-leaved forests in Kochi, Japan (Fujimoto et al., 1997), but within the widely reported range of 15–30% for many broad-leaved evergreen forests around the global (Crockford and Richardson 2000, Iroume et al, 2002). The difference may attribute to the variation of forest structure and the rainfall characteristic, as well as the sampling design (Lloyd et al., 1988; Xu et al., 2005).

In forest ecosystems, the forest floor has been identified as a primary source for DOC (Cronan and Aiken, 1985, Currie et al., 1996, Qualls and Haines, 1991). At the study site, the annual DOC fluxes input to the soil was 309.5 kg^{-1} ha^{-1} yr^{-1}, which was comparable to the highest values recorded in temperate forests (100–482 kg^{-1} ha^{-1} yr^{-1}, Michalzik et al., 2001, Fujii et al., 2001), nevertheless, it was much higher than that reported in another evergreen broadleaved forest in Japan (149.4 kg ha^{-1} yr^{-1}, Fujii et al., 2011b), this result may be explained by the differences of annual precipitation amounts, vegetation types (lignin concentration, C/N ratio), the amounts of litterfall (Godde et al., 1996, Currie and Aber 1997, Michalzik et al., 2001, Fujii et al., 2001) and even the difference of throughfall, considering 13.6% of total annual DOC fluxes was provided by throughfall. And most of total annual DOC fluxes was from litter leachate (73.5%, 227.5 kg^{-1} ha^{-1} yr^{-1}), while stemflow only attributed 3.6% of total annual DOC fluxes (6.6 kg^{-1} ha^{-1} yr^{-1}), indicating that the major source of DOC input to soil depends on litter decomposition.

Precipitation is the dominant driver of DOC fluxes in stemflow and litter leachate at monthly scale (Table 4.3), this had also been found in the previous studies (Michalzik et al., 2001, Fujii et al., 2009). However, DOC fluxes in throughfall were not significantly correlated to precipitation but significantly related to its DOC concentration at monthly scale (Table 4.3). Moreover, monthly DOC fluxes in litter leachate were positively related to the DOC fluxes in throughfall (Table 4.3), this relationship has also been reported by Michalzik et al., (2001). Previous studies showed that nearly 50% of DOC fluxes in throughfall consists of carbohydrates that are dominated by microbial metabolites washed from canopy, and about 80% of those carbohydrates were easily decomposable, thus, throughfall provides easily decomposable carbon compounds, which probably act as co-substrates or promoters for decomposition and mineralization processes of organic carbon in forest floor (Guffenberger and Zech, 1994; Michalzik et al., 2001). Beyond that, monthly DOC fluxes in throughfall, stemflow and litter leachate were statistically correlated to temperature, which further supported the supposition that annual mean air temperature might be one of the main factors influencing annual DOC fluxes, because many biological processed in the production and consumption of DOC depend on temperature (Michalzik and Matzner, 1999; Watmough et al., 2004; Schaefer and Alber, 2007).

Table 4.1. Annual average DOC concentration, pH and EC in different water flux in evergreen forest in 2017.

Water flux	n	Annual mean DOC (mg L^{-1})	DOC range (mg L^{-1})	pH	EC (mS m^{-1})
Bulk precipitation	36	2.80 ± 0.37 a	0.68–5.33	5.69 ± 0.13 b	4.41 ± 0.57 a
Throughfall	108	6.62 ± 1.62 ab	1.01–28.23	5.32 ± 0.14 ab	5.17 ± 0.45 a
Stemflow	144	11.87 ± 0.96 b	2.96–26.41	5.00 ± 0.11 a	4.87 ± 0.39 a
Litter leachate	108	19.78 ± 3.23 c	3.79–45.06	5.49 ± 0.09 b	5.99 ± 0.67 a

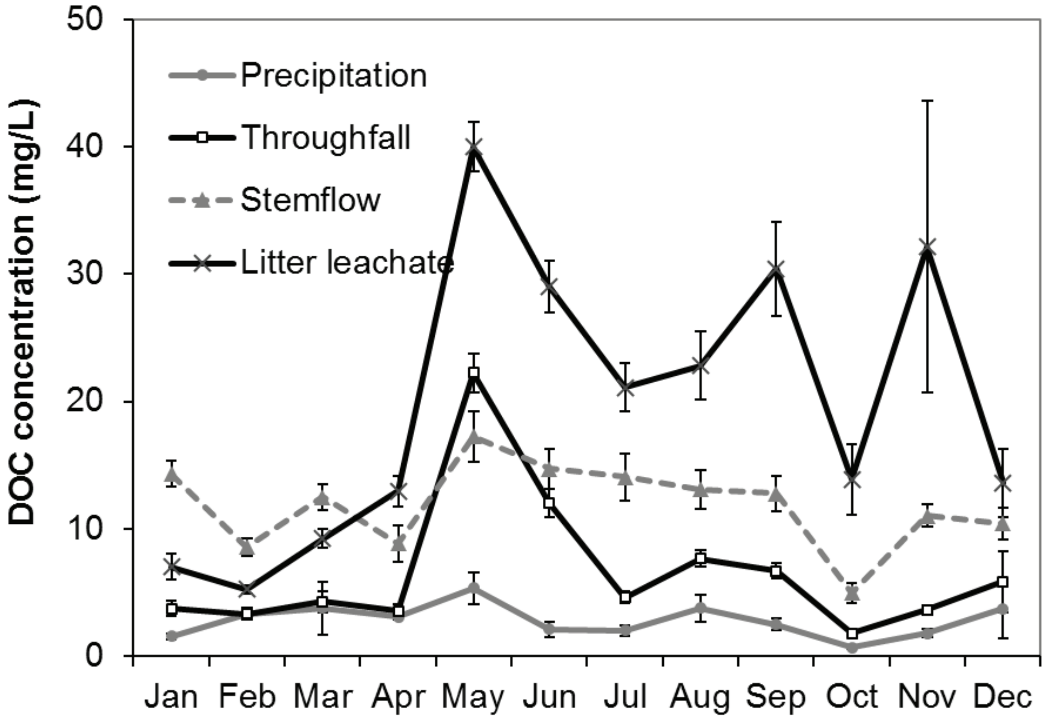

Fig 4.1 Monthly mean DOC concentrations of different water flux in evergreen forest.

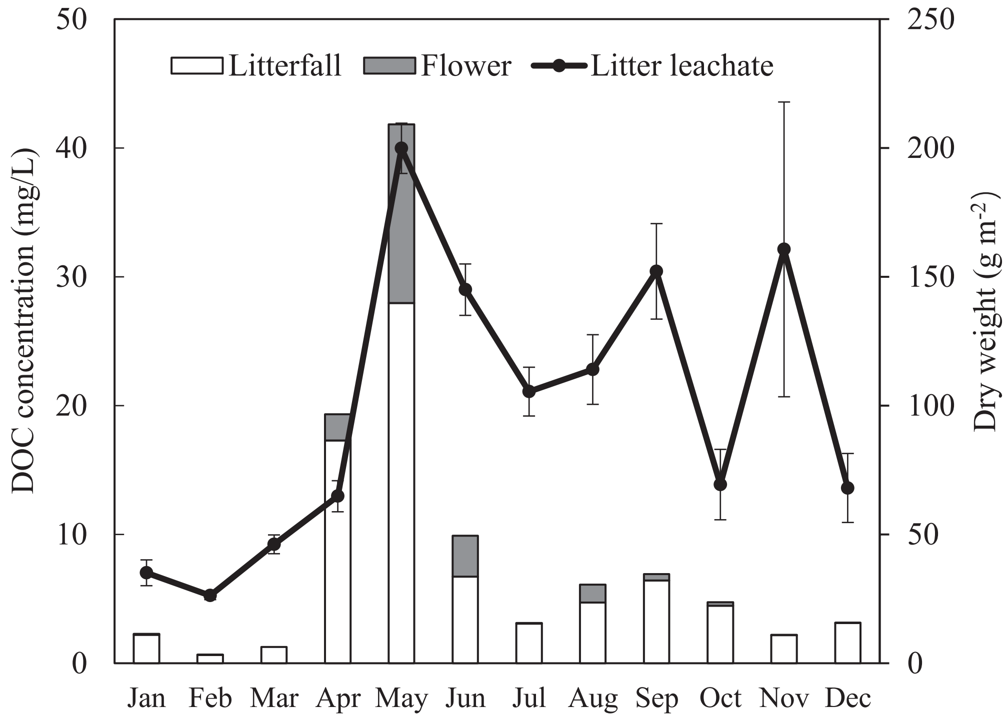

Fig 4.2 Monthly mean dry weight of different flower and litterfall in evergreen forest.

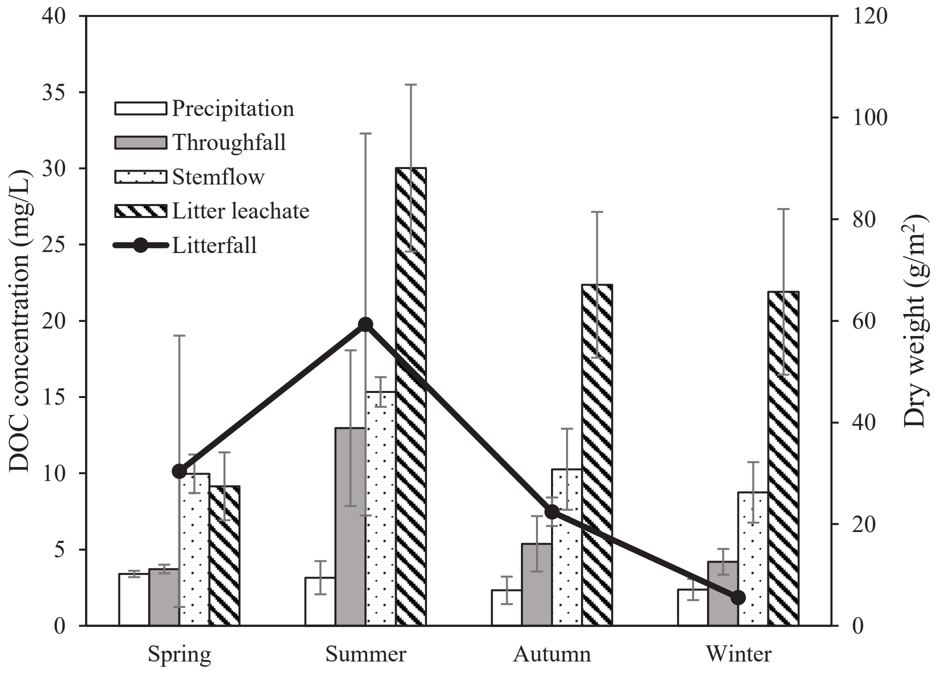

Fig 4.3 Seasonal changes of DOC concentration in different water flux and seasonal change of litterfall in evergreen forest.

Table 4.2 Correlation coefficients between DOC concentrations in throughfall (TF), stemflow (SF) and litter leachate (LL) vs. DOC concentration in throughfall (TF), dry weight of litter fall and flower, temperature and rainfall in evergreen forest.

Evergreen	TF DOC mg/L	Dry Weight of litterfall g/m^2	Dry Weight of flower g/m^2	Temp. ℃	Rainfall mm
SF DOC	0.708**	0.345	0.542	0.318	-0.475
mg/L	n=12	n=12	n=12	n=12	n=12
LL DOC	0.716**	0.529	0.625*	0.622*	-0.049
mg/L	n=12	n=12	n=12	n=12	n=12
TF DOC	-	0.756**	0.937**	0.364	-0.210
mg/L	-	n=12	n=12	n=12	n=12

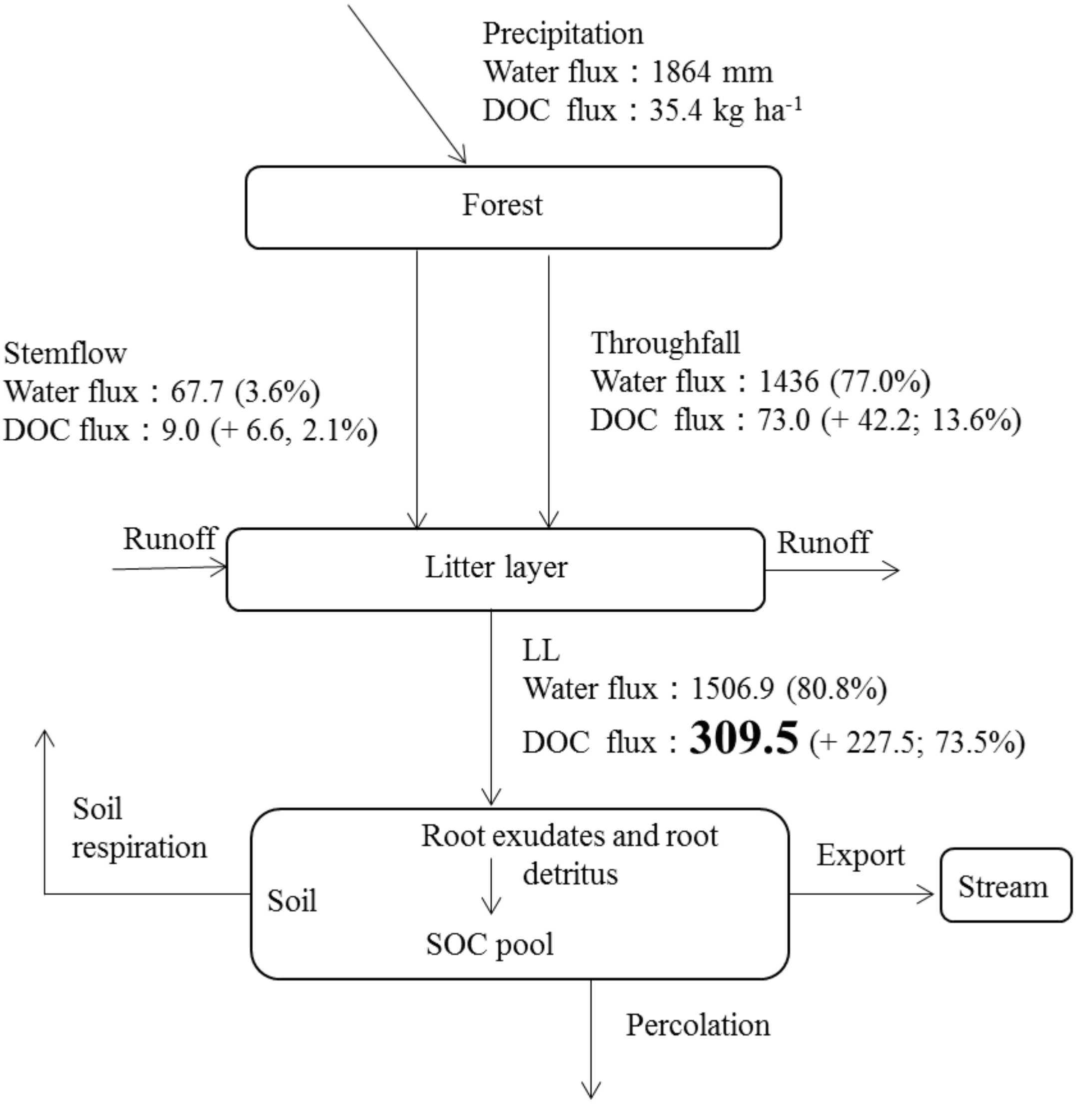

Fig.4.4 Annual water fluxes and DOC fluxes in different water flux in the evergreen forest in 2017.

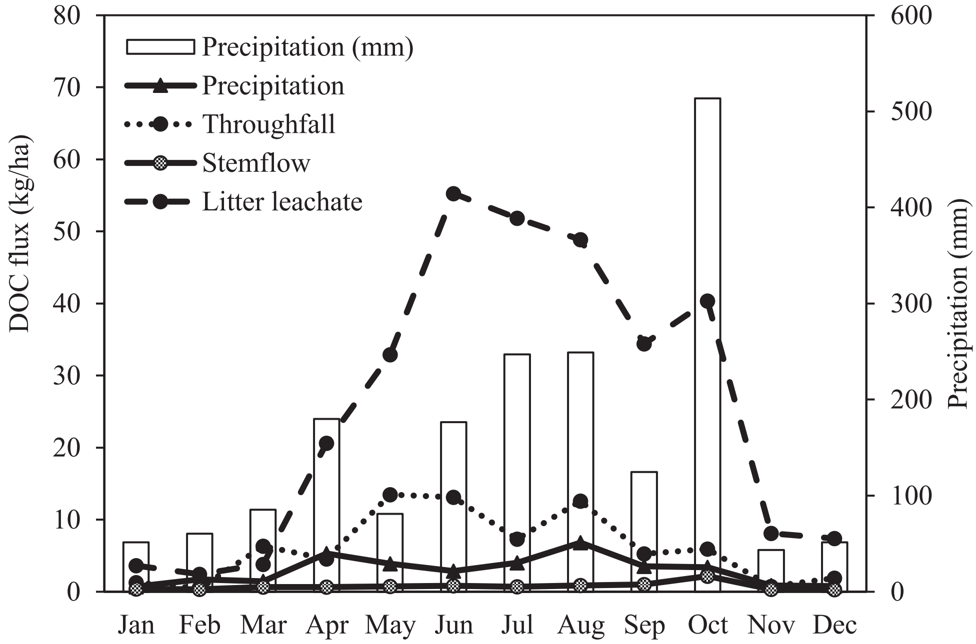

Fig. 4.5 Monthly DOC flux in different water flux and precipitation amount in evergreen forest.

Table 4.3. Correlation coefficients between monthly DOC fluxes in throughfall (TF), stemflow (SF) and litter leachate (LL) vs. monthly DOC concentrations in throughfall (TF), stemflow (SF) and litter leachate (LL), and monthly precipitation in evergreen

Monthly DOC flux (kg^{-1} ha^{-1} $month^{-1}$)	Precipitation	Monthly DOC concentration ($mg\ L^{-1}$)			Monthly DOC Fluxes (kg^{-1} ha^{-1} $month^{-1}$)			Temp
	mm	TF	SF	LL	TF	SF	LL	
TF	0.323	0.726**	–	–	–	0.329	0.783**	0.534*
	n=12	n=12	–	–	–	n=12	n=12	n=12
SF	0.917**	–	-0.432	–	0.329	–	0.553	0.534*
	n=12	–	n=12	–	n=12	–	n=12	n=12
LL	0.637*	–	–	0.520	0.783**	0.553	–	0.779**
	n=12	–	–	n=12	n=12	n=12	–	n=12

5. General Discussion

5.1 Controls of DOC Concentration

Leaf emergence of *Castanopsis* mainly occurred end of April, and early of May, leaf fall was more or less synchronized with the leaf emergence in the evergreen forest. Moreover, leaf fall also occurred in the autumn (Nitta & Ohsawa, 1997). However, the leaf emergence of the deciduous forest is from late May, and leaf fall is during the mid-late October. Fig. 5.1 showed the different patterns of canopy phenology change and the dynamics of litterfall amounts in evergreen and deciduous forest. Interestingly, understory vegetation of studied deciduous forest is dwarf bamboo, which is evergreen species, the litterfall from May to July in the deciduous forest mainly consisted of dwarf bamboo litter (Fig. 5.1b).

Regarding litter leachate DOC concentration, the monthly changes of DOC concentration in litter leachate were affected by the species composition of two studied forests. Litter leachate DOC concentration of deciduous forest was also high in spring was due to the dense understory—dwarf bamboo and its litterfall occurred in spring (Fig. 5.2). Beyond that, litter leachate DOC concentration in the evergreen forest was positively correlated with throughfall DOC concentration, the dry weight of flower and also temperature, while litter leachate DOC concentration in the deciduous forest was only positively related to the previous monthly dry weight of litterfall (Table 5.1). The different litter leachate DOC concentration dynamics in evergreen and deciduous forests may mainly attribute to the different season of litter inputs. Considering the litterfall was more or less synchronized with the leaf emergence of evergreen forest occurred in spring, and the temperature was generally increasing after litterfall, while litterfall of deciduous forest mainly occurred in autumn and the temperature was decreasing; thus the litterfall in the deciduous forest may be decomposed slowly than it in the evergreen forest.

Furthermore, we found that there was a rapid increase of throughfall DOC concentration along with the leaf emergence in May, then decreased along with leaf fall in the evergreen forest. The previous study has indicated that throughfall DOC concentrations in the leafed canopy were more than 20 times greater than during leafless conditions (Comiskey, 1978). Similarly, there was also a sharp increase in throughfall DOC concentration when leaf emergence in June in the deciduous forest (Fig. 5.3). Additionally, throughfall DOC concentration had significant correlations with the dry weight of litterfall and flower in the evergreen forest (Table 5.1). These results indicating that canopy phenology (leaf emergence, florescence, and leaf fall) was an essential factor control the throughfall DOC concentration in both evergreen and deciduous forests. Moreover, stemflow DOC concentration had a significant correlation with throughfall DOC concentration in both studied forests (Table 5.1).

Previous studies reported the controls on the forest floor DOC concentration including climate (Meentemeyer 1978, Aerts 1997), the microenvironment surrounding the litter (Whitney 1991, Hornsby et al., 1995), the chemical composition of the litter (Pereira et al., 1998, Lill and Marquis 2001), and the decomposer community structure (Zak et al., 1990, Gartner and Cardon 2004). The results found in the present study indicating that the litter inputs was main control on the DOC concentration of litter leachate were litter inputs, and the different season of litterfall inputs would make the different seasonal dynamics of litter leachate DOC concentrations, and also has effects on the relationship between litter leachate DOC concentration and temperature. Moreover, throughfall DOC concentration also has an impact on the litter leachate DOC concentration but depends on the forest type. Taken together, canopy phenology change patterns of different forests are the main reason result in the variabilities of litter leachate DOC concentrations.

5.2 Controls of Rainfall Partitioning

The precipitation amount at deciduous and evergreen forests during the studied periods were 1592 mm and 1864 mm, respectively (Fig. 5.4). The deciduous and evergreen forests contained 581 and 541 trees/ha (DBH $\geq$ 10 cm), respectively, with basal areas of 28.45 and 42.13 m^2/ha, respectively. However, the canopy interception in the deciduous plot was 26.8% (427.5 mm) compared with 19.3% in the evergreen plot (360.3 mm, Fig. 5.5). As stated previously, canopy storage capacity, leaf area index (LAI), leaf angle and cover, and hydrophobicity (water repellency) of leaf and wood and also the rainfall characteristics can affect the rainfall partitioning. Although the basal area was lower in the deciduous forest than in the evergreen forest, the tree density was higher in the deciduous forest; this may be one reason due to the higher canopy interception in the

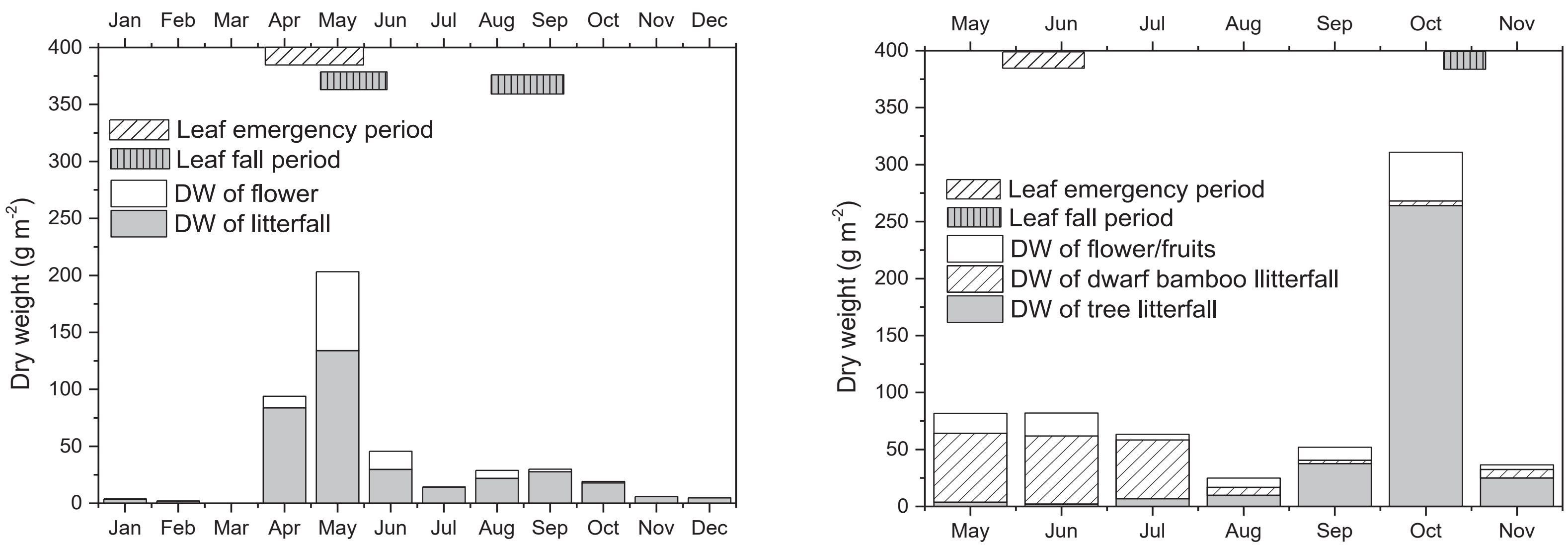

Fig.5.1 Monthly mean dry weight of different flower and litterfall, and leaf emergence period and leaf fall period of (a) evergreen forest and (b) deciduous forest.

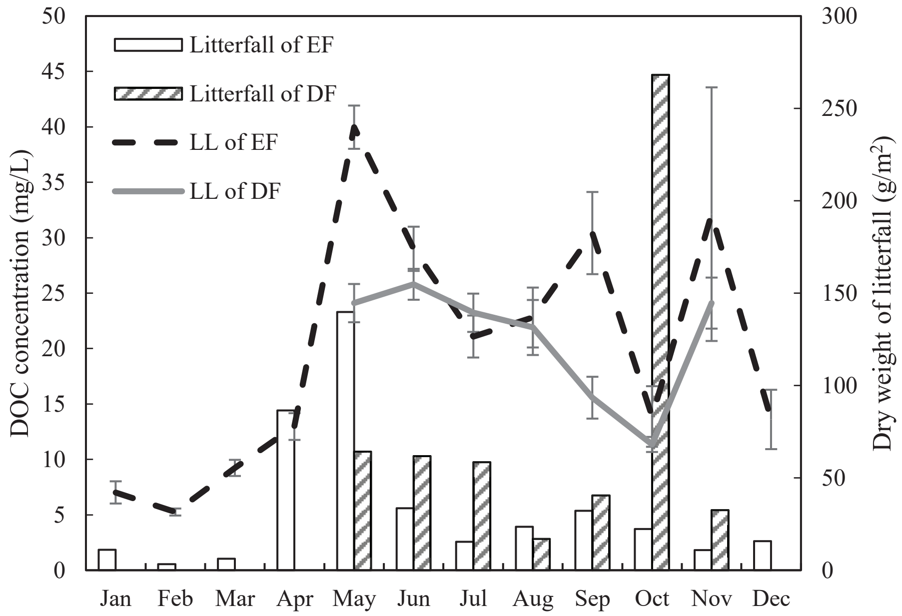

Fig.5.2 Monthly mean DOC concentration of litter leachate (LL) and dry weight of litterfall in evergreen (EF) and deciduous (DF) forests.

Table 5.1. Correlation coefficients between DOC concentrations in throughfall, stemflow and litter leachate vs. DOC concentration in throughfall, dry weight of litter fall, temperature and rainfall.

Forest type	DOC concentration mg/L	Throughfall mg/L	Dry Weight of litterfall g/m²	Temp. ℃	Rainfall mm
Evergreen	Stemflow	0.708**	0.348	0.318	-0.475
		n=12	n=12	n=12	n=12
	Litter leachate	0.716**	0.534	0.622*	-0.049
		n=12	n=12	n=12	n=12
	Throughfall	-	0.765**	0.364	-0.210
		-	n=12	n=12	n=12
			Dry Weight of previous monthly litterfall g/m²		
Deciduous	Stemflow	0.842*	-	0.548	-0.402
		n=7	-	n=7	n=7
	Litter leachate	0.583	0.847*	0.235	0.372
		n=7	n=7	n=7	n=7
	Throughfall	-	-	0.072	-0.109
		-	-	n=7	n=7

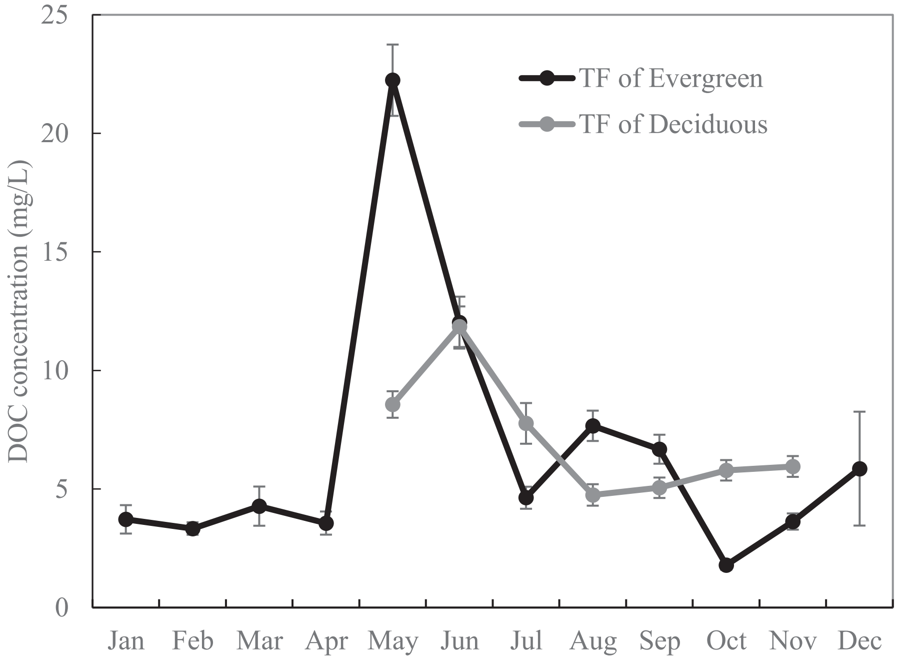

Fig. 5.3 Monthly mean DOC concentration of throughfall (TF) in evergreen and deciduous forests.

Table 5.2. Correlation coefficients between monthly DOC fluxes in throughfall, stemflow and litter leachate vs. monthly mean DOC concentrations in throughfall, stemflow and litter leachate, rainfall, and temperature.

Forest type	Monthly DOC flux (kg^{-1} ha^{-1} $month^{-1}$)	Precipitation	Monthly DOC concentration ($mg\ L^{-1}$)			Monthly DOC Fluxes (kg^{-1} ha^{-1} $month^{-1}$)			Temp
		mm	TF	SF	LL	TF	SF	LL	
Evergreen	TF	0.323	0.726**	–	–	–	0.329	0.783**	0.534*
		n=12	n=12	–	–	–	n=12	n=12	n=12
	SF	0.917**	–	-0.432	–	0.329	–	0.553	0.534*
		n=12	–	n=12	–	n=12	–	n=12	n=12
	LL	0.637*	–	–	0.520	0.783**	0.553	–	0.779**
		n=12	–	–	n=12	n=12	n=12	–	n=12
Deciduous	TF	0.538	0.724*	–	–	–	-0.436	0.699*	0.270
		n=7	n=7	–	–	–	n=7	n=7	n=7
	SF	-0.767	–	0.424	–	-0.436	–	-0.5	-0.073
		n=7	–	n=7	–	n=7	–	n=7	n=7
	LL	0.751*	–	–	0.284	0.699*	-0.500	–	0.405
		n=7	–	–	n=7	n=7	n=7	–	n=7

Table 5.3. Comparing annual DOC fluxes of litter leachate in different study sites.

Location	Climate	Dominant vegetation	DOC fluxes (kg ha^{-1} yr^{-1})	Reference
Coulissenhieb,Waldstein,Bavaria, Germany	Temperate, 1100 mm yr^{-1}; 5°C	Coniferous forest, *Picea*	172.7	Michalzik and Matzner, 1999
Steinkreuz, Steigerwald, Bavaria, Germany	Temperate, 750 mm yr^{-1}; 7.5°C	Hardwood forest, *Fagus, Quercus*	274	Solinger, 2001
Calhoun Experimental Forest South Carolina,	Temperate, 1170 mm yr^{-1}; 16°C	Coniferous forest, *Pinus*	251	Richter and Markewitz, 1996
Navasfrias, Spain	Temperate, 1580 mm yr^{-1}; 14.1°C	Hardwood forest, *Quercus*	299	Gallardo and Vicente Esteban, 2000
Birkenes, Norway	Temperate, 1300 mm yr^{-1}; 5.3°C	Coniferous forest, *Picea*	363	Mulder and Clarke, 2000
Harvard Forest Massachusetts, U.S.	Temperate, 1100 mm yr^{-1}; 220–410 m a.s.l.	Coniferous forest , *Pinus*	398	Currie et al., 1996
		Mixed hardwood forest, *Quercus, Acer*	225	
Gifu, Japan	Warm-temperate 1866mm; 16.1 ◦C	Evergreen broad-leaved forest, *Castanopsis*	**309.5**	Present study
Takayama, Japan	Cool-temperate 2400mm; 7.3 ◦C	Deciduous broad-leaved forest, *Quercus, Betular*	**311.5 (kg ha^{-1} 7 $month^{-1}$)**	Present study

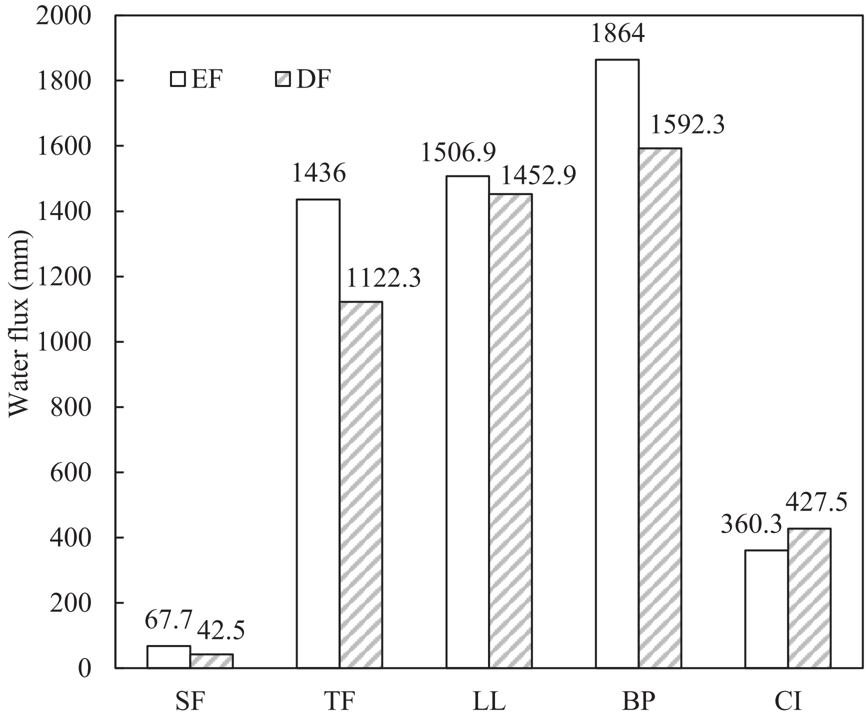

Fig.5.4 Water flux of stemflow (SF), throughfall (TF), litter leachate (LL), bulk precipitation (BP), and canopy interception (CI) of in evergreen (EF) and deciduous (DF) forests during the study period.

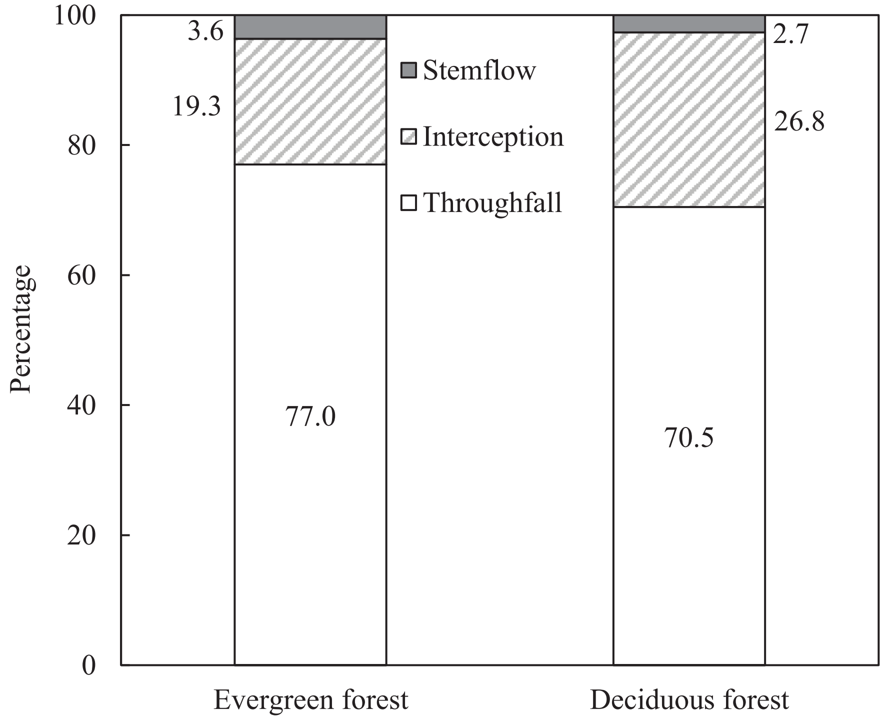

Fig.5.5 Percentage of different water flux in evergreen and deciduous forests during the studied period.

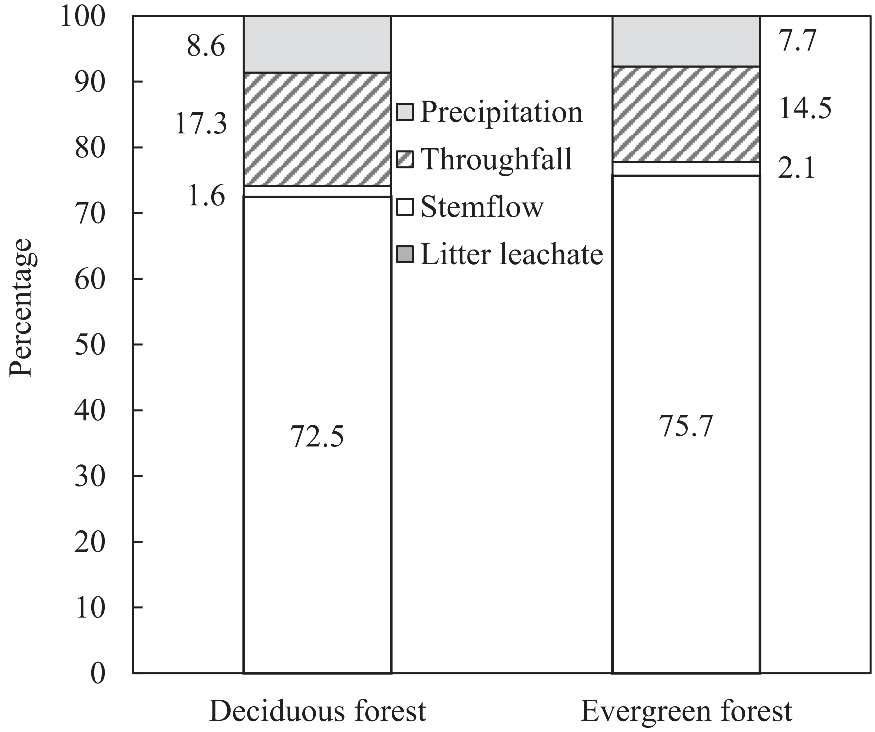

Fig.5.6 The net contribution percentage of DOC from precipitation, stemflow, throughfall and litter leachate input to the soil in evergreen and deciduous forests during the study period.

deciduous forest. Another possibility is the composition of tree species in the deciduous forest (Shannon's diversity index: 2.74) was more complicated than in the evergreen forest (Shannon's diversity index: 1.19), leads to a diversity of tree shapes and leaf angles; thus the canopy interception was higher. Moreover, the epiphytes were concentrated in the upper parts of the trees also could enhance interception, considering the main species in the deciduous forest–*Quercus crispula* (Table 2.1), its branch and stem were mostly covered by epiphytes, it may be a factor influencing the higher interception. Due to the high interception in deciduous forest, throughfall (70.5%) was lower than it in the evergreen forest (77.0%, Fig.5.5). Concerning the stemflow in the evergreen forest was 3.6% (67.7 mm) compared with 2.7% for the deciduous forest (42.5 mm, Fig.5.4), one explanation is that the basal area in the evergreen forest was larger than it in the deciduous forest. Furthermore, the main species *Castanopsis cuspidata* (Table 2.3) is a smooth-barked tree, which potentially good for stemflow. Beyond that, it is also possible that climatic factors such as wind, temperature and rainfall intensity will be of influence. In summary, the rainfall partitioning was regulated by forest structure, including tree species composition, tree density and basal area.

5.3 Controls of DOC Fluxes

DOC flux is a result of DOC concentration and water budget, as reported in the previous studies that DOC fluxes were mostly dependent on the water flux (Solinger et al., 2001; Michalzik et al., 2001; Pelster et al., 2009). In both studied deciduous and evergreen forests, DOC fluxes from different water fluxes were closely related to the rainfall amounts (Table 5.2). DOC fluxes in throughfall and litter leachate were positively related to rainfall amount at monthly scale in both forests (Table 5.2).

The primary sources of DOC are the canopy and the O horizon (Schwendenmann and Veldkamp, 2005; Fujii et al., 2013). The annual fluxes of DOC from the litter leachate could vary depending on annual precipitation, vegetation type (lignin concentration, C/N ratio), the chemical properties of soils, and the amount of litterfall (Fujii et al., 2009b; Godde et al., 1996; Michalzik et al., 2001). The litter leachate DOC fluxes were 311.5 kg ha^{-1} $7month^{-1}$ and 309.5 kg ha^{-1} yr^{-1} for deciduous and evergreen forest during the study period, which were comparable to the highest values recorded for temperate forests (Table 5.3). Considering the DOC fluxes of the growing season (May-Nov) in the deciduous forest was even higher than the annual DOC fluxes in the evergreen forest, implied that the annual DOC fluxes in the studied deciduous forest might be much higher than it in the evergreen forest. The DOC flux of forest floor has been reported to increase with lignin concentrations in the foliar litter (Godde et al., 1996), as well as the annual precipitation and litter input (Fujii et al., 2009b; Fujii et al., 2013). One reason for the difference of DOC fluxes between two forests could be the different rainfall amount; another reason could be explained by the different canopy phenology and species composition of two forests; thus the litter input, lignin concentration of foliar litter were different. The total litter production was 2554.8 kg C ha^{-1} yr^{-1} in deciduous forest comparing 2001.9 kg C ha^{-1} yr^{-1} in evergreen forest. Furthermore, 87.5% of litterfall in the study evergreen forest was from *C. cuspidata*, while the litterfall of deciduous forest was consist of many species, and 32.4% was from understory—dwarf bamboo, previous study at this site implied that dwarf bamboo might be an important factor affecting the litter decomposition rate. However, comparing the net contribution of DOC fluxes from different water fluxes in the two forests, similarly, the net contribution of litter leachate DOC flux was largest, which was 72.5% and 75.7% in deciduous and evergreen forest, respectively. Whereas, stemflow DOC flux was least in both studied forest ecosystem (Fig. 5.6).These results indicated that the proportions of DOC fluxes from precipitation, throughfall, stemflow and litter leachate in the total DOC fluxes input to the soil were comparable in different forests; nevertheless, DOC fluxes of precipitation, throughfall, stemflow and litter leachate exhibited variabilities among different forests.

6. Conclusion

The results indicating that the canopy phenology patterns and forest structure (tree species composition, tree density and basal area) are the main reasons resulting in the variability of DOC in evergreen and deciduous forest.

In the evergreen forest, the leaf fall was more or less synchronized with the leaf emergence occurred in May. Thus the DOC concentration of throughfall, stemflow and litter leachate were all highest in May. In the deciduous forest, throughfall DOC concentration was highest in the leaf emergence season (June). However, litter leachate DOC concentrations had two peaks in the deciduous forest, which were high in spring and autumn, because the studied deciduous forest was covered by dense evergreen plant—dwarf bamboo and its litterfall occurred in spring. Moreover, litter leachate DOC concentration in the evergreen forest was positively correlated with throughfall DOC concentration, the dry weight of flower and also temperature, while litter leachate DOC concentration in the deciduous forest was only positively related to the previous monthly dry weight of litterfall. Considering the litterfall was more or less synchronized with the leaf emergence of evergreen forest occurred in spring, and the temperature was generally increasing after litterfall, while litterfall of deciduous forest mainly occurred in autumn and the temperature was decreasing, thus the litterfall in the deciduous forest may be decomposed slowly than it in the evergreen forest. Therefore, canopy phenology (leaf emergence, florescence and leaf fall) characteristics were essential factors control the variabilities of litter leachate DOC concentrations.

DOC flux is a result of DOC concentration and water budget. Water partitioning was affected by forest structure. Canopy interception in the deciduous forest was higher than it in the evergreen forest; this may be one reason due to the higher stem density in the deciduous forest. Another possibility is the composition of tree species in the deciduous forest was more complicated than in the evergreen forest, leads to a diversity of tree shapes and leaf angles. Corresponding the high interception in deciduous forest, throughfall (70.5%) was lower than it in the evergreen forest (77.0%). Stemflow was also lower in deciduous forest; one explanation is that the larger basal area in the evergreen forest, the other reason may be the main species of evergreen forest – *C. cuspidata* is a smooth-barked tree, which potentially good for stemflow. Although the water partitioning was different, DOC fluxes in throughfall and litter leachate were positively related to rainfall amount at monthly scale in both forests. The litter leachate DOC fluxes were 311.5 kg ha^{-1} 7month^{-1} and 309.5 kg ha^{-1} yr^{-1} for deciduous and evergreen forest during the study period, which were comparable to the highest values recorded for temperate forests (100–398 kg ha^{-1} yr^{-1}). One reason for the difference of DOC fluxes between two forests could be the different rainfall amount, and another reason could be explained by the different canopy phenology and species composition of two forests. However, the net contribution of DOC fluxes from throughfall, stemflow and litter leachate were similar in the two forests. The most significant contribution was from litter leachate while stemflow contributed least. These results indicated that the proportions of DOC fluxes from precipitation, throughfall, stemflow and litter leachate in the total DOC fluxes input to the soil were comparable in different forests; nevertheless, DOC fluxes of precipitation, throughfall, stemflow and litter leachate exhibited variabilities among different forests.

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