The influence of bigleaf maple on chemical properties of throughfall, stemflow, and forest floor in coniferous forest in the Pacific Northwest

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The influence of bigleaf maple on chemical properties of throughfall, stemflow, and forest floor in coniferous forest in the Pacific Northwest

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Abstract: It is predicted that bigleaf maple (*Acer macrophyllum* Pursh) will almost double in frequency in British Columbia by 2085 due to climate change. We address whether its frequency increase could influence chemical properties of throughfall, stemflow, and forest floor due to species-specific effects. Eight plots with a single bigleaf maple tree in the centre of conifers were paired with eight Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plots without bigleaf maple. Compared with conifer plots, bigleaf maple throughfall and stemflow had higher pH and K concentration. The under-canopy and near-trunk forest floor associated with bigleaf maple showed higher pH, total exchangeable bases, cation-exchange capacity, and concentrations of exchangeable Ca and Mg. In addition, the near-trunk forest floor had higher base saturation and concentrations and contents of NO_3-N and contents of total N and S. Throughfall and stemflow beneath bigleaf maple appear to contribute to higher pH and N availability in the forest floor. The results suggest that there is a soil microsite around bigleaf maple stems that is influenced by stemflow. These enriched microsites proximal to bigleaf maple trunks would allow bigleaf maple to have legacy effects on soil fertility and promote conifer productivity later in succession following bigleaf maple mortality.

Résumé : On prédit que la fréquence de l'érable à grandes feuilles (*Acer macrophyllum* Pursh) va presque doubler en Colombie-Britannique vers 2085 à cause des changements climatiques. Nous examinons si l'augmentation de sa fréquence pourrait influencer les propriétés chimiques de la précipitation au sol, du ruissellement sur écorce et de la couverture morte à cause des effets propres à cette espèce. Huit places échantillons avec, au centre, un seul érable à grandes feuilles entouré de conifères ont été appariées à huit places échantillons avec des douglas vert (*Pseudotsuga menziesii* (Mirb.) Franco), sans érable à grandes feuilles. Comparativement aux places échantillons occupées par des conifères, la précipitation au sol et le ruissellement sur écorce associés à l'érable à grandes feuilles avaient un pH et une concentration en K plus élevés. La couverture morte sous couvert et près du tronc de l'érable à grandes feuilles avait un pH, des bases échangeables totales, une capacité d'échange cationique et des concentrations de Ca et Mg échangeables plus élevés. De plus, la couverture morte près du tronc avait une saturation en bases ainsi qu'une concentration et une teneur en N-NO_3 et des teneurs en N total et S plus élevées. La précipitation au sol et le ruissellement sur écorce sous l'érable à grandes feuilles semblent en partie responsables de l'augmentation du pH et de la disponibilité de N dans la couverture morte. Les résultats indiquent qu'il y a un microsite dans le sol autour des tiges d'érable à grandes feuilles influencé par le ruissellement sur écorce. Ces microsites enrichis à proximité du tronc des érables à grandes feuilles permettraient à cette espèce d'avoir des effets rémanents sur la fertilité du sol et d'améliorer la productivité des conifères plus tard au cours de la succession, après la mort des tiges d'érable à grandes feuilles.

[Traduit par la Rédaction]

Introduction

Climate change is predicted to cause a shift in ecosystem structure including predominant vegetation, age class distribution, and species composition (Gayton 2008). In forest ecosystems, species-specific effects on forest hydrology and soil fertility have been reported (Gast 1937; Zinke 1962; Levia and Frost 2003; Turk et al. 2008; Alexander and Arthur 2010; Sabau et al. 2010). Species-specific variation in morphological characteristics influences incident rainfall interception and distribution, evaporation, transpiration, understory microclimate, nutrient inputs, and leaching (Levia and Frost 2003). Species-specific difference in leaf litter quantity and quality influences decomposition rates and nutrient availability (Turk 2006). Therefore, a shift in forest structure and species composition will lead to a shift in ecosystem function including forest hydrology, decomposition and nutrient cycling, and site fertility and productivity (Gayton 2008).

In the Pacific Northwest, it is predicted that many naturally occurring deciduous tree species will gain habitat due to climate change (Hamann and Wang 2006). Bigleaf maple (*Acer macrophyllum* Pursh) is a large deciduous tree that is abundant in western North America. Its native range extends from northern Vancouver Island south into California and

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within 300 km of the Pacific Ocean (Peterson et al. 1999; US Department of Agriculture Forest Service 2004). Bigleaf maple is one of the most naturally abundant deciduous species in the Coastal Douglas-fir and Coastal Western Hemlock biogeoclimatic zones of British Columbia (Peterson et al. 1999). It is predicted that bigleaf maple will have a frequency increase of 97% in British Columbia by 2085 because of climate change where frequency is a measure of percentage of ground cover (Hamann and Wang 2006).

Forest managers in the Pacific Northwest traditionally view many deciduous trees, including bigleaf maple, as weeds that compete with conifers for resources (Peterson et al. 1999). However, the presence of deciduous species in conifer stands can improve site fertility and overall productivity, which in turn increases the capacity of ecosystems to recover, renew, and reorganize after disturbance and hence enhances the overall ecosystem resilience (Seybold et al. 1999; Turk et al. 2008; Sabau et al. 2010). Recent studies suggest that bigleaf maple can modestly improve soil fertility within conifer forests (Turk et al. 2008). The predicted future abundance of bigleaf maple suggests that this species will have an ecological role that is greater than currently perceived by forest managers. Hence, it is important to understand the effects of bigleaf maple on ecosystem processes such as nutrient cycling and hydrology to predict how forests will respond to climate change and to make sound management decisions.

Although there have been several studies examining litter quality and decomposition of bigleaf maple and other deciduous species in coastal mixed forest of British Columbia (Ogden and Schmidt 1997; Prescott et al. 2000, 2004; Turk et al. 2008), the impact of bigleaf maple on nutrient inputs via throughfall and stemflow in conifer forest has not yet been assessed. Furthermore, little is known about the degree and spatial extent of the impact of bigleaf maple on the surrounding forest floor. The present study thus investigates whether the predicted frequency increase of bigleaf maple could have species-specific effects on incident rainfall distribution and soil fertility in a coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest. This was addressed by assessing the chemical properties of throughfall, stemflow, and under-canopy forest floor and near-trunk forest floor in the vicinity of bigleaf maple.

Materials and methods

Study area and sampling design

The study area is located within University of British Columbia's Malcolm Knapp Research Forest, Maple Ridge, British Columbia. The dominant trees in the stands are Douglas-fir, western redcedar (*Thuja plicata* Donn ex D. Don), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Several deciduous species including bigleaf maple, balsam poplar (*Populus balsamifera* L.), and red alder (*Alnus rubra* Bong.) are also common. Understory vegetation includes vine maple (*Acer circinatum* Pursh), western swordfern (*Polystichum munitum* (Kaulfuss) K. Presl), salal (*Gaultheria shallon* Pursh), and California blackberry (*Rubus ursinus* Cham. & Schltdl.) (Pojar and Mackinnon 1994). The study site is located within the Dry Maritime Coastal Western Hemlock subzone (CWHdm) (Green and Klinka 1994). The CWHdm subzone experiences mean annual incident rainfall of 1827 mm and a mean annual temperature of 9.8 °C (Pojar et al. 1991). The soils within the study area were derived from morainal and colluvial parent materials and are sandy loam Gleyed Dystric Brunisols (Agriculture Canada Expert Committee on Soil Survey 1998).

Two conifer-dominated stands that include some bigleaf maple trees were located using forest cover maps, local knowledge from Malcolm Knapp Research Forest personnel, and field data obtained from previous studies (Turk 2006). The two stands in this study are 140 and 125 years old and regenerated naturally following fires that occurred in 1868 and 1880, respectively. Throughfall, stemflow, and forest floor properties were compared between vegetation types (bigleaf maple and conifer) using a paired-tree approach. Four sets of paired plots were selected within each stand, yielding a total of eight pairs (16 plots). Each bigleaf maple plot had one bigleaf maple tree at plot centre surrounded by conifers, and conifer plots had a Douglas-fir tree at plot centre. Pair selection was based upon the following criteria: (1) similarity in slope, elevation, and aspect to reduce incident rainfall and site variation, (2) similarity in canopy density and gap size to reduce sampling error, (3) similarity in tree diameter at breast height to reduce error and variation in stemflow dynamics, and (4) similar tree stand density as a means of controlling for evaporative loss.

All of the selected trees were assessed for the following characteristics: diameter at breast height, canopy density, canopy width, canopy area, canopy volume, bark roughness, and epiphyte cover percentage. Canopy and stem observations were taken at 22.5° intervals determined on a rotating dial compass from the tree trunk. Canopy density was visually estimated. Canopy width was estimated by measuring the farthest extent of the canopy observed at ground level. Stem observations included bark roughness and the presence of epiphytes on bark. Bark roughness was measured by finding a representative bark fissure for the interval being measured and inserting a plastic tape measure into the full depth of the bark fissure and measuring outwards to the outer bark surface. The percentage of bark epiphytes was visually estimated in the interval being measured over 10 cm^2 at breast height. Epiphytes included in the analysis were lichen, moss, and ferns. Percentages observed were indexed in the same categories outlined by Alexander and Arthur (2010) as follows: 0 = <20%, 1 = 21%–40%, 2 = 41%–60%, 3 = 61%–80%, and 4 = 81%–100%. Values for canopy width, bark roughness, and epiphyte index were averaged to determine a value for each tree. The average canopy width measurements were then added to trunk radius to determine the full canopy width. Crown height dimensions were estimated using a Suunto optical clinometer.

Throughfall and stemflow sampling and analysis

One wedge-type rain gauge (0.06 m × 0.065 m) and one rainfall trough (0.67 m × 0.07 m) were randomly placed in each of four distinct clearings within 0.5 km of the study plots. These locations provided the incident rainfall measurements for the study. Each plot was outfitted with two throughfall collection systems (similar to the rainfall trough placed in clearings) that were positioned randomly under the canopy within 1–8 m of each tree trunk. Each system consisted of a longitudinally slit tube (0.67 m × 0.07 m) placed 0.4 m above the ground, having a hose that yielded the collected water to a 4 L plastic container.

Stemflow collars consisted of 2.0 cm diameter rubber hose that was slit longitudinally and affixed angled slightly downward to the trunk with nails. The nail holes and the cracks between the tubing and the tree were sealed with a silicon sealant. The flexible tubing collar was secured to each tree at breast height and was coiled 1.5 times around the perimeter of the trunk. The tubing was drained into a tight fitting 4 L plastic container to collect stemflow. On a monthly basis, collars were tested for leaks using deionized water. Points along the collar with leakage were resealed with silicone sealant. The throughfall and stemflow collecting apparatus occasionally malfunctioned for various reasons such as extreme weather, debris falling on the device, or destruction by a black bear. Missing values for throughfall and stemflow represented 10% of the total collections and were estimated by a simple linear regression method.

The volumes of incident rainfall, throughfall, and stemflow were measured on 10 dates over a 6 month period from 18 May to 17 November 2009 (see Table 2). At each of the 10 collection dates, the rainfall, throughfall, and stemflow containers were emptied into a graduated cylinder and the quantity of water was recorded. Subsamples were stored in 500 mL plastic bottles and brought to the laboratory for further processing and analysis. Samples were then filtered through a 0.45 μm membrane filter and two sets of 70 mL subsamples were stored in the dark at 4 and –20 °C, respectively. Samples collected from 22 September to 26 October and from 27 October to 17 November were composited separately on a volume basis into two composite samples, reducing the samples collected over the 10 collection dates to seven samples per gauge/trough or stemflow collar (see Table 2). For each period P1 to P7 (see Table 2), there were a total of eight rainfall samples (one for each rain gauge and one for each rainfall trough), 16 stemflow samples (eight for bigleaf maple and eight for Douglas-fir plots), and 32 throughfall samples (16 for bigleaf maple and 16 for Douglas-fir plots).

The set of subsamples stored at 4 °C was used for determining pH and total dissolved organic C (DOC). The pH was measured by immersing a glass electrode pH meter into the sample. DOC was measured by the high-temperature catalytic oxidation method (Sharp et al. 1993) (Shimadzu TOC-V CSH with OCT-1 eight-port autosampler). The two throughfall samples from each plot were then composited into one sample, reducing the 32 throughfall samples per period to 16. Samples representing the seven periods were then composited on a volume basis into one sample for each of rainfall, throughfall, and stemflow for each plot for the study period, yielding a total of 40 composited samples. Composited samples were then sent to the Ministry of Forests and Range, Research Branch Laboratory, Victoria, British Columbia, and were analyzed for elemental concentrations of P, K, Mg, Ca, and S by an inductively coupled plasma – atomic emission spectrometer.

Samples stored at –20 °C were composited as described for the first set, yielding a total of 40 subsamples. These subsamples were used to measure nitrate (NO_3-N) and ammonium (NH_4-N) colorimetrically using an Alpkem Flow System IV analyzer (Carter 1993; Bremner 1965). A subsample was then taken and subjected to an alkaline persulphate digestion and analyzed colorimetrically to obtain total N concentration. The difference between total N and the sum of NO_3-N and NH_4-N was assumed to be dissolved organic nitrogen (DON). Deposition estimates were calculated as content (concentration × volume) divided by the collecting area, which was either the area of the rain guage/trough or throughfall trough or the basal area of the tree. The percentages of throughfall and stemflow of each species were determined by dividing the throughfall and stemflow volume by total rainfall volume, respectively. The funnelling ratio was determined using the equation SF/($B \times P$), where SF is the stemflow volume (litres), B is the trunk basal area (square metres), and P is the depth equivalent of gross incident precipitation (millimetres) (Herwitz 1986).

Forest floor sampling and analysis

At each of the 16 plots, three forest floor samples were collected at the stem (within 1 m from the stem) and six forest floor samples were collected under the canopy but away from the stem (three samples within 1 m from each throughfall trough). The samples were collected by removing a 10 cm × 10 cm section of the forest floor down to the mineral soil with a trowel, retaining F and H forest floor material, and placing it into a labelled sample bag for transport to the Soil Laboratory at Simon Fraser University.

The pH testing was conducted on field moist subsamples and followed standard procedures with a 1:4 soil-to-solution ratio with 0.01 mol·L^{-1} $CaCl_2$ as the suspension solution and using a glass electrode pH meter (Kalra and Maynard 1991). The forest floor samples were then air-dried and the three samples per collection point were composited to yield one sample near the stem and two samples under the canopy per plot. Further chemical analysis was conducted at the Ministry of Forests and Range, Research Branch Laboratory, Victoria, British Columbia. Subsamples were oven-dried and a correction factor (air-dried to oven-dried) was used to determine the oven-dried mass of each sample. Total C, N, and S were measured on a Fison NA-1500 elemental analyzer. NO_3-N and NH_4-N were measured colorimetrically using an Alpkem Flow System IV analyzer (Carter 1993; Bremner 1965). Exchangeable K, Mg, and Ca were determined using an ARL 3600 inductively coupled argon plasma spectrometer using the barium chloride method (Hendershot and Duquette 1986). The sum of cations (K, Mg, Ca, Na, Fe, Al, and Mn) measured with the inductively coupled argon plasma spectrometer was used to measure effective cation-exchange capacity (CEC) (Carter 1993; Hendershot and Duquette 1986). The sum of K, Mg, and Ca was used to calculate total exchangeable bases (TEB). Base saturation was determined by dividing TEB by CEC (Hendershot and Duquette 1986). Total concentration values were converted to kilograms per hectare based on the oven-dry mass of the forest floor per unit area.

Statistical analysis

All data were analyzed using SPSS 17 software, with plots being considered as individual sample units. A significance level of 0.1 was used for all analyses due to considerable natural heterogeneity within measured properties. All variables

Table 1. Tree characteristics of bigleaf maple (*Acer macrophyllum*) and Douglas-fir (*Pseudotsuga menziesii*) (n = 8).

	Bigleaf maple		Douglas-fir		
Tree characteristic	Mean	SD	Mean	SD	P (t test)
Diameter at breast height (cm)	50.7	11.4	49.4	11.4	0.17
Canopy density (%)	80.0	1.5	77.5	3.7	0.24
Basal area (cm^2·tree^{-1})	2111	908	2007	877	0.18
Height (m)	33.9	7.9	42.0	8.9	***0.028***
Canopy width (m)	7.10	2.39	4.72	2.24	***0.017***
Canopy area (m^2)	173.9	119.1	83.7	58.1	***0.031***
Canopy depth (m)	21.3	8.0	17.9	8.4	0.87
Canopy volume (m^3)	3521	3034	1769	1328	***0.031***
Bark roughness (mm)	4.8	2.1	14.8	5.7	***0.001***
Bark epiphyte index	2.71	0.95	1.09	1.09	***0.012***

Note: Bold-italic values indicate a significant difference at $P < 0.05$.

were checked for normality using Q–Q plots. A one-way ANOVA with Tukey multiple comparison test was used to compare chemical variables of incident rainfall, throughfall, and stemflow samples. Standardized volumes of rain gauges and rainfall troughs expressed in millimetres per day were used for calculating average rainfall volumes. Incident rainfall volume, pH and DOC concentration, and pH and DOC concentration in incident rainfall, throughfall, and stemflow of bigleaf maple and Douglas-fir were subjected to separate Pearson correlation analysis. In addition, volumes for each collection period and pH and DOC concentration for each of the seven periods were subjected to separate paired sample t tests. A paired sample t test was used to analyze tree characteristics and vegetation (bigleaf maple and conifer) effect on throughfall and stemflow volumes and nutrient concentrations and contents in the forest floor samples collected from under the canopy and near the tree trunk.

Results

Throughfall volumes and chemical properties

Bigleaf maple and Douglas-fir trees exhibited quite different characteristics (Table 1). Bigleaf maple trees were shorter in average height than Douglas-fir. The average canopy width, depth, and volume of bigleaf maple trees were greater than those of Douglas-fir. Bigleaf maple had a smoother bark and a greater epiphyte cover as well.

The mean recorded incident rainfall over the study period (May–November 2009) was 659 mm, representing 36% of the long-term mean annual rainfall. For the study period, the percentage of incident rainfall falling as throughfall was higher at bigleaf maple plots (85%) than at Douglas-fir plots (76%) (Table 2). There was a trend of increasing throughfall volumes at bigleaf maple and Douglas-fir plots with increasing incident rainfall. In addition, a trend of higher throughfall volume was observed at bigleaf maple plots as compared with Douglas-fir plots in all of the collection periods (Table 2). Despite this trend, throughfall volume was significantly higher at bigleaf maple plots at only two periods (P9 and P10).

Mean-weighted pH for incident rainfall was not different from pH for throughfall at bigleaf maple plots but was higher than for throughfall at Douglas-fir plots (Table 2). The pH of incident rainfall showed a very strong negative correlation with incident rainfall volume (r = –0.93, $P < 0.1$). The pH in throughfall of bigleaf maple and Douglas-fir showed a strong and a moderate positive correlation, respectively, with rainfall pH (r = 0.95 and 0.56, respectively, with $P < 0.1$). The t tests showed significant differences between pH in throughfall of bigleaf maple and Douglas-fir during all periods (Table 2).

Mean-weighted DOC concentration in throughfall of bigleaf maple was significantly lower than that of Douglas-fir but greater than incident rainfall (Table 2). DOC concentration of incident rainfall did not correlate with incident rainfall volume. Similarly, DOC concentration in throughfall of bigleaf maple and Douglas-fir did not correlate with DOC concentration of incident rainfall (all r values were below 0.3 with $P > 0.1$). The t tests showed a significantly lower DOC concentration in throughfall of bigleaf maple in all periods except for P5 as compared with Douglas-fir (Table 2).

Concentrations of K, Mg, and S and depositions of Ca, K, and S were significantly higher when associated with bigleaf maple as compared with incident rainfall. Similarly, concentrations of total N, NO_3-N, DON, and Ca and depositions of Ca and K were significantly higher when associated with Douglas-fir as compared with incident rainfall (Table 3).

In comparison with Douglas-fir throughfall, bigleaf maple throughfall had higher volume per unit area per day and pH and higher concentrations of P and K as well as higher deposition of and P, K, and S, while bigleaf maple throughfall had lower concentrations of DOC and Ca.

Stemflow volumes and chemical properties

Stemflow collected from bigleaf maple as a percentage of incident rainfall (7%) was lower than Douglas-fir stemflow (13%) (Table 2). There was a trend of increasing stemflow volumes at bigleaf maple and Douglas-fir plots with increasing incident rainfall. In addition, a trend of lower stemflow volume was observed at bigleaf maple plots as compared with Douglas-fir plots in all of the collection periods (Table 2). The t tests showed significant differences between stemflow volume of bigleaf maple and Douglas-fir during one period (P8). Bigleaf maple and Douglas-fir funnelling ratio was too small (<0.15) to provide meaningful comparisons.

Table 2. Incident rainfall and bigleaf maple (*Acer macrophyllum*) and Douglas-fir (*Pseudotsuga menziesii*) throughfall and stemflow average volumes, pH, and DOC concentration (n = 8) for each measurement period.

						Throughfall (mm·day^{-1})				Stemflow (mm·day^{-1})			
				Rainfall (mm·day^{-1})		Bigleaf maple		Douglas-fir		Bigleaf maple		Douglas-fir	
Variable	Period	Date	Days	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Volume (mm·day^{-1})	P1	18–25 May	7	3.13 ad	0.47	2.41 b	0.41	2.08 b	0.58	0.09 e	0.09	0.25 e	0.26
	P2	26 May – 26 June	31	0.79 ad	0.13	0.52 b	0.09	0.52 b	0.20	0.02 e	0.02	0.03 e	0.02
	P3	27 June – 12 July	16	1.44 ad	0.21	0.96 b	0.23	0.86 b	0.45	0.04 e	0.03	0.06 e	0.06
	P4	13 July – 17 Aug.	36	1.78 ad	0.36	1.62 a	0.54	1.35 a	0.68	0.10 e	0.08	0.15 e	0.10
	P5	18 Aug. – 21 Sept.	35	2.01 ad	0.28	1.61 ab	0.48	1.22 b	0.51	0.07 e	0.04	0.16 e	0.14
	P6	22 Sept. – 19 Oct.	28	2.68 ad	0.45	2.09 b	0.33	2.06 b	0.53	0.13 e	0.07	0.28 e	0.22
	P7	20 Oct. – 26 Oct.	7	11.46 ad	1.92	10.53 a	2.21	9.16 a	3.32	1.15 e	0.81	2.00 e	0.87
	P8	27 Oct. – 3 Nov.	8	7.62 ad	0.40	6.71 ab	1.15	5.64 b	2.32	0.67 e	0.33	1.67 f	0.70
	P9	4 Nov. – 9 Nov.	6	11.62 ad	1.51	10.80 a	1.65	8.94 b	1.57	1.03 e	0.56	0.93 e	0.52
	P10	10 Nov. – 17 Nov.	8	13.99 ad	1.83	10.63 b	1.56	8.63 c	1.70	1.35 e	0.87	1.96 e	1.12
Mean-weighted volume (mm·day^{-1})				3.45 ad	0.49	2.86 ab	0.58	2.49 b	0.83	0.24 e	0.15	0.44 f	0.26
pH	P1	18–25 May	7	4.80 ad	0.33	5.82 b	0.20	4.97 a	0.15	5.62 e	0.19	4.63 d	0.48
	P2	26 May – 26 June	31	5.58 ade	0.90	5.97 a	0.32	4.98 b	0.12	6.42 d	1.40	4.71 e	0.71
	P3	27 June – 12 July	16	5.60 abd	0.18	6.02 a	0.21	4.76 b	1.27	7.31 e	0.41	5.77 d	1.09
	P4	13 July – 17 Aug.	36	5.26 ad	0.33	5.67 a	0.24	3.58 b	1.26	6.21 e	1.24	4.33 f	0.45
	P5	18 Aug. – 21 Sept.	35	5.84 ad	0.65	6.32 a	0.44	4.17 b	1.50	7.95 e	2.04	6.36 de	1.25
	P6	22 Sept. – 26 Oct.	35	4.88 abd	0.41	5.64 a	0.32	4.15 b	1.22	6.58 e	2.13	4.07 d	0.69
	P7	27 Oct. – 17 Nov.	22	4.15 abd	0.46	4.96 a	1.04	3.28 b	1.31	5.55 e	0.30	3.92 d	0.40
Mean-weighted pH				5.41 ad	0.39	5.47 a	0.38	3.87 b	0.97	5.71 d	0.36	4.02 e	0.63
DOC (mg·L^{-1})	P1	18–25 May	7	1.63 ad	0.26	6.36 b	1.19	7.76 c	1.36	11.43 e	7.65	15.58 e	11.01
	P2	26 May – 26 June	31	4.59 ad	5.36	10.04 b	1.60	14.46 c	1.70	16.56 d	9.93	44.04 d	43.49
	P3	27 June – 12 July	16	4.02 ad	1.87	14.05 a	2.86	31.40 b	14.59	44.57 e	6.95	45.93 e	32.88
	P4	13 July – 17 Aug.	36	2.64 ad	0.72	8.18 b	3.33	12.73 c	2.86	16.56 e	8.09	39.90 e	33.13
	P5	18 Aug. – 21 Sept.	35	2.66 ad	0.58	9.82 b	3.88	13.03 b	2.50	26.63 e	7.70	55.60 f	19.26
	P6	22 Sept. – 26 Oct.	35	1.52 ad	0.50	11.72 b	1.98	21.07 c	7.50	36.24 d	14.56	136.4 e	51.56
	P7	27 Oct. – 17 Nov.	22	1.21 ad	0.21	6.22 b	2.17	8.39 c	2.00	21.43 d	7.45	64.63 e	44.37
Mean-weighted DOC (mg·L^{-1})				2.60 ad	1.30	7.91 b	1.24	13.39 c	3.88	25.85 e	9.64	82.67 f	34.17
Mean-weighted DOC (kg·h^{-1})				25.64 ad	24.80	39.85 ab	10.14	58.81 b	25.97	11.09 d	7.50	61.24 e	38.67

Note: a, b, and c designate significant differences in rainfall versus bigleaf maple throughfall versus Douglas-fir throughfall and d, e, and f designate significant differences in rainfall versus bigleaf maple stemflow versus Douglas-fir stemflow at $P < 0.1$.

Table 3. Rainfall, throughfall, and stemflow chemical properties for bigleaf maple (*Acer macrophyllum*) and Douglas-fir (*Pseudotsuga menziesii*) plots (n = 8).

			Throughfall				Stemflow			
	Rainfall		Bigleaf maple		Douglas-fir		Bigleaf maple		Douglas-fir	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Concentration (mg·L^{-1})										
Total N	0.54 ad	0.37	0.76 ab	0.19	1.34 b	1.15	5.05 d	7.30	3.24 d	1.53
NH_4-N	0.16 ad	0.19	0.10 a	0.06	0.14 a	0.24	3.54 d	7.15	1.22 d	1.17
NO_3-N	0.09 ad	0.02	0.12 ab	0.05	0.47 b	0.24	0.20 d	0.24	0.28 d	0.41
DON	0.29 ad	0.18	0.54 ab	0.13	0.72 b	0.36	0.74 e	0.37	1.09 e	0.57
P	0.07 abd	0.07	0.14 b	0.11	0.04 a	0.02	0.62 d	0.82	0.09 d	0.05
Ca	0.24 ad	0.05	0.73 a	0.08	1.30 b	0.74	5.90 e	4.26	3.44 de	1.54
K	0.60 ad	0.26	4.91 b	0.91	2.76 c	1.34	13.25 e	7.54	5.86 d	2.11
Mg	0.08 ad	0.02	0.22 b	0.04	0.29 b	0.14	0.98 e	0.67	0.64 e	0.18
S	0.21 ad	0.05	0.44 b	0.09	0.38 b	0.13	1.57 e	1.13	0.91 de	0.35
Deposition (kg·ha^{-1})										
Total N	3.32 ad	2.40	3.61 a	0.77	4.60 a	5.87	3.69 d	6.60	1.97 d	1.04
NO_3-N	0.55 ad	0.16	0.58 a	0.22	1.72 a	2.88	0.14 e	0.22	0.12 e	0.14
NH_4-N	1.01 ad	1.27	0.48 a	0.21	0.58 a	1.19	2.80 d	6.34	0.70 d	0.76
DON	1.77 ad	1.16	2.55 a	0.63	2.31 a	1.92	0.75 e	0.36	1.15 de	0.64
P	0.49 abd	0.46	0.71 a	0.54	0.19 b	0.11	0.28 de	0.37	0.07 e	0.04
K	3.62 ad	1.59	24.22 b	3.58	10.86 c	2.81	5.53 d	3.72	3.95 d	2.09
Ca	1.51 ad	0.40	3.64 b	0.34	5.34 b	2.86	2.53 d	2.17	2.53 d	1.67
Mg	0.40 ad	0.28	0.58 a	0.50	0.76 a	0.74	0.43 d	0.38	0.46 d	0.25
S	1.30 ad	0.38	2.21 b	0.42	1.58 a	0.34	0.66 e	0.51	0.63 e	0.40

Note: a, b, and c designate significant differences in rainfall versus bigleaf maple throughfall versus Douglas-fir throughfall and d, e, and f designate significant differences in rainfall versus bigleaf maple stemflow versus Douglas-fir stemflow at $P < 0.1$.

Mean-weighted pH of the incident rainfall was higher than the pH for Douglas-fir stemflow but did not differ from the pH for bigleaf maple stemflow. The pH in stemflow of bigleaf maple and Douglas-fir showed a strong positive correlation with rainfall pH (r = 0.73 and 0.72, respectively, with $P < 0.1$). The t tests showed significant differences between pH in stemflow of bigleaf maple and Douglas-fir during all periods except for period P5 (Table 2).

Mean-weighted DOC concentration and deposition in stemflow of bigleaf maple were significantly lower than those of Douglas-fir (Table 2). DOC concentration in stemflow of bigleaf maple and Douglas-fir did not correlate with DOC concentration of incident rainfall (all r values were below 0.3 with $P > 0.1$). The t tests showed a significantly lower DOC concentration in stemflow for bigleaf maple in periods P5, P6, and P7.

Deposition of P and concentrations of DON, Ca, K, Mg, and S were significantly higher for stemflow of either bigleaf maple or Douglas-fir trees as compared with incident rainfall (Table 3). As compared with Douglas-fir stemflow, bigleaf maple stemflow had higher pH and higher K concentration. Bigleaf maple stemflow DOC concentrations and depositions were significantly lower as compared with Douglas-fir stemflow.

Forest floor chemical properties

For under-canopy samples, forest floor mass per unit area, forest floor pH, exchangeable Ca, exchangeable Mg, TEB, and CEC were significantly higher for bigleaf maple plots when compared with conifer plots (Table 4).

For near-trunk samples, forest floor mass per unit area, forest floor pH, total N content, NO_3-N concentration and content, exchangeable Ca, exchangeable Mg, total S content, TEB, base saturation, and CEC were significantly higher for bigleaf maple plots when compared with conifer plots (Ta-Table 5). Total C concentration and content and C:N ratio were significantly higher at conifer plots.

Discussion

Throughfall and stemflow

Our research indicates a potential positive impact of throughfall and stemflow associated with bigleaf maple on site fertility of conifer forest. Although we measured a positive impact of bigleaf maple on throughfall and stemflow chemistry, the degree of difference between bigleaf maple and Douglas-fir was less than originally expected. We found nine and five of 22 measured properties to be significantly different between bigleaf maple and Douglas-fir throughfall and stemflow, respectively. These differences suggest a modest improvement in the stemflow and throughfall inputs to site fertility beneath bigleaf maple. The temporal data revealed that the potential positive impact can become enlarged with predicted incident rainfall increase in the autumn and winter due to climate change in the Pacific Northwest (Gayton 2008).

Species morphological variation such as canopy architecture, leaf area, deciduousness, and foliage density are some of the factors that affect throughfall (Mina 1967; Levia and Frost 2003). It was anticipated that bigleaf maple would have a greater throughfall volume than Douglas-fir, since it

Table 4. Forest floor (under-canopy) chemical properties for bigleaf maple (*Acer macrophyllum*) and Douglas-fir (*Pseudotsuga menziesii*) plots (n = 8).

	Bigleaf maple		Douglas-fir		
	Mean	SD	Mean	SD	P (t test)
Forest floor (kg·ha^{-1})	6322	1527	4806	996	***0.031***
pH	4.00	0.48	3.59	0.42	**0.058**
C:N ratio	23.89	2.52	33.65	20.83	0.245
Concentration					
Total C (g·kg^{-1})	302.98	82.42	407.21	202.90	0.236
Total N (g·kg^{-1})	12.74	3.71	13.38	3.90	0.728
NO_3-N (mg·kg^{-1})	45.60	41.28	24.02	26.31	0.165
NH_4-N (mg·kg^{-1})	118.87	69.20	143.88	164.51	0.671
Total S (g·kg^{-1})	1.47	0.34	1.55	0.39	0.669
Exch K (cmol·kg^{-1})	1.01	0.16	0.81	0.41	0.238
Exch Ca (cmol·kg^{-1})	34.89	12.39	22.59	8.78	***0.006***
Exch Mg (cmol·kg^{-1})	4.68	1.52	2.45	0.86	***0.013***
TEB (cmol·kg^{-1})	40.69	12.56	25.99	9.23	***0.006***
CEC (cmol·kg^{-1})	43.27	13.03	28.81	8.47	***0.005***
Base saturation (%)	94.03	6.14	90.21	7.91	0.238
Content					
Total C (kg·ha^{-1})	1930.18	817.93	2019.77	1097.21	0.829
Total N (kg·ha^{-1})	81.05	36.21	64.93	26.95	0.295
NO_3-N (kg·ha^{-1})	0.30	0.27	0.13	0.14	0.165
NH_4- N (kg·ha^{-1})	0.73	0.43	0.63	0.66	0.671
Total S (kg·ha^{-1})	9.27	3.38	7.51	2.70	0.588

Note: Bold and bold-italic values indicate a significant difference at P < 0.1 and P < 0.05, respectively.

Table 5. Forest floor (near-trunk) chemical properties for bigleaf maple (*Acer macrophyllum*) and Douglas-fir (*Pseudotsuga menziesii*) plots (n = 8).

	Bigleaf maple		Douglas-fir		
	Mean	SD	Mean	SD	P (t test)
Forest floor (kg·ha^{-1})	5323	1213	3629	1174)	***0.044***
pH	4.78	0.65	3.47	0.49	***0.002***
C:N ratio	18.56	8.89	34.48	9.75	**0.004**
Concentration					
Total C (g·kg^{-1})	264.94	145.87	474.13	103.21	***0.016***
Total N (g·kg^{-1})	15.58	8.35	14.04	1.77	0.651
NO_3-N (mg·kg^{-1})	70.89	62.30	18.90	20.87	***0.030***
NH_4-N (mg·kg^{-1})	97.99	67.70	134.10	92.09	0.362
Total S (g·kg^{-1})	1.63	0.79	1.63	0.28	0.996
Exch K (cmol·kg^{-1})	1.13	0.60	0.88	0.16	0.267
Exch Ca (cmol·kg^{-1})	54.62	30.09	25.58	9.75	**0.050**
Exch Mg (cmol·kg^{-1})	7.05	4.31	2.60	0.47	***0.019***
TEB (cmol·kg^{-1})	62.93	30.74	29.22	9.96	***0.045***
CEC (cmol·kg^{-1})	64.22	34.07	32.32	9.04	**0.052**
Base saturation (%)	97.99	5.37	90.40	6.53	***0.05***
Content					
Total C (kg·ha^{-1})	1321.30	576.90	1705.70	622.76	***0.017***
Total N (kg·ha^{-1})	80.70	39.30	49.95	12.49	***0.041***
NO_3-N (kg·ha^{-1})	0.43	0.45	0.05	0.06	***0.030***
NH_4-N (kg·ha^{-1})	0.49	0.32	0.55	0.48	0.362
Total S (kg·ha^{-1})	8.45	3.67	5.79	1.55	**0.064**

Note: Bold and bold-italic values indicate a significant difference at P < 0.1 and P < 0.05, respectively.

is a deciduous species with larger crown surface area to intercept rainfall (Comerford and White 1977). Despite the trend of more throughfall at bigleaf maple plots, differences were only significant in the two periods that were characterized by the highest recorded daily mean rainfall. This may indicate that a certain rainfall threshold value must be attained before

Table 6. Bigleaf maple (*Acer macrophyllum*) plot properties as compared with Douglas-fir (*Pseudotsuga menziesii*) plots ($n = 8$, $P < 0.1$).

	Throughfall	Under-canopy forest floor	Stemflow	Near-trunk forest floor
Volume or weight/area	↑	↑	↓	↑
pH	↑	↑	↑	↑
DOC (concentration)	↓	na	↓	na
DOC (deposition)	—	na	↓	na
Total C (concentration)	na	↓	na	↓
Total C (content)	na	↓	na	↓
Total N (concentration)	—	—	—	—
Total N (deposition/content)	—	—	—	↑
NO_3-N (concentration)	—	—	—	↑
NO_3-N (deposition/content)	—	—	—	↑
C:N ratio	na	—	na	↓
P (concentration)	↑	na	—	na
P (deposition)	↑	na	—	na
Ca (concentration)	↓	↑	—	↑
K (concentration)	↑	—	↑	—
Mg (concentration)	—	↑	—	↑

Note: na, not applicable; —, no difference; ↑, significantly higher; ↓, significantly lower.

a significant difference is established between the species. Furthermore, we had expected that bigleaf maple would have greater stemflow volumes due to its relatively smooth bark as compared with the rough bark of Douglas-fir, but surprisingly, we found 46% less stemflow for bigleaf maple than for Douglas-fir. Possible reasons for the lower stemflow volume for bigleaf maple are the greater epiphyte cover found on bigleaf maple, which can lead to great water absorption, and the moderate branch angle inclination of Douglas-fir, which directs water flow toward the stem (Hutchinson and Roberts 1981; Levia and Herwitz 2002; Steinbuck 2002).

It was expected that throughfall of bigleaf maple would have a lower DOC concentration because it is a deciduous species (Liu and Sheu 2003) and because of the smaller C concentration in bigleaf maple foliage as compared with Douglas-fir (Cross and Perakis 2011). Bigleaf maple throughfall and rainfall mean-weighted DOC concentration were significantly lower than those of Douglas-fir. The lack of correlation between incident rainfall DOC concentration and rainfall volume, or DOC concentration in throughfall and stemflow, and the lower DOC concentration in bigleaf maple throughfall throughout the study periods could be due to the small atmospheric contribution of DOC in pristine sites in the Pacific Northwest (Edmonds et al. 1995) that would enlarge the relative percentage contribution of DOC in the throughfall and stemflow of individual species due to DOC washing and leaching from tree foliage.

The concentration and deposition of P were significantly higher for bigleaf maple throughfall than for Douglas-fir. This can possibly be explained by the higher P content of bigleaf maple leaves as compared with Douglas-fir needles (Cross and Perakis 2011). In addition, a higher leachability of P from bigleaf maple foliage could contribute to the higher P concentrations (Parker 1983). Henderson et al. (1977) reported a higher P concentration in oak throughfall as compared with pine throughfall. Similarly, Comerford and White (1977) reported a higher P concentration in paper birch throughfall as compared with red pine.

The base-rich leaves of bigleaf maple (Cross and Perakis 2011) were expected to produce throughfall enriched with K, Ca, and Mg. As expected, K concentrations were greater in throughfall of bigleaf maple plots as compared with conifer plots; however, Ca concentrations were lower and Mg concentrations were not significantly different. These variable results likely relate to the different leachability rates of the different bases in each species (Eaton et al. 1973; Henderson et al. 1977).

Bigleaf maple stemflow K concentration was significantly higher than that of Douglas-fir. This can be partially explained by the thick, fissured bark of Douglas-fir that would provide greater potential for the removal of K by ion exchange, thus limiting the enrichment of K in stemflow (André et al. 2008). In addition, the data presented show a much greater enrichment of stemflow than throughfall, which suggests either a channelling of leaf leachate to the stems or considerable leaching from the bark (Thomas 1969).

The pH for bigleaf maple throughfall was significantly higher than that of Douglas-fir throughfall. This may be due to the lower DOC concentration of bigleaf maple throughfall. DOC is composed of several compounds, ranging from short-chain acids to large molecules such as fulvic and humic acids, and thus may influence water acidity (Dalva and Moore 1991). In addition, the higher base content of bigleaf maple foliage could have contributed to the higher pH in throughfall as well (Cross and Perakis 2011). The significant correlation between rainfall pH and rainfall volume in our study could be due to the fact that the first 5–10 mm of rainfall in the coastal forests of British Columbia reflects oceanic effect. However, when rainfall exceeds 10 mm, then rainfall chemistry reflects the atmospheric components in the local area. The study area is in close proximity to an urban area with acid-forming factors, and hence, there is a decrease in rainfall acidity (O. Hertzman, personal communication (2011)). The trend of increased pH value as water passed through bigleaf maple canopy and along its trunk irrespective of rainfall volume indicates a certain acid-buffering capacity of bigleaf maple that is not hindered by current and predicted future rainfall volumes.

Forest floor

Differences in forest floor properties were greater in the near-trunk area than away from the trunk with 16 and six of 23 measured properties being significantly different between bigleaf maple and Douglas-fir plots in the near-trunk and under-canopy areas, respectively. These results indicate improved soil fertility under the canopy of bigleaf maple with the best conditions near the tree stems. Reasons for the improved conditions beneath bigleaf maple include inputs of nutrient-rich litterfall from bigleaf maple (Turk 2006) and inputs of relatively nutrient-enriched throughfall. In addition, in the vicinity of the bigleaf maple stems there is an input of stemflow with relatively high pH.

Near-trunk forest floors at bigleaf maple plots showed a significantly lower C concentration and content than at Douglas-fir plots. Possible reasons for the lower C concentrations and contents beneath bigleaf maple include higher total C concentrations of Douglas-fir litter as compared with bigleaf maple litter (Valachovic et al. 2004; Turk 2006), lower DOC concentration and deposition in stemflow at bigleaf maple plots (Table 6), and differences in litter quality (C:N ratio) that lead to differences in type and activity of soil organisms and soil respiration beneath bigleaf maple and Douglas-fir (Raich and Tufekciogul 2000). It is possible that near bigleaf maple stems, there is a greater degree of mixing of forest floor and mineral soil horizons by soil organisms, resulting in lower C concentrations in forest floors. In addition, there could be a higher soil respiration rate associated with bigleaf maple, as deciduous trees were reported to be associated with soil of a higher CO_2 efflux (Raich and Tufekciogul 2000).

Total N content as well as NO_3-N concentration and content were higher in the near-trunk forest floor samples at the bigleaf maple sites. Possible reasons for the enhanced N status near bigleaf maple stems are greater N concentrations in bigleaf maple litter as compared with Douglas-fir litter (Turk et al. 2008) and higher pH near stems from litterfall and stemflow inputs that can enhance microbial activity and mineralization and nitrification rates (Boerner and Koslowsky 1989; Chang and Matzner 2000). Our study supports the idea of Alexander and Arthur (2010) that leaf litter and stemflow are controlling factors of species N mineralization rates in areas surrounding stems.

Our results suggest that throughfall and stemflow make a minimal contribution to forest floor exchangeable bases. It seems that the base-rich bigleaf maple litterfall and decomposition (Valachovic et al. 2004; Turk 2006) and the chemical weathering of the parent materials dominate the influence of throughfall and stemflow. In addition, the higher leachability of K likely causes it to move to the lower mineral soil horizons.

The pH values in the under-canopy and near-trunk forest floor at bigleaf maple plots were significantly higher as compared with conifer plots. Factors responsible for the higher pH beneath bigleaf maple include more basic litter and throughfall for bigleaf maple, more basic stemflow received by the near-trunk forest floor at bigleaf maple plots, higher total C in Douglas-fir litter and forest floor releasing H^+, making the soil solution more acidic, and higher CEC and base saturation for forest floor beneath bigleaf maple resulting in higher pH (Fisher and Binkley 2000). The CEC of both under-canopy and near-trunk forest floors at bigleaf maple sites was significantly higher as compared with Douglas-fir sites, which may be due to greater concentrations of organic colloids in the forest floor beneath bigleaf maple (Turk et al. 2008).

Management implications

Bigleaf maple, like other hardwoods, is managed to minimize its competitive influence in conifer forests (Turk et al. 2008). Conventionally, the presence of bigleaf maple has been deemed competitive and even detrimental to conifer survival (Haeussler et al. 1990). Recent studies suggest that bigleaf maple may enhance nutrient availability (Turk et al. 2008). In coastal forests of British Columbia, bigleaf maple has low to moderate shade intolerance and it is an early to middle successional species (Peterson et al. 1999). Our findings of enriched microsites proximal to bigleaf maple trunks suggest that bigleaf maple has a potential legacy effect on soil fertility and hence may promote conifer productivity later in succession following bigleaf maple mortality. Biological legacies are central for sustainable forest management. The establishment and (or) retaining of biological legacies aid in maintaining crucial structural elements as components of managed stands, thereby sustaining many organisms and ecological processes dependent upon these structures (Franklin et al. 2002). This would allow the ecosystem to restore its structural and functional integrity and enhance its resilience in our ever-changing environment (Seybold et al. 1999). In this context, bigleaf maple may be a desirable species for forest management. Our current findings provide evidence that increased bigleaf maple presence would likely lead to few but important changes in forest hydrology and nutrient cycling. These changes could act as additional mechanisms by which bigleaf maple creates conditions of improved site fertility that potentially foster the proliferation of conifer species at later stages of succession.

Conclusion

Our results suggest that bigleaf maple growing within conifer forests has the potential to modestly improve site conditions under its canopy and to a greater extent in the vicinity of its trunk. The greater degree of soil fertility improvement near bigleaf maple trunks is likely due to these areas being influenced by stem-related processes such as stemflow, in addition to canopy-related processes such as litterfall and throughfall. We found higher pH and greater K inputs for both throughfall and stemflow as well as greater P and S inputs in throughfall at bigleaf maple plots compared with conifer plots. Furthermore, areas that are near bigleaf maple trunks are more strongly influenced by bigleaf maple, whereas areas beneath the bigleaf maple canopy but farther away from the trunk are influenced by bigleaf maple as well as the surrounding conifers. The result is a zone around bigleaf maple stems that likely has enhanced microbial activity and increased nutrient availability. Changes in soil properties induced by bigleaf maple may be long-lasting. For example, Mina (1967) found that after stemflow ceases, changes that had taken place earlier in the soil may be preserved for many years. Thus, the enriched microsites proximal to bigleaf maple trunks may form fertile spots for conifer growth at later stages of forest development.

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