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Review

A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems

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Abstract

Stemflow is a spatially localized point input of precipitation and solutes at the plant stem and is of hydrological and ecological significance in forested and agricultural ecosystems. The purpose of this review is to: (1) critically evaluate our current understanding of stemflow; (2) identify gaps in our present knowledge of stemflow; and (3) stimulate further research in areas where present knowledge is weak. The review begins by analyzing stemflow drainage and nutrient inputs under diverse vegetal cover. Stemflow inputs are then examined as a function of meteorological conditions, seasonality, interspecific and intraspecific differences among and within species, canopy structure, spatiality, and atmospheric pollutants in urban environments. Stemflow modeling studies are also reviewed and evaluated. Stemflow yield and chemistry are the result of the interaction of the many complex variables listed. By analyzing each separately, it may be possible to isolate their individual affects on stemflow production and chemistry. A comprehensive understanding of each influencing factor would enable the accurate modeling of stemflow water and nutrient inputs into agricultural and forest soils which may result in the optimization of timber and crop harvests.

Some areas where present knowledge is particularly weak are: (1) stemflow production and nutrient transfers in northern boreal forests (aspen, birch, conifers) and desert cacti; (2) chemical enrichment of stemflow from live trees charred by forest fires; (3) stemflow yield and nutrient inputs during the winter season; (4) intraspecific variation in stemflow production and chemistry; (5) stemflow chemistry from standing dead trees; (6) influence of canopy structure on stemflow chemistry; (7) understory stemflow generation and nutrient transfer; and (8) stemflow enrichment associated with insect infestations.
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1. Introduction

Concern for the ecological status of water resources has resulted in physical process-based studies that examine the influence of vegetation on water quantity and quality at the catchment scale. From catchment scale experimental manipulations in the southern Appalachians, Swank and Douglass (1974) found that streamflow was reduced by 20% by converting a deciduous hardwood stand to *Pinus strobus* L. (eastern white pine). They attributed the decreased streamflow to the greater aboveground vegetative surface area of *Pinus strobus*. Forest age

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and stand growth also have been found to decrease water yield from experimental catchments (Helvey, 1967). Bosch and Hewlett (1982) have substantiated these findings in a comprehensive review of 94 catchment experiments. Some more recent catchment scale studies have focused on the biogeochemistry of potassium (Likens et al., 1994), the impacts of clear-cutting on nitrification (Duggin et al., 1991), and carbon dynamics (Dai et al., 2001).

Many catchment and sub-catchment studies concerned with the affect of forested ecosystems on water quality have partitioned the incident gross precipitation in to throughfall and stemflow. Among the factors reported to affect throughfall chemistry were the following: latitude (Parker, 1983), elevation (Rustad et al., 1994), seasonality (Verry and Timmons, 1977; Hamburg and Lin, 1998), proximity to the sea (Potts, 1978; Graustein, 1980; Soulsby, 1997), species composition (Verry and Timmons, 1977; Neary and Gizyn, 1994; Bellot et al., 1999), forest age (Parker, 1983; Stevens, 1987), and local land-use (Soulsby, 1997; Hamburg and Lin, 1998). Stemflow chemistry has been found to vary as a function of: species (Kaul and Billings, 1965; Verry and Timmons, 1977; Freedman and Prager, 1986; Herwitz, 1991; Tajchman et al., 1991; Levia, 2000), seasonality (Verry and Timmons, 1977; Neary and Gizyn, 1994; Soulsby, 1997), meteorological conditions (Lindberg, 1989; Crockford et al., 1996a; Levia, 2000; Levia and Herwitz, 2000), and canopy structure (Crockford et al., 1996a; Levia and Herwitz, 2002). Throughfall and stemflow have been documented to significantly impact forest biogeochemical cycles (Parker, 1983; Escudero et al., 1991; Stöckli, 1991; Soulsby, 1997).

Throughfall and stemflow are the two hydrological processes responsible for the transfer of precipitation and solutes from a vegetative canopy to the soil. Generally calculated as the difference between incident gross precipitation and interception, throughfall and stemflow typically account for 70–90% of the incident gross precipitation in temperate forests (Leonard, 1961; Lawson, 1967; Freedman and Prager, 1986; Johnson, 1990; Neary and Gizyn, 1994; Likens and Bormann, 1995; Carlyle-Moses and Price, 1999; Muoghalu and Oakhumen, 2000). Although stemflow has been documented to account for as much as 5 to >10% of the incident gross precipitation (Nihlgard, 1970; Clements, 1971, 1972; Aldridge and Jackson, 1973; Herwitz, 1986a; Bui and Box, 1992; Tang, 1996; Herwitz and Levia, 1997; Crockford and Richardson, 2000), some studies have marginalized its hydrological significance because it is volumetrically insignificant when compared to throughfall (Kittredge et al., 1941; Rogerson and Byrnes, 1968; Tiedemann et al., 1980; Butler and Huband, 1985; Lloyd and de Marques, 1988; Price et al., 1997; Marin et al., 2000). As a result, stemflow is underrepresented in the literature. Stemflow is, however, of hydro-ecological and biogeochemical importance in forested and agricultural ecosystems because it is a spatially localized point input of water and nutrients at the plant stem (Voigt, 1960; Eschner, 1967; Gersper and Holowaychuk, 1971; Herwitz, 1986b; Herwitz, 1991; Tanaka et al., 1991; Escudero et al., 1991; Chang and Matzner, 2000; Levia and Herwitz, 2000). Hydrologists and other scientists have documented that stemflow has a significant influence the following: runoff generation (Neave and Abrahams, 2002), soil erosion (Herwitz, 1988), groundwater recharge (Taniguchi et al., 1996), spatial patterning of soil moisture (Pressland, 1976; Durocher, 1990; Chang and Matzner, 2000), soil solution chemistry (Stevens et al., 1989; Escudero et al., 1991; Haworth and McPherson, 1995; Chang and Matzner, 2000; Matschonat and Falkengren-Grerup, 2000), and the distribution of understory vegetation and epiphytes (Crozier and Boerner, 1984; Falkengren-Grerup, 1989; Andersson, 1991; Awasthi et al., 1995).

The purpose of this review is to: (1) critically evaluate our current understanding of stemflow; (2) identify gaps in our present knowledge of stemflow; and (3) stimulate further research in areas where present knowledge is weak. Periodic reviews of the state of scientific research are necessary for a consolidation of present knowledge and efficient advancement of disciplines. A better understanding of the partitioning of incident gross precipitation into stemflow will result in improved models of its influence on soil solution chemistry, groundwater recharge, leaching of fertilizer applications near the plant stem, and intrasystem biogeochemical cycles. Further research could ultimately lead to greater efficiency in the management of forests and agricultural lands and harvest optimization.

2. Stemflow measurement methods

2.1. Measuring stemflow production and chemistry

There is no standard protocol as to the number and type of gages necessary to adequately sample stemflow volume or chemistry. The lack of a standard protocol is, in part, likely the result of the diverse vegetation cover from which stemflow is collected and the differing objectives among stemflow studies. Stemflow drainage, however, is typically collected from forest trees using flexible tubing that is cut longitudinally and wrapped in an upward spiral around a tree trunk (Herwitz, 1988; Durocher, 1990; Levia and Herwitz, 2000; Nakanishi et al., 2001). The tubing is nailed or stapled to the tree trunk, and silicone sealant is applied to seal the collar to the trunk and to plug nail heads (Herwitz, 1988; Herwitz and Levia, 1997). The uncut section of each stemflow collar is connected to a collection bin. Overflow bins may be connected to the primary stemflow collection bin of trees that funnel large stemflow volumes (Levia, 2000). Instead of a stemflow collection bin, stemflow may also be channeled into a tipping-bucket gage connected to a datalogger to determine stemflow volume (Herwitz, 1988; Durocher, 1990). When sampling stemflow generated from snowmelt under frozen conditions during winter, stemflow collection bins, rather than tipping-bucket rain gages, should be used; stemflow volumes may be computed using a portable scale. Others have employed collar type gages to measure stemflow volumes that collect stemflow drainage in a collecting collar concentric with the tree (Rutter, 1963; Wright, 1977; Durocher, 1990). Durocher (1990) stated that collar type gages are less likely to be blocked by litter. Both spiral and collar type gages have been used successfully to measure stemflow volume from forest trees.

Several methodologies have been utilized to collect stemflow generated from agricultural crops. Under *Zea mays* L. (maize), Paltineanu and Starr (2000) measured stemflow volume using polyethylene bags attached to the plant stem. Stemflow water was removed from the bags with a portable pump and flexible tubing. Bui and Box (1992) measured stemflow generated by *Zea mays* canopies using stemflow-collection cups fitted to individual plant stems. Stemflow volumes were measured from *Sorghum bicolor* [L.] Merr. (sorghum) and banana plants using aluminum foil that was fitted around the plant stem in an upward spiral and secured with either silicone sealant or glass filament tape (Bui and Box, 1992; Harris, 1997). For canopies of *Triticum aestivum* cv. Tommi (spring wheat) and *Triticum aestivum* cv. Bounty (winter wheat), stemflow volume was found by comparing interrow throughfall with row throughfall plus stemflow (Butler and Huband, 1985). Stemflow plus throughfall was computed for row positions using bottomless boxes (220 mm × 113 mm) inserted around and between adjacent rows of wheat (Butler and Huband, 1985). An application of natural latex around each of the stems and at the sides of the bottomless boxes sealed the ground and made measurements of throughfall plus stemflow in the row positions possible (Butler and Huband, 1985). Throughfall in the interrow positions was collected by gutters (Butler and Huband, 1985).

For studies investigating the chemical constituents of stemflow, collection bins should be lined with chemically inert bags that are changed after every precipitation event to ensure sample integrity. Such studies should acquire stemflow samples for chemical analysis as soon as practicable. Although there may be logistical constraints in accessing a study site, care should also be taken to collect and analyze samples for constituents of interest soon after a precipitation event to minimize erroneous readings. Many of the base cations, for instance, have a maximum recommended storage time of 6 months, while nitrate is 48 h, and pH only 2 h (American Public Health Association, 1995). Depending on the chemical species of interest, a weekly collection interval may be too long to obtain accurate readings. It is recommended that: (1) stemflow grab samples be collected using chemically inert gloves in an appropriate container for a particular chemical species (plastic or glass); (2) stemflow be collected within the appropriate time frame for each chemical species of interest; and (3) only stemflow collection bins lined with chemically inert sample bags be employed to collect stemflow for chemical analysis since the metal surfaces in most tipping-bucket gages are likely to contaminate the stemflow sample.

2.2. Interpreting stemflow studies

Caution must always be exercised in forming generalizations in any critical review because information drawn from a large number of studies having different objectives and employing different methodologies is difficult. Given the lack of a standard protocol for stemflow sampling and the varied methods of stemflow collection and chemical analysis, stemflow studies should report standard errors for data analyzed. Standard errors give the reader a better sense of variability of the mean and are useful for comparing results among studies. For instance, in cases where the standard error is large, a reader will know that the mean is meaningless but where the standard error is small the mean may be considered with a greater degree of certainty, allowing generalizations to be forwarded with confidence. Realizing that many studies have not reported standard errors, the present review has: (1) carefully interpreted the results of each study; (2) made comparisons among selected studies with caution; and (3) avoided making sweeping generalizations.

3. Stemflow hydrology and chemistry in different ecoregions

3.1. Ecoregion and stemflow generation

Stemflow quantities input into forest and agricultural soils are highly variable between and within types of vegetation cover characteristic of tropical, temperate, and semi-arid and arid ecoregions (Table 1).On the basis of the selected studies in Table 1, the mean maximum stemflow generation values expressed as a percentage of the incident gross precipitation were approximately 3.5, 11.3, and 19.0% for tropical, temperate, and semi-arid and arid ecoregions. Variability in stemflow production between forest types can be attributed in part to differences in climatic patterns, meteorological conditions, and species composition. The variability of stemflow generation was greater within than between areas under diverse vegetation cover. The stemflow values range through 13.0, 19.0, and 44.0% for the three ecoregions (Table 1). The highly variable stemflow production quantities within a particular

ecoregion are likely the result of: site-specific differences, including three dimensional geometry of canopy structure and stand density (Kittredge, 1948; Olson et al., 1981; Herwitz, 1987; Durocher, 1990; Saugier and Pontailler, 1991; Martinez-Meza and Whitford, 1996), the presence or absence of epiphyte mats (Veneklaas and Van Ek, 1990), species composition (Durocher, 1990; Saugier and Pontailler, 1991; Návar et al., 1999), variation in bark texture (Horton, 1919; Kittredge, 1948; Voigt and Zwolinski, 1964; Návar, 1993; Aboal et al., 1999; Návar et al., 1999), and precipitation event frequency, duration, magnitude, and intensity (Opakunle, 1989; Tang, 1996; Crockford and Richardson, 2000; Kuraji et al., 2001). With specific regard to the studies included in Table 1, under temperate forest cover, significant variation in stemflow yield was attributed to species-specific differences, including bark texture and bark water storage capacity (Voigt, 1960) and rainfall magnitude and seasonality (Tang, 1996). Wide ranges in stemflow yield reported in Table 1 under diverse semi-arid vegetal cover were explained by morphological differences among species, such as leaf type and position, branch hydrophobicity, and total stem area (Martinez-Meza and Whitford, 1996), and rainfall intensity (Mauchamp and Janeau, 1993).

3.2. Ecoregion and stemflow chemistry

Total stemflow nutrient inputs of K^+ and Mg^{2+} were also variable between ecoregions (Table 2). For the selected studies in Table 2, Quercus ilex L. (Mediterranean holm oak) forests were found to have the greatest mean maximum K^+ stemflow input of 2.4 kg ha^{-1} yr^{-1} but the lowest mean maximum Mg^{2+} stemflow input of 0.03 kg ha^{-1} yr^{-1}. Plausible reasons for this difference would be that K^+ is more prevalent in dry deposition than Mg^{2+} in Quercus ilex forests (Rodrigo and Avila, 2002) and K^+ is leached at a greater rate than Mg^{2+} (Waring and Schlesinger, 1985). Temperate forests had the greatest variability of K^+ stemflow input with a range of 2.8 kg ha^{-1} yr^{-1}. Verry and Timmons (1977) argued that the wide range in K^+ stemflow was partly due to site effects. Specifically, nutrient content of the soil was argued to influence nutrient concentrations in stemflow and throughfall (Verry and Timmons, 1977). The Picea forest leached less because it was located on a site

Table 1
Range of selected stemflow production values under diverse vegetation cover in tropical, temperate, semi-arid and arid ecoregions

Vegetation type	Stemflow (% of incident precipitation)	Reference
Tropical montane rainforest	13.6	Herwitz (1986a)
Tropical rainforest	1.8	Lloyd and de Marques (1988)
Cacao plantation	1.99	Opakunle (1989)
Tropical dry forest	0.6–0.9	Kellman and Roulet (1990)
Tropical montane rainforest	<1.0	Veneklaas and Van Ek (1990)
Tropical rainforest	0.9–1.5	Marin et al. (2000)
Pine-hemlock-beech plots	1.2–9.6	Voigt (1960)
Pinus radiata plantation	3.1–3.9	Crockford and Khanna (1997)
Dry sclerophyll forest	4.8	Crockford and Richardson (1990b)
Subalpine balsam fir forest	3.0–8.0	Olson et al. (1981)
Northern red oak plantation	4.0	Durocher (1990)
Pinus radiata plantation	11.2	Crockford and Richardson (1990b)
Evergreen-broadleaf forest	14.0–20.0	Masukata et al. (1990)
Slash pine forest	0.94–10.4	Tang (1996)
Japanese pine forest	6.6–15.7	Taniguchi et al. (1996)
Chihuahuan desert shrubs	4.0–45.0	Mauchamp and Janeau (1993)
Semi-arid shrubs	0.76–5.14	Návar (1993)
Chihuahuan desert shrubs	2.0–27.0	Martinez-Meza and Whitford (1996)
Creosotebushes	5.9–26.9	Whitford et al. (1997)
Thornscrub community	3.0	Návar et al. (1999)
Laurel forest	1.2–13.6	Aboal et al. (1999)
Mediterranean holm oak forest	2.6–12.1	Bellot et al. (1999)

with poorer soils and lower nutrient availability, accounting for observed differences between the two species (Verry and Timmons, 1977). The Mg^{2+} stemflow input range of 0.9 kg ha^{-1} yr^{-1} was greatest for tropical forests. Additional factors that may account for the variability of stemflow nutrient inputs between and within ecoregions may be: differences in species composition and canopy structure (Verry and Timmons, 1977; Freedman and Prager, 1986; Crockford et al., 1996a; Levia, 2000), presence or absence of adventitious roots (Herwitz, 1991), the availability of nutrients from atmospheric (Westman, 1978; Bellot

Table 2
Range of selected stemflow enrichment values of K$^+$ and Mg^{2+} in tropical, temperate, and Mediterranean ecoregions

Vegetation type	Stemflow		Reference
	K$^+$ (kg ha^{-1} yr^{-1})	Mg^{2+} (kg ha^{-1} yr^{-1})	
Tropical rainforest	1.5–2.8	0.2–0.3	Jordan (1978)
Subtropical eucalypt forest	0.9	1.1	Westman (1978)
Tropical lowland dipterocarp	0.66	0.18	Radzi Abas et al. (1992)
Sessile oak forest	1.48	0.58	Carlisle et al. (1967)
Aspen-black spruce forest	0.01–2.8	0.006–0.5	Verry and Timmons (1977)
Sugar maple-yellow birch	0.8–1.25	0.04–0.05	Foster and Nicholson (1988)
Northern hardwood forest	0.9	0.06	Likens and Bormann (1995)[a]
Mediterranean holm oak forest	0.3–2.2	0.02–0.2	Bellot and Escarre (1991)
Mediterranean holm oak forest	0.5–2.6	0.06–0.3	Bellot et al. (1999)

[a] Stemflow nutrient input assumed to be 3% of total throughfall and stemflow nutrient flux (Ragsdale et al., 1992).

et al., 1999) and rock weathering sources (Brinson et al., 1980), and exposure to acid precipitation (Lovett et al., 1985; Falkengren-Grerup, 1989; Matschonat and Falkengren-Grerup, 2000).

3.3. Evaluation

From a careful review of the literature, it may be concluded that northern boreal forests and deserts have been under-studied with specific regard to stemflow generation and corresponding nutrient transfer. Buttle et al. (2000) have acknowledged that hydrologic studies in Canada have had a geographic bias to southern boreal forests. Another reason for the apparent lack of stemflow studies in northern boreal forests may be logistical constraints of field sampling under extreme environmental conditions. Although stemflow generation has been extensively studied for shrub type vegetation in semi-arid and arid regions (Návar and Bryan, 1990; Mauchamp and Janeau, 1993; Návar, 1993; Martinez-Meza and Whitford, 1996; Aboal et al., 1999; Bellot et al., 1999; Návar et al., 1999), relatively few studies have examined the chemical enrichment of stemflow drainage from shrub type vegetation. The semi-arid *Quercus ilex* forest is an exception because it has been studied in relation to stemflow generation and chemistry (Bellot and Escarre, 1991; Bellot et al., 1999). In addition, no known studies have been conducted on stemflow generation or chemistry from cacti, nor stemflow chemistry from live trees charred by fire in areas prone to frequent forest fires. Stemflow production from cloud presence is negligible in lower tropical montane forests and subalpine temperate forests (Lovett et al., 1982; Bruijnzeel and Proctor, 1995) but can account for as much as 10% in elfin cloud forests (Weaver, 1972; Bruijnzeel and Proctor, 1995). In areas subject to frequent radiation and advection fog events at lower elevations, the relationship between antecedent fog conditions and stemflow generation during precipitation events immediately following or during the fog event is unclear. If the fog events saturate the vegetative surface of a plant, increased stemflow volumes could be the result. Research should be conducted to determine whether or not stemflow volumes generated during a precipitation event following or during a fog event differ as a function of the characteristics of the fog event.

Few studies examining stemflow generation and chemistry are conducted for a full year or a series of successive years. Year long studies are necessary to better understand the volume of stemflow produced and total nutrient input expressed on a $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ basis. Annual total stemflow nutrient input calculations based on an extrapolation from a certain season could be erroneous. In temperate areas, for instance, variations of precipitation type between seasons (summer has a significant proportion of convective precipitation, winter has frontal precipitation) can generate significantly different stemflow volumes and alter stemflow nutrient inputs. Therefore, studies that list total annual stemflow nutrient input values, without sampling stemflow volumes and chemistry for a full year, may be suspect. Catchment scale nutrient budgets based on partial year sampling also must be examined with caution.

4. Influence of meteorological conditions on stemflow generation and chemistry

4.1. Meteorological conditions and stemflow yield

Many forest and agricultural hydrologists have observed that stemflow production increases with the magnitude of a precipitation event (Lawson, 1967; Clements, 1972; Opakunle, 1989; Matsubayashi et al., 1995; Harris, 1997; Paltineanu and Starr, 2000; Xiao et al., 2000a; Kuraji et al., 2001). Once the interception storage capacity is reached for smooth-barked trees, stemflow generation has been documented to closely match the rainfall pattern of the precipitation event (Durocher, 1990). With the possible exception of hot windy weather where high rainfall intensities might induce increased stemflow volumes due to larger raindrop size and decreased probability of evaporation as compared to less intense events with smaller raindrop size, stemflow production has been observed to decrease with the intensity of incident gross precipitation (Mauchamp and Janeau, 1993; Crockford and Richardson, 2000). Even for *Zea mays* and *Sorghum bicolor* plants with morphological structures more favorable than trees for retaining stemflow, a positive relationship between stemflow volume and rainfall intensity was not observed (Bui and Box, 1992). Intense precipitation events may

increase the probability of branch drip and decrease stemflow volumes by overloading preferential flow paths on tree trunks and forcing stemflow to become throughfall (Crockford and Richardson, 2000). During precipitation events with angled rain where only one side of a tree trunk is wetted, stemflow can be generated in appreciable quantities if steeply inclined branches are wetted even when the interception storage capacity of plant stems and branches is not reached (Crockford et al., 1996b). Even without inclined rainfall, stemflow can be generated without the interception storage capacity of the bark surface being reached since stemflow tends to flow along preferential flow paths on the underside of inclined branches, leaving parts of the branch underside dry (Herwitz, 1987). In dry sclerophyll eucalypt forests of Australia, stemflow may also be produced with only a small proportion of a tree's interception storage capacity being reached due to water repellancy (Crockford et al., 1991).

Stemflow quantities have also been acknowledged to be influenced by wind speed (Kittredge et al., 1941; Tang, 1996; Xiao et al., 2000a; Kuraji et al., 2001) and direction (Kittredge et al., 1941; Herwitz and Slye, 1995). For isolated trees in urban environments, Xiao et al. (2000a) reported that increases in wind speed resulted in increased stemflow yields. Increased wind speeds were also found to increase stemflow yield in forested environments (Kuraji et al., 2001). Greater stemflow yields have been found when a greater extent of the tree stem is wetted (Tang, 1996) but it is unclear whether or not wind will result in more or less surface area being wetted. The angle of wind-driven precipitation has been documented to significantly affect stemflow yields (Crockford and Richardson, 2000). Redistribution of intercepted rain drops by strong persistent winds will reduce drop size leading to a random dispersion of the rain drops, perhaps wetting a greater tree surface area downwind. Incident rain falling at an angle will be intercepted by a greater projected surface area because tree crowns and branches are more efficient collectors of wind-driven rain than tree trunks (Kuraji et al., 2001) and high winds enhance stemflow production (Xiao et al., 2000a), potentially wetting a larger proportion of the tree's woody frame and generating greater stemflow volumes as branchflow converges on the tree trunk. Thus, during events with greater wind speeds,

a greater surface area may be wetted and contribute to stemflow production. Wind may also lead to the preferential saturation of the windward side of a tree trunk during the initial stages of a precipitation event, leading to an early onset of measurable stemflow production along preferred flow channels (Tang, 1996).

Kittredge et al. (1941) recognized and Herwitz and Slye (1995) showed that wind-driven rainfall striking the forest canopy at an angle creates a lateral rainshadow which determines the actual crown area intercepting precipitation. The actual crown area of a tree intercepting gross incident precipitation is defined as the effective crown area (Herwitz and Slye, 1995). A tree's effective crown area and its potential to intercept gross incident precipitation changes as a function of wind direction (Herwitz and Slye, 1995). Therefore, stemflow yield may be spatially and temporally variable within a forest or polyculture field of crops because of its dependence on wind direction and canopy position of individual tree crowns and their plant stems.

Only one known study has specifically focused on stemflow generation during snow and icy precipitation events. Mean stemflow inputs ranged from 2.0 to 25.0% of the incident gross precipitation under *Populus grandidentata* (Herwitz and Levia, 1997). These stemflow averages were comparable to those reported by Clements (1971) for summer rain events under the same vegetation cover. Expressed as depth equivalents per unit trunk basal area, stemflow exceeded 100 mm for winter precipitation events associated with glaze type precipitation (Herwitz and Levia, 1997). Glaze type precipitation was hypothesized to be a prerequisite for significant mid-winter stemflow yields because it cemented intercepted snow to the branch surface, limiting wind displacement (Herwitz and Levia, 1997). The significant stemflow quantities generated at sub-zero air temperatures were attributed to localized melting at the tree-bark interface due to the lower albedo of the bark tissue (Herwitz and Levia, 1997). It also may be possible that the melting and subsequent stemflow production was the result of the longwave radiative flux emitted from the tree (Male and Granger, 1981; Hashimoto et al., 1994; Levia and Underwood, 2002) or heat released from latent heat of fusion as rainfall or

snowmelt infiltrates an intercepted snow mass and freezes (Levia and Underwood, 2002).

4.2. Meteorological conditions and stemflow chemistry

Few studies have examined how meteorological conditions may impact stemflow leachate chemistry from plant stems. For eucalypt species, Crockford et al. (1996a) observed that the chemical concentrations of leached nutrients in stemflow drainage was greatly influenced by the intensity of a precipitation event. Stemflow chemical concentrations for high intensity, short duration precipitation events were relatively low (Tukey, 1970; Crockford et al., 1996a; Levia, 2000) compared to events of longer duration and lower intensity (Tukey, 1970; Levia, 2000) due to shorter contact times with the bark surface. The total stemflow nutrient input at the tree base, however, is likely to be greater during precipitation events with higher rainfall intensities because shorter contact times increase the concentration gradient and diffusion of a nutrient from the bark, leading to a kinetic solubility gradient (Levia, 2000; Levia and Herwitz, 2000). The angle of intercepted incident precipitation was also reported to affect stemflow leachate chemistry (Crockford et al., 1996a). From field observations, Crockford et al. (1996a) reported that rain falling at a constant angle wetted only one side of the tree trunk leaving the other side dry, preventing leachate losses.

Meteorological conditions of precipitation events also determine the physical properties of intercepted precipitation and stemflow drainage. The viscosity and surface tension of water retained on the tree crown vary directly as a function of air temperature. In a study conducted from mid-winter to early spring, Levia and Herwitz (2000) found that low intensity mixed precipitation events which experience air temperature oscillations around the freezing point were significantly enriched compared to warmer rain events. They attributed the differential chemical enrichment to the increased residence time of intercepted precipitation on the bark surface due to colder air temperatures and increased kinematic viscosity and surface tension of stemflow (Levia and Herwitz, 2000).

To better understand the influence of meteorological conditions on stemflow yield and chemistry, data must be collected at a high temporal resolution (Durocher, 1990; Kazda, 1990; Llorens et al., 1997; Xiao et al., 2000a). The minimal sampling interval should be each discrete precipitation event. The preferable sampling interval would be every 20 min. The preferable sampling interval may be even less during very high intensity rainfall events that generate substantial stemflow quantities. Kazda (1990) employed a sequential intrastorm sampling routine to differentiate the original sources of the chemical constituents of stemflow drainage. By sampling stemflow concentrations regularly throughout a precipitation event, Kazda (1990) was able to partition stemflow inputs into proportions derived from washoff of dry deposition and precipitation scavenging and leaching. The proportion of a particular nutrient derived from a certain source was modeled using non-linear regression and determined by dividing the area under the curve into two integrals (Kazda, 1990). The first integral represented the steady decrease in stemflow drainage concentration during the first phase of the event and the second integral represented the steady concentrations of stemflow drainage that is attributable to leaching and absorption (Kazda, 1990). Leaching was determined to account for 38.1% of Ca^{2+}, 50.7% of Mg^{2+}, 73.9% of K^{+}, and 60.9% of Mn^{2+} in stemflow drainage from *Fagus sylvatica* L. (European beech) (Kazda, 1990).

4.3. Evaluation

Although there appears to be a sufficient understanding on the influences of rain intensity and magnitude on stemflow generation, there are only a few studies examining how precipitation intensity and magnitude may impact stemflow chemistry. An ideal intrastorm sequential sampling routine would expand on the work of Kazda (1990) by examining intrastorm meteorological conditions and search for possible relationships between storm characteristics, residence time of intercepted precipitation, and stemflow enrichment. While it could simply be argued that residence time is the key factor controlling the extent of chemical enrichment, the emphasis of stemflow studies should be how meteorological conditions interact to influence stemflow chemistry. Snow,

sleet, rain, and mixed precipitation events of equal magnitude and duration are likely to result in dissimilar residence times of intercepted precipitation and differential stemflow yields and chemical enrichment.

The influence of plant surface albedo and emission of longwave radiative flux from trees has been examined in relation to snowmelt on the forest floor (e.g. Hashimoto et al., 1994) but not in terms of stemflow generation and chemistry. The complex interaction between meteorological conditions, plant surface albedo, and stemflow yield and chemistry at the intrastorm scale will permit a comprehensive understanding of the stemflow process and better models to predict the range of influences that stemflow can potentially exert on intrasystem hydrological and nutrient transfers.

Models represent a simplification of reality. The purpose of hydrological models is to give improved insights into physically based and spatially distributed processes to ultimately facilitate decision making capabilities to increase water quantity and quality and timber or agricultural harvests. A better understanding of how wind speed and direction influence stemflow production and chemistry through the vertical profile of a canopy may lead to complex stochastic models of stemflow nutrient input and yield. Such a stochastic model should be tiered into a minimum of three categories, representing isolated trees, forests, and agricultural crops, to account for differences in canopy structural characteristics, such as canopy roughness and density, to better simulate the effects of wind on stemflow yield and enrichment. Other variables that should be included in such a model would be drop size of rain, angle of inclined rainfall, leaf size and orientation, branch angle, season, and antecedent conditions before a precipitation event. It is recognized that such complex models may be applicable only for a narrow range of conditions but the enhanced insights they may provide about hydrological processes may justify their development.

Although Neal et al. (1993) have reported that the mean ratio between net precipitation and precipitation increases after storm damage and branch breakage, no known studies have examined the influences of storm damage on stemflow generation. Changes in stemflow chemistry resulting from storm damage also merits investigation. It would be useful to know the extent to which storm damage effects a canopy's ability to generate stemflow. Research should be conducted to determine to what extent newly exposed vegetative tissue leaches nutrients, following branch breakage from an overburden of snow or wind, and whether or not these exudates affect stemflow chemistry significantly. An examination of how much damage must occur to initiate significant stemflow nutrient inputs to the forest floor should also be undertaken. Answers to these issues may be particularly important for cyclone prone forests, forests with a high incidence of icing events, and exposed eucalypt forests where branch breakage is common during windy conditions.

5. Seasonality

5.1. Stemflow yield and seasonality

Stemflow yields expressed as a percentage of the incident gross precipitation in deciduous forests are greater during winter than summer (Helvey and Patric, 1965; Brown and Barker, 1970; Dolman, 1987; Neal et al., 1993; Sood et al., 1993). The reasons for greater dormant season stemflow yields are: annual precipitation patterns (Sood et al., 1993), lower rates of evaporation (Masukata et al., 1990; Neal et al., 1993), and leaf abscission (Helvey and Patric, 1965; Neal et al., 1993). Although the rainy season generated the greatest stemflow yields from three hardwood species in India, the winter season generated greater stemflow yields than summer because of the larger seasonal precipitation amounts, despite the fact that significant proportions of the winter precipitation are snow (Sood et al., 1993). The generation of significant stemflow volumes following snow events may be attributable to its relatively high interception efficiency (Johnson, 1990) and subsequent melt. For *Fagus sylvatica*, winter stemflow volumes accounted for 6–16% of the incident gross precipitation compared to only 1–2% for the growing season (Neal et al., 1993). Winter stemflow volumes were greater than those of summer because leaf abscission exposes a greater orthogonally projected branch area to incident precipitation and lower evaporation losses (Neal et al., 1993). Stemflow yields were found to be consistent between seasons for coniferous species (Cape et al., 1991).

5.2. Seasonality and the chemical enrichment of stemflow

The greatest extent of chemical enrichment of base cations in stemflow has been observed in winter rather than summer (Brinson et al., 1980; Farmer et al., 1991; Potter, 1992; Neary and Gizyn, 1994). Stemflow may be significantly enriched because bark has the greatest potential to alter the chemistry of the incident gross precipitation (Foster and Nicholson, 1988) and during winter a larger portion of a tree's woody crown is exposed to incident gross precipitation, wetted, and leached. Increased chemical enrichment of stemflow drainage in winter compared to summer may also be attributed to: (1) the lower air temperatures and saturated vapor pressure of colder air and the corresponding increase in the residence time of stemflow drainage on the bark surface; and (2) lower rainfall intensities generally associated with frontal precipitation and mixed precipitation events.

In *Quercus patraea* woodlands of northwest Britain, Farmer et al. (1991) observed that the stemflow concentrations of base cations fluctuated widely between winter and summer. They noted that the increased chemical enrichment of winter stemflow drainage coincided with the lower pH of bark and stemflow during winter and its lower proton buffering capacity. Dormant season stemflow chemical concentrations of base cations were also found to be greater than those of the growing season in a mixed hardwood forest in southern Ontario (Neary and Gizyn, 1994). Greater winter stemflow nutrient concentrations may be partly attributed to increased residence time of intercepted precipitation due to colder winter air temperatures and increased kinematic viscosity and surface tension of intercepted precipitation (Levia and Herwitz, 2000). K^+ concentrations were roughly 1.5 times greater during the dormant season than summer (Neary and Gizyn, 1994). The least K^+ was leached from the canopy during September (Eaton et al., 1973). Total dormant season stemflow nutrient inputs (kg ha^{-1} yr^{-1}) of K^+ and Mg^{2+} were approximately twice that of the growing season in an alluvial swamp forest (Brinson et al., 1980).

The greater winter stemflow nutrient concentrations and inputs may be even larger than those during the growing season when dry deposition is considered because dry deposition is lower during winter than summer for forests (Lindberg et al., 1986; Lovett and Lindberg, 1986; Ross and Lindberg, 1994). Total dry deposition of NO_3^- at Walker Branch Watershed was 3.80 kg ha^{-1} yr^{-1} during the growing season and 0.98 kg ha^{-1} yr^{-1} during the dormant period (Lovett and Lindberg, 1986). Dry deposition of sulfur was also found to be significantly lower during the dormant period than growing season (Butler and Likens, 1995). Total summer atmospheric deposition is roughly 2–3 times greater than winter for all ions because wet deposition is dominant during winter (Lindberg et al., 1986). Dry deposition may be less than wet deposition in deciduous forests during winter because of leaf abscission and reduced vegetative surface area as well as an increased incidence of rainy days.

To quantify the extent of chemical enrichment of stemflow drainage during mid and late winter and early spring, Levia and Herwitz (2000) developed an enrichment ratio. Essentially, the enrichment ratio compares on a precipitation event basis how enriched the stemflow drainage is in relation to the incident gross precipitation per unit trunk basal area (Levia and Herwitz, 2000). In equation form,

$$E = (C_s S)/(C_p P_g B_a) \tag{1}$$

where E is the enrichment ratio, C_s is the chemical concentration of stemflow, S is stemflow volume collected, C_p is the chemical concentration of incident gross precipitation, P_g is the depth equivalent of gross precipitation, and B_a is trunk basal area (Levia and Herwitz, 2000). The enrichment ratio standardizes stemflow chemical inputs per unit area. On the basis of the enrichment ratio, Levia and Herwitz (2000) found that dormant stemflow inputs of K^+ and Mn^{2+} were significantly enriched. The mean enrichment ratios of K^+ and Mn^{2+} were 580 and 1450, with maximum values of 1715 and 4400 (Levia and Herwitz, 2000). Dormant season precipitation events may be chemically enriched compared to spring and summer rain events due to colder air temperatures and increased kinematic viscosity and surface tension of stemflow drainage. These physical properties lengthen the residence time of intercepted precipitation on a tree crown and promote its funneling from inclined branches. The enrichment ratio may be used

in the future to compare differential chemical enrichment between seasons.

5.3. Evaluation

Most studies examining stemflow generation and chemistry are conducted during the growing season. Given the significant quantities of stemflow yield (Brown and Barker, 1970; Xiao et al., 2000a) and extent of chemical enrichment from forest trees during dormancy (Foster and Nicholson, 1988; Neary and Gizyn, 1994; Levia and Herwitz, 2000; Levia, 2000), further research should be planned that examines the extent of stemflow enrichment during the dormant period. The current literature is especially weak on winter stemflow generation and chemical enrichment in deciduous forests. Particular emphasis should be placed on stemflow nutrient transfer as a function of precipitation event type, air temperature, wind speed and direction, and seasonal temperature means, minima, and maxima to be able to discern any influence of warmer or colder seasons on stemflow nutrient transfer.

Once these initial field-based studies are completed and the mid-winter data gap reduced, it may be possible to link these findings with the global change literature and the research agenda of the global change and terrestrial ecosystems and biospheric aspects of the hydrologic cycle research groups and others conducting research on the hydrobiogeochemical aspects of the hydrologic cycle. The goal of the integrated research would be to better understand the influence of global change on forest biogeochemistry. Although linking field-based hydrologic research with studies on global change may be complex, Wilby (1995) and Clifford (2002) stress the need for hydrologists and other scientists to examine environmental change scenarios on hydrological processes in forested ecosystems. Global change and a corresponding increase in the frequency of mixed precipitation events has been found to substantially increase the stemflow nutrient input of some base cations to the forest floor of a leafless deciduous forest in southern New England (Levia, 2003). Such environmental change scenarios should be examined for boreal and alpine forests and desert ecosystems given the research bias toward temperate forests (Clifford, 2002).

6. Interspecific and intraspecific variation in stemflow hydrology and chemistry

Apart from inherent species-specific differences in canopy structure (e.g. branching geometry, orthogonally projected branch area, branch count) that will determine stemflow production and the residence time and chemical enrichment of intercepted precipitation on the aboveground vegetative surfaces of trees, topics treated in detail in the subsequent section, there are physiological differences in bark tissue chemistry of species and bark porosity that will cause differences in stemflow yield and leachate chemistry. Other factors that determine the length of time bark is wetted and potentially cause interspecific differences in stemflow generation and leaching are texture, water-holding capacity, and air-drying rate of bark tissue.

6.1. Interspecific stemflow generation

Canopy storage capacity is a key factor in determining the quantity of precipitation intercepted (Herwitz, 1985; Liu, 1998) and stemflow generated (Herwitz, 1987). Bark has a greater water-holding capacity than foliar surfaces (Herwitz, 1985; Liu, 1998). Herwitz (1985) found interspecific differences between the water-holding capacities of tropical trees on the basis of bark texture. The interception storage capacities of bark ranged from 0.51 to 0.97 ml cm^{-3}. Flaky-barked species were found to have significantly greater water storage capacities than smooth-barked species. Mean whole tree bark interception storage capacities differed by 297 l for *Argyrodendron peralatum* (F.M. Bailey) H.L. Edlin ex I.H. Boas (red tulip oak), a flaky-barked species, and smooth-barked *Aleurites moluccana* L. Willd. (candleberry) (Herwitz, 1985). Total bark interception storage capacity for these two species was 378 and 81 l, respectively (Herwitz, 1985). For temperate vegetation, similar results were found (Crockford and Richardson, 1990a; Liu, 1998). Smooth-barked *Nyssa sylvatica* var. *biflora* Marshall. (black gum) stored significantly less stem water than rough-barked *Taxodium ascendens* Brongn. (cypress) (Liu, 1998). Stemflow generation can begin before the woody frame of a tree is completely wetted (Herwitz, 1987),

the majority of the woody surface area need not be thoroughly wetted before stemflow is produced.

Horton (1919) and Voigt (1960) noted that interspecific stemflow generation may be explained by the biophysical characteristics of the bark surface. Smooth-barked *Fagus grandifolia* Ehrh. (American beech) trees produced almost twice the volume of stemflow than *Tsuga canadensis* L. Carr. (eastern hemlock) because the smoother bark had a lower total surface area and water storage capacity (Voigt, 1960). The smooth barked *Fagus grandifolia* also offered less resistance to stemflow drainage than the rougher bark of *Tsuga canadensis*. In a later paper, Voigt and Zwolinski (1964) reported that *Pinus resinosa* Ait. (red pine) had a lower stemflow yield than *Pinus strobus* because the rougher bark disrupted the continuous film of water on the bark surface. They concluded that stemflow yield was more sensitive to bark characteristics than meteorological conditions. Brown and Barker (1970), however, concluded that stemflow yield was more sensitive to storm magnitude than bark characteristics in a mixed oak forest. Recent studies acknowledge that both bark texture and meteorological conditions are significant in determining stemflow yield (Crockford and Richardson, 1990b, 2000; Crockford et al., 1996a; Xiao et al., 2000a).

For upland sites, interspecific differences in stemflow generation may be attributed to differential vegetative surface areas (Cape et al., 1991). *Picea abies* L. (Norway spruce) was observed to generate stemflow depth equivalents of 13–14% of the incident gross precipitation (Cape et al., 1991). In contrast, *Pinus sylvestris* L. (Scots pine), *Quercus patraea* Matt. (sessile oak), and *Alnus glutinosa* L. Gaerta (black alder) produced stemflow depth equivalents representing 7–10% of the incident gross precipitation (Cape et al., 1991). Differences were explained by the ability of *P. abies* to efficiently collect occult deposition from hill clouds because of its greater aboveground vegetative surface area.

Four co-occurring species of eucalypts were found to differ significantly in stemflow volumes expressed on a per hectare basis (Crockford et al., 1996a). *Eucalyptus rossii* R.T. Baker and H.G. Sm. (scribbly gum) produced the greatest stemflow volume of $21.0 \, \mathrm{l \, m^{-2}}$ basal area $\mathrm{mm^{-1}}$ rain. *Eucalyptus macrorhyncha* F. Muell. ex Benth. (red stringybark) generated the smallest stemflow volume of $4.0 \, \mathrm{l \, m^{-2}}$ basal area $\mathrm{mm^{-1}}$ rain (Crockford et al., 1996a). In the same location, *Pinus radiata* D. Don (Monterey pine) generated $32.0 \, \mathrm{l \, m^{-2}}$ basal area $\mathrm{mm^{-1}}$ rain (Crockford et al., 1996a). Stemflow fluxes of base cations were also found to be greater for *Pinus radiata* than the native Siempreverde forest in southern Chile (Uyttendaele and Iroume, 2002). Differential stemflow production values were linked to interspecific variation in bark thickness and porosity. The debarking process of smooth-barked eucalypt species was also cited as a probable reason for interspecific differences in stemflow yield (Crockford et al., 1996a).

Increased stemflow yields are viewed as a disadvantage in agriculture because fertilizer applications may be leached from the soil at the tree base. Interspecific differences in stemflow production were reported for citrus trees and agroforestry monocultures and polycultures (Li et al., 1997a; Schroth et al., 1999; Schroth et al., 2001). Statistically significant differences in stemflow production were found beneath citrus canopies of *Citrus paradisi* Macf. (Marsh grapefruit), *Citrus sinensis* L. Uzbek (Hailin orange), and *Citrus* hybrid (Temple orange) (Li et al., 1997a). *Citrus sinensis* produced the maximum stemflow yield of 4.7% of the incident gross precipitation, followed by *Citrus paradisi* at 1.0%, and *Citrus* hybrid at 0.5% (Li et al., 1997a). In central Brazil, *Bactris gasipaes* Kunth. (peach palm) for fruit monocultures and *Bactris gasipaes* for palmito monocultures generated stemflow that accounted for 24.7 and 20.6% of the incident gross precipitation (Schroth et al., 1999). However, in a multi-strata perennial polyculture stemflow only amounted to 3.4% of the incident precipitation (Schroth et al., 1999). In primary forest stemflow yield accounted for 20.3% of the incident precipitation (Schroth et al., 1999). The lowest stemflow amounts, constituting 0.3% of the incident precipitation, were found under *Theobroma grandiflorum* Willd. ex. Spreng K. Schrum. (cupuacu) monoculture (Schroth et al., 1999). Therefore, the optimum strategy to increase yield would be the polyculture and *Theobroma grandiflorum* monoculture due to lower quantities of stemflow generated. To avoid leaching of fertilizer applications in fruit palm monocultures, Schroth et al. (1999) argued that fertilizers be spread between trees

instead of around the boles of individual trees. For both citrus and agroforestry canopies, differences in stemflow yields were ascribed to canopy structural variables (Li et al., 1997a; Schroth et al., 1999, 2001).

Zea mays and *Sorghum bicolor* were observed to generate significant stemflow quantities (Bui and Box, 1992). *Zea mays* was documented to generate larger stemflow amounts than *Sorghum bicolor* (Bui and Box, 1992). Stemflow quantity was significantly and positively correlated with total leaf area and differences between the two species were attributed to different numbers and geometric arrangement of leaves and plant height (Bui and Box, 1992). The higher stemflow yields from *Zea mays* may be ascribed to the helical arrangement of its leaves compared to the overlying, lumped leaf structure of *Sorghum bicolor* (Bui and Box, 1992). All stemflow under sorghum was reported to be available for infiltration (Bui and Box, 1992). Soil under corn canopies may be more susceptible to rill erosion because as much as one-third of the stemflow may be converted to runoff (Bui and Box, 1992).

6.2. Intraspecific stemflow generation

Intraspecific variation of the magnitude of stemflow drainage was documented from five *Populus grandidentata* Michx. (bigtooth aspen) trees of roughly the same age and trunk diameter during mid-winter (Herwitz and Levia, 1997). The maximum stemflow yield from 1 January to 31 March from a single tree was 9.9% of the incident gross precipitation (Herwitz and Levia, 1997). The corresponding minimum stemflow production value was 5.4%. Maximum stemflow inputs for all trees during three discrete precipitation events ranged from 9.6 to 29.4% of the gross incident precipitation (Herwitz and Levia, 1997). Calculated per unit trunk basal area, stemflow depth equivalents reached 743.7 mm during a late winter precipitation event (Herwitz and Levia, 1997). Intraspecific variability in stemflow production rates was ascribed to differences in branch inclination angle and geometry. Durocher (1990) also credited differential stemflow generation from *Quercus rubra* L. (northern red oak) to differences in crown shape and dimension. These results demonstrate that canopy structure is a key factor controlling stemflow yield and that it may be difficult to assume that stemflow

production quantities are constant for trees of the same size and species.

6.3. Interspecific variation in stemflow chemistry

The influence of bark water-holding capacity on stemflow leachate potential has received scant consideration in the literature. Because rough-barked species store greater quantities of water and generate smaller stemflow yields (Herwitz, 1987; Crockford et al., 1996a), the residence time of intercepted precipitation is likely to be longer and account for significant chemical enrichment. Levia and Herwitz (2000) attributed significant stemflow enrichment from *Carya glabra* Mill. (pignut hickory) to its rough, furrowed bark and the increased contact time of stemflow drainage with the bark surface. During the leafless period, *C. glabra* was documented to have higher stemflow nutrient concentrations than *Quercus rubra* and *Betula lenta* L. (sweet birch) but lower total stemflow nutrient inputs (Levia, 2000). The lower total stemflow nutrient inputs of *Carya glabra* were ascribed to its bark morphology, characterized by overlapping forking ridges, and much lower stemflow yields (Levia, 2000). Bark thickness and morphology are two key factors influencing stemflow leachate chemistry (Crockford et al., 1996a; Levia, 2000).

Stemflow nutrient concentrations and total nutrient inputs were reported to be greater under a *Populus tremuloides* Michx. (quaking aspen) canopy than *Picea mariana* Mill. (black spruce) during both growing and dormant seasons (Verry and Timmons, 1977). Differences in the total stemflow nutrient input beneath the canopy of the two species was greatest for Ca^{2+} (Verry and Timmons, 1977). *Populus tremuloides* input 2.96 kg ha^{-1} yr^{-1} of Ca^{2+} to the forest floor via stemflow and *Picea mariana* only 0.05 kg ha^{-1} yr^{-1} of Ca^{2+} (Verry and Timmons). *Populus tremuloides* was also found to be significantly more leachable than *Populus grandidentata* and *Betula papyrifera* Marsh. (white birch) for ten rain events during the growing season (Price and Watters, 1989). Expressed on a μeq m^{-2} event^{-1} basis, *Populus tremuloides* input approximately twice the amount of Ca^{2+} and Mg^{2+} than *Populus grandidentata* in stemflow (Price and Watters, 1989). Mahendrappa (1974) found that stemflow from three coniferous species, *Picea glauca* (Moench) Voss

(white spruce), *Larix laricina* (Du Roi) K. Koch. (larch), and *Abies balsamea* (L.) Mill. (balsam fir), was twice as enriched in K^+ than *Populus grandidentata*. Concentrations of Mg^{2+} and Na^+ were also greater from coniferous species than *Populus grandidentata* (Mahendrappa, 1974). Gordon et al. (2000) noted significant differences in nutrient inputs among *Picea glauca*, *Picea mariana*, and *Picea rubens* Sarg. (red spruce) with *Picea glauca* having higher leachate losses for N, P, and K. In contrast, Houle et al. (1999) found that K^+ concentrations were greater from deciduous than coniferous species.

Potter (1992) examined stemflow nutrient inputs to the soil in a regenerating *Quercus prinus* L. (chestnut oak) forest during fifteen rain events during both growing and dormant seasons. To examine the influence of forest age on stemflow leaching, he compared the results of his study with stemflow leachate values from mature forests at other locations. He concluded that SO_4^- and K^+ stemflow fluxes were consistently greater from a successional forest than mature forests. In contrast, some studies have reported that older plants have a greater susceptibility to leaching (Tukey, 1970; Lemèe, 1974).

Phosphorus is usually the limiting nutrient in forest growth because of its relative insolubility and is therefore tightly held in the intrasystem nutrient cycle (Wood et al., 1984; Zhang and Mitchell, 1995). During the growing season, Zhang and Mitchell (1995) found that stemflow from *Fagus grandifolia* was significantly more enriched in P than *Acer saccharum* Marsh. (sugar maple). Volume-weighted total P concentration was $3.31 \pm 0.03 \, \mu mol \, l^{-1}$ for *Fagus grandifolia* and $0.92 \pm 0.02 \, \mu mol \, l^{-1}$ for *Acer saccharum* (Zhang and Mitchell, 1995). They hypothesized that the difference may be due to organisms (lichens, fungi) that inhabit the rougher bark of *Acer saccharum* and sequester P in their metabolic processes (Zhang and Mitchell, 1995). Total P stemflow flux for both species was $30 \, g \, ha^{-1} \, yr^{-1}$.

For an Australian eucalypt forest, *Eucalyptus melliodora* A. Cunn ex. Schauer (yellow-box) was the most leachable species with mean stemflow inputs of $93.0 \, g \, ha^{-1} \, mm^{-1}$ of stemflow for K^+ and $36.6 \, g \, ha^{-1} \, mm^{-1}$ of stemflow for Mg^{2+} (Crockford et al., 1996a). The next most leachable species, *Eucalyptus mannifera*, leached $72.8 \, g \, ha^{-1} \, mm^{-1}$ of stemflow for K^+ and $16.0 \, g \, ha^{-1} \, mm^{-1}$ of stemflow

for Mg^{2+} (Crockford et al., 1996a). Crockford et al. (1996a) attributed the greater stemflow leachate losses of *Eucalyptus melliodora* to its debarking process. As the older bark peels from the bole, the nutrient-rich inner bark is exposed to stemflow drainage thereby leaching greater nutrient quantities (Crockford et al., 1996a). However, once the old bark is replaced with new bark, smooth-barked eucalypts may leach less nutrients because the new bark is water repellent (Crockford et al., 1996a). The hydrophobic nature of the new bark will concentrate stemflow into preferential flow paths on the bark surface a couple of centimeters in width, keeping much of the bark surface dry and unleached (Crockford et al., 1996a).

Tree species with adventitious roots in a montane tropical rainforest were observed to have greater stemflow leachate concentrations than those species lacking adventitious roots (Herwitz, 1991). *Ceratopetalum virchowii* F. Muell., a species with adventitious roots emerging from the tree trunk, had K^+ and Mg^{2+} stemflow concentrations of 7.10 and $4.20 \, mg \, l^{-1}$ and corresponding total nutrient inputs of K^+ and Mg^{2+} of 536 and $317 \, mg \, cm^{-2} \, yr^{-1}$ (Herwitz, 1991). Two species without adventitious roots, *Balanops australiana* F. Muell. and *Elaeocarpus fovelatus* F. Muell., had K^+ and Mg^{2+} stemflow concentrations of 0.60 and $0.70 \, mg \, l^{-1}$ and 0.80 and $0.30 \, mg \, l^{-1}$, respectively (Herwitz, 1991). Total stemflow inputs of K^+ and Mg^{2+} for each species was 47 and $54 \, mg \, cm^{-2} \, yr^{-1}$ and 30 and $11 \, mg \, cm^{-2} \, yr^{-1}$ (Herwitz, 1991). The presence of adventitious roots on the bole of *Ceratopetalum virchowii* was hypothesized to be an evolutionary adaptation to recover highly enriched stemflow (Herwitz, 1991). Given the low nutrient availability of tropical soils and the intense competition for limited nutrients from atmospheric sources, it is plausible that the development of adventitious roots is an evolved strategy to reclaim nutrient-rich stemflow drainage that would otherwise infiltrate into the soil and rhizosphere of other plants.

Epiphytic lichens have also been found to alter the chemical composition of net precipitation in *Abies balsamea* (L.) Mill. (balsam fir) forests (Lang et al., 1976) and *Quercus douglasii* H. and A. (blue oak) woodlands (Knops et al., 1991). Epiphytic lichens not only uptake N containing anions, but also can influence cation nutrient cycles (Lang et al. 1976;

Pike 1978; Kershaw 1985; Knops et al. 1991; Levia, 2002). During winter precipitation events, corticolous macrolichens were documented to actively sequester significant quantities of nitrate, thereby lowering nitrate stemflow inputs to the forest floor (Levia, 2002). Epiphytic lichens may further reduce stemflow nutrient inputs to the forest floor because: (1) they appear to obtain nutrients from the leachates of other canopy components (e.g. plant stem, branches); and (2) their leachate losses are minor (Pike, 1978). In a montane subtropical moist forest, the presence of epiphytic bryophytes were also found to correspond with decreased stemflow nitrate inputs (Liu et al., 2002). They also observed lower stemflow nutrient input for many of the base cations for trees with epiphytic bryophytes.

Stemflow from citrus canopies of *Citrus paradisi*, *Citrus sinensis*, and *Citrus* hybrid demonstrated chemical enrichment in comparison with the incident bulk precipitation (Li et al., 1997b). Interspecific differences in stemflow chemical enrichment were also observed for some nutrients (Li et al., 1997b). K^+ stemflow concentrations from *Citrus paradisi* was twice that of *Citrus sinensis* and *Citrus* hybrid (Li et al., 1997b). Concentrations of Ca^{2+} and Mg^{2+} were also greater from *Citrus paradisi* than the other two citrus species (Li et al., 1997b). Nitrate concentrations were found to be significantly greater from *Citrus* hybrid than *C. paradisi* or *C. sinensis* (Li et al., 1997a). The lowest mean stemflow pH was recorded under *Citrus* hybrid and the most alkaline under *C. paradisi* (Li et al., 1997b).

Only one known study has been conducted that examined stemflow chemistry from live and dead trees of different species. In agreement with a later study by Price and Watters (1989) and Watters and Price (1988) found that stemflow drainage from live *Populus tremuloides* trees was more enriched than live *Populus grandidentata* trees. Live aspen trees also were found to leach more nutrients from stemflow drainage than *Acer rubrum* L. (red maple) (Watters and Price, 1988). Mean stemflow leaching from standing dead aspens and *Acer rubrum* was greater than from live trees of the same species by a factor of 46 for PO_4^-, 3 for NO_3^-, and 1.5 for K^+ (Watters and Price, 1988). PO_4^- stemflow leachate losses from dead *Populus tremuloides* and *Populus grandidentata* trees were 35 and 20 times greater than

live trees of each species (Watters and Price, 1988). Hauck and Runge (2002), however, found that stemflow leachate concentrations of S, H^+, K, Fe, Mn, and Al were lower in a dieback-affected stand of *Picea abies* than a healthy stand. They attributed lower stemflow leachate concentrations in the dieback-affected stand to reduced interception and needle loss.

6.4. Evaluation

Forest and agricultural hydrologists have made considerable progress in understanding interspecific differences in stemflow yield and chemistry. With regard to intraspecific differences, our current understanding is limited to the recognition that older trees generally have lower stemflow yields and a higher leachate potential. Intraspecific variation of stemflow yield should be investigated further for dominant and economically valuable trees and staple crops. A better understanding of intraspecific differences in stemflow production at this level may improve existing models of stemflow yield and increase timber and crop harvests. Mahendrappa (1990) suggested that species-specific nutrient cycling characteristics may be related to forest growth and yield. Intraspecific studies may also elucidate the relationships between stemflow generation and nutrient transfer as a function of meteorological conditions and canopy structure because the species variable in the experimental design would be held constant. No known studies have specifically examined intraspecific differences in stemflow chemistry at the species level are needed. Further work should also be directed to stemflow nutrient transfers from standing dead trees given the magnitude of stemflow nutrient flux reported by Watters and Price (1988).

7. Canopy structure

7.1. Canopy structure and stemflow production

Most studies that have examined the influence of canopy structure on stemflow generation have focused on branch inclination angle (e.g. Herwitz, 1987; Van Elewijck, 1989a; Návar, 1993; Martinez-Meza and Whitford, 1996). In a laboratory-based experiment

utilizing a rainfall simulator and isolated branches from tropical tree species, Herwitz (1987) found a linear relationship between branchflow yield, expressed as a percentage of total simulated rainfall, and branch inclination angle when the branches were dry. The relationship was logarithmic for wet branches (Herwitz, 1987). At branch inclination angles greater than 60° above the horizontal, branchflow yields were more than 80% of the simulated rainfall (Herwitz, 1987). The greatest stemflow yields from the semi-arid shrub *Flourensia cernua* DC were associated with branch inclinations greater than 45° (Martinez-Meza and Whitford, 1996). Steeper branch inclination angles were also observed to increase stemflow volumes in tropical dry, laurel, and eucalypt forests (Kellman and Roulet, 1990; Aboal et al., 1999; Crockford and Richardson, 1990b, 2000) and maritime pine stands (Loustau et al., 1992a). Although steeper branch inclination angles may increase stemflow yield from the woody surfaces of trees and shrubs, there is likely a critical threshold where the steeper branch inclination angle will be offset by the decrease in orthogonally projected crown area and stemflow yields will begin to decline.

For a sloping surface, $\cos \alpha$ illustrates the projected vertical length of the surface and $\sin \alpha$ will influence the velocity and quantity of water draining the plant stem (Van Elewijck, 1989a). In contrast to the relatively steep branch inclination angles that generated the greatest stemflow volumes for trees and woody shrubs, maximum stemflow yields were observed from maize at leaf inclination angles of 5–20° above the horizontal in a rainfall simulation experiment (Van Elewijck, 1989a). Van Elewijck (1989a) attributed the increased stemflow yield from maize leaves at low inclination angles to their relatively large diameter and lower splash losses. For branch surfaces of tropical trees, rainsplash can be significant for inclination angles less than 45° (Herwitz, 1987).

Some studies have observed positive correlations between stemflow production and tree basal area (Crockford and Richardson, 1990b, 2000) and stem length (Martinez-Meza and Whitford, 1996). Presumably, taller larger trees have the potential to produce greater stemflow yields because of the greater projected surface area (Ford and Deans, 1978; Bui and Box, 1992; Martinez-Meza and Whitford, 1996).

Návar (1993), however, found that total branch area was a poor control on stemflow yields from three semi-arid shrub species. Stemflow yield also decreases as trees age and the bark roughness and interception storage capacity increase (Helvey and Patric, 1965; Johnson, 1990), despite the greater crown size. To better understand the relationship between stemflow yield, projected branch area, and tree age, additional species-specific studies should be conducted because the biophysical traits of each species may dictate the interactions between each of these variables. It is recognized that meteorological variables, such as rainfall intensity, rain angle and direction, and rain drop size, should be isolated and considered in greater detail to more fully comprehend stemflow volumes generated among and within species.

Other canopy structure variables that have been reported to influence stemflow yields are branch number (Návar, 1993); presence of canopy gaps (Crockford and Richardson, 2000); and flow path obstructions (Crockford and Richardson, 2000). Branch number and position within the canopy were determined to be the primary controls of stemflow yield for semi-arid shrubs (Návar, 1993). Despite a lower branch area, *Diospyrus texana* Scheele (Texas persimmon) was observed to produce significantly greater stemflow volumes than *Acacia farnesiana* (L.) Willd. (cassie) or *Prosopis laevigata* (Humb. and Bonpl. ex Willd.) M.C. Johnst. (mesquite) because of a greater number of branches oriented 70–80° above the horizontal and a larger mean branch inclination angle (Návar, 1993). Dominant branches at the top of the canopy were found to produce the greatest stemflow quantities (Návar, 1993). There was, however, no correlation between the presence of canopy gaps and stemflow quantity in a young dense *Picea sitchensis* (Bong.) Carr. (sitka spruce) plantation because of the significant overlap among crowns (Ford and Deans, 1978). It is hypothesized that as the plantation thins with age crown overlap will decrease and increase stemflow yield in canopy gaps. Stemflow yield in canopy gaps is likely to increase by exposing a greater surface area to incident precipitation (Crockford and Richardson, 2000). Because stemflow drainage flows on the underside of branches (Herwitz, 1987), stemflow yields may be lowered by flow path obstructions, such as detaching bark, that create drip

points where stemflow disjoins the branch underside becoming throughfall (Crockford and Richardson, 2000).

The ability of a tree to generate stemflow varies within the vertical profile of a tree's canopy (Hutchinson and Roberts, 1981; Kuraji et al., 2001). Using an isolated 15-yr-old *Pseudotsuga menziesii* (Mirb.) Franco tree (Douglas fir) in a rainfall simulation experiment producing vertical rain drops, Hutchinson and Roberts (1981) observed that 98% of the stemflow was produced by the upper half of the canopy volume. Sheltered branches in the lower canopy contributed insignificantly to the total stemflow yield (Hutchinson and Roberts, 1981). Their findings suggest that stemflow production is not proportional to the interception storage capacity of each vertical division of the canopy. Vertical variation in stemflow generation was explained by differences in branch inclination angle over the entire branch length between upper and lower branches (Hutchinson and Roberts, 1981). For *Chamaecyparis obtusa* Endl. (Japanese cypress) forest, Kuraji et al. (2001) also reported that the upper portion of a tree's crown contributed the greater proportion of total stemflow yield. It should be noted that sheltered branches in the lower canopy could contribute to stemflow during precipitation events with wind-driven angled rainfall. Kuraji et al. (2001) noted that stemflow volume collected just under the tree crown was greater than that collected near the ground. Differences in crown stemflow yield and canopy-and-stem stemflow yield were attributed to the large water holding capacity of bark tissue (Kuraji et al., 2001).

7.2. Canopy structure and stemflow chemical enrichment

Most stemflow is generated in understory vegetation because of the increased stem density compared to the fewer number of branches comprising the canopy (Helvey and Patric, 1965). Understory vegetation stemflow nutrient transfers in an aspen forest were approximately six times greater than throughfall inputs (Price and Watters, 1989). The greater stemflow nutrient input may be partly explained by the greater stem area of the understory which was approximately three times greater than the overstory (Price and Watters, 1989). The larger

understory stemflow nutrient inputs may also be explained by a positive correlation between stand density and nutrient flux (Olson et al., 1981).

Using a set of isolated branches in a field-based winter experiment, Levia and Herwitz (2002) investigated the effect of branch inclination angle on branchflow leachate chemistry. The experimental branches were positioned at 5, 20, and 38° above the horizontal (Levia and Herwitz, 2002). They tested the null hypothesis that during winter branch inclination angle did not have a detectable influence on differences in leachate chemistry and the quantity of intercepted precipitation from the branch surface. Leachate concentrations were found to be significantly greater from branches inclined at 20° than 5 or 38° (Levia and Herwitz, 2002). Absolute nutrient inputs were also greatest for branches inclined at 20° (Levia and Herwitz, 2002). The significantly enriched branchflow and greater total nutrient input of branches inclined at 20° were attributed to the increased residence time of intercepted precipitation with the branch surface, the lower probability of branch drip than branches inclined at 5°, and only minimal differences in branchflow quantity compared to branches inclined at 38°.

7.3. Evaluation

Very few studies have examined the influence of canopy structure on stemflow chemistry. Kuraji et al. (2001) is the only known study to investigate variation in stemflow chemistry through a forest canopy vertically. They found that the vertical variation of stemflow leaching was ion-specific and exhibited a wide range of variability throughout the *Chamaecyparis obtusa* canopy. Given the findings of Price and Watters (1989), understory stemflow transfers of water and solutes merits further study. Stemflow leachate chemistry should also be examined as a function of woody surface area, orthogonally projected branch area, and branch inclination angle. Further work on the influence of branch inclination angle should employ detached experimental branches since it is impossible to isolate the effect of certain branch angles for individual trees. To make the results of branch inclination angle experiments of practical significance, a wide range of variables would have to be considered. As discussed in Levia and Herwitz

(2002), the extrapolation of isolated branch experiments to the stand level would require a better understanding of many issues including: (1) determination of how mean primary branch inclination angle may vary among species; (2) what the distribution is; and (3) whether or not the mean primary branch inclination angle may adequately represent the population of primary branch angles for a given species. The scale at which primary branch inclination angle is examined should also be addressed as canopy architecture is spatially heterogeneous (Song et al., 1997). The relationship between branch inclination angle and leaching for a given solute must also be known to effectively extrapolate results from an experiment utilizing isolated branches. Remote sensing technologies and computer modeling exercises may prove useful in identifying any influence that woody surface area and orthogonally projected branch area may have on stemflow chemistry. The acquisition of stereopairs from low-flying aircraft may be a useful approach to model the three dimensional geometry of individual canopy trees and quantify surface and projected branch areas.

8. Spatiality of stemflow inputs

8.1. Spatial variability of stemflow inputs

To quantify the extent to which the outlying branches of canopy trees spatially concentrate stemflow inputs and operate as a collection funnel of incident gross precipitation, Herwitz (1986a) devised a funneling ratio. The funneling ratio (F) is given by the equation

$$F = V/(BG) \tag{2}$$

where V is stemflow volume, B trunk basal area, and G the depth equivalent of incident gross precipitation (Herwitz, 1986a). The product of BG is the volume of stemflow one would expect in a rain gage occupying an area equal to the trunk basal area. For selected tropical rainforest tree species, Herwitz (1986a) reported funneling ratios ranging from 7 to 112.

Spatial variability of stemflow transfers to the forest soil may be attributable to inclined rainfall that is differentially intercepted by canopy trees. Inclined rainfall creates lateral rainshadows over

less prominent canopy trees because they may be fully or partially shaded by neighboring trees that are taller and intercept the incident precipitation (Herwitz and Slye, 1992, 1995). Those trees located within the rainshadow necessarily intercept less precipitation than if the rainfall was vertical, while the prominent canopy trees intercept a greater proportion of the incident precipitation than would otherwise be expected due to a greater orthogonally projected area. Herwitz and Slye (1995) noted that the presence of inclined rainfall may account for negative interception values in wind prone areas. In general, the spatial variability of stemflow generation decreases as the magnitude of a precipitation event increases (Lloyd and de Marques, 1988).

Stemflow inputs to the forest floor are more concentrated and have a greater spatial variability than throughfall (Durocher, 1990; Návar and Bryan, 1990). Expressed per unit trunk basal area, stemflow inputs at the bases of selected trees have been documented to be 30–40 times larger than mean throughfall inputs (Durocher, 1990). The highly localized nature of stemflow inputs have also been reported to dramatically effect soil moisture recharge (Durocher, 1990; Gomez et al., 2002) and hillslope hydrology and hydrochemistry (Crabtree and Trudgill, 1985). The strong vertical movement of stemflow into the soil created saturated zones within the vadose zone that extend to the watertable beneath canopy trees (Durocher, 1990). The water potential between trees, however, changed only slightly because stemflow movement is primarily vertical (Durocher, 1990). On forested hillslopes, Crabtree and Trudgill (1985) found that spatially concentrated stemflow inputs at the tree base bypassed the soil matrix via macropores leading to rapid solute-rich inputs to a nearby stream.

The spatial concentration and channelization of stemflow at plant stems has also been documented increase soil moisture recharge in arid environments (Návar and Bryan, 1990; Mauchamp and Janeau, 1993; Martinez-Meza and Whitford, 1996). *Flourensia cernua* is capable of channeling approximately 50% of the incident gross precipitation to the plant stem (Mauchamp and Janeau, 1993). In a laurel forest, incident gross precipitation was concentrated up to 12.8 times near plant stems (Aboal et al., 1999). Using chloride as a tracer, Martinez-Meza and Whitford

(1996) found that stemflow was channeled along preferential flow paths near the roots of *Flourensia cernua*, leading to deep storage of soil moisture. The stemflow-root channelization process of shrubs was hypothesized to be an adaptive mechanism to survive seasonal drought (Martinez-Meza and Whitford, 1996). Water redistribution by stemflow-root channelization results in spatial heterogeneity of soil moisture in semi-arid and arid climates and may explain the stability of *Flourensia cernua* and other shrubs in drought prone areas (Martinez-Meza and Whitford, 1996).

Tanaka et al. (1991) recognized that the spatial variability of stemflow may significantly influence the physical and chemical properties of subsurface water. They noted that the actual amount of stemflow, infiltrating in a radial pattern around the tree trunk, may represent as much as 10–20% of the incident gross precipitation resulting in soil moisture recharge. In a later study, the funneling of stemflow water at the tree base was also shown to result in significant groundwater recharge (Taniguchi et al., 1996). Using a mass balance approach, stemflow was argued to be one of the key processes responsible for groundwater recharge in forests, accounting for 19.1% of the total groundwater recharge under a *Pinus densiflora* Sieb. et Zucc. (Japanese red pine) canopy (Taniguchi et al., 1996). The significance of stemflow in groundwater recharge has been adequately modeled using a cylindrical infiltration model (Tanaka et al., 1996).

8.2. Spatial variability of stemflow chemical inputs

Forest canopy trees have long been known to alter the physical (Gersper and Holowaychuk, 1970a) and chemical properties of the soil (Shear and Stewart, 1934) in a radial pattern with respect to the tree stems (Gersper and Holowaychuk, 1970b; Gersper and Holowaychuk, 1971). In most cases, the stemflow induced microsite around the tree stem has: a lower pH (Gersper and Holowaychuk, 1970b; Falkengren-Grerup, 1989; Chang and Matzner, 2000; Matschonat and Falkengren-Grerup, 2000), lower base saturation (Gersper and Holowaychuk, 1970b; Falkengren-Grerup, 1989), and lower cation exchange capacity (Gersper] and Holowaychuk, 1970b; Matschonat and Falkengren-Grerup, 2000) than soils located

further from the plant stem unaffected by stemflow. The proximal stem area, most influenced by stemflow, extends one square meter around the stem and as a 60 cm deep cylinder (Chang and Matzner, 2000). Distal stem areas are defined as those only influenced by throughfall nutrient transfers (Chang and Matzner, 2000). The neutralizing capacity of the proximal area is four times less than distal areas because of acidic stemflow inputs (Chang and Matzner, 2000). Although aluminum saturation had declined after the experimental removal of stemflow around the trunks of *Fagus sylvatica*, the soil was not completely recovered after eight years (Matschonat and Falkengren-Grerup, 2000). In fact, the reduction of soil acidity near the tree stem was only 15% after fifteen years (Falkengren-Grerup and Björk, 1991).

The 'fertile island' effect can be described as the accumulation of soil nutrients under vegetation in arid environments. The presence of this phenomenon has been documented by a number of researchers (e.g. Charley and West, 1975; West and Klemmedson, 1978; Parker et al., 1982; Virginia and Jarrell, 1983) but the processes responsible for its formation are not well understood (Whitford et al., 1997). For *Larrea tridentata* DC. (creosotebush) in the Chihuahuan Desert, Whitford et al. (1997) have argued that stemflow is a contributor to the 'fertile island' effect. They observed that stemflow concentrates nutrients at the shrub base and explains the spatial heterogeneity of soil chemistry by funneling dry-fall inputs during rain events. Another reason for stemflow initiated chemical enrichment at the tree base may be the leaching of the microbial crust present on many *Larrea tridentata* shrubs (Whitford et al., 1997).

Decreased growth (Wittig and Neite, 1985) and distinct spatial patterning (Andersson, 1991) of understory vegetation has been documented to occur within the stemflow induced microsite at the bases of tree trunks generating significant stemflow quantities. In contrast to the lower pH reported by most other studies near the tree trunk, Andersson (1991) observed an increased pH near the stems of *Quercus robur* L. (common oak). The increased pH was attributed to the uptake of calcium by the deep roots of the older oaks, and subsequent leaching and deposition by stemflow

(Andersson, 1991). Two vernal herbs, *Mercurialis perennis* L. (dogs mercury) and *Hepatica nobilis* Mill. (anemone), that only inhabit areas with relatively high pH were noted to be restricted to a narrow zone at the tree base with the highest pH (Andersson, 1991). Andersson (1991) attributed the sharp species zonation to stemflow nutrient inputs because the zones were too narrow to be explained by differences in light availability or leaf litter chemistry.

8.3. Spatial variability of stemflow inputs and geomorphological processes

Stemflow has been reported to differentially transport leaf litter downslope at the base of some tropical trees (Douglas, 1967), making the soil more susceptible to rainsplash and sheetwash erosion. Erosional scour marks have been observed around the bases of trees in temperate and tropical forests and attributed to the concentrated stemflow inputs to the forest floor (Herwitz, 1986a; Tanaka et al., 1991).

Buttresses of tropical trees have been observed to influence the spatiality of stemflow inputs to the forest floor (Herwitz, 1988). Buttressing lowers the probability of stemflow induced overland flow by promoting stemflow divergence on the tree trunk and increasing its contact area with the litter layer (Herwitz, 1988). During heavy rainfall events, it is plausible that buttresses limit soil erosion on tropical hillslopes by bifurcating stemflow inputs and increasing the likelihood of infiltration (Herwitz, 1988).

Stemflow has also been hypothesized to explain the formation of solution pipes in Bermuda eolianite (Herwitz, 1993). A prerequisite for the formation of solution pipes was the funneling of large quantities of highly acidic stemflow around the boles of forest trees to dissolve the soluble eolianite (Herwitz, 1993). The concentrated nature of acidic stemflow chemical inputs to the soil was argued to form the solution pipes because of their physical form and high areal densities (Herwitz, 1993). The cylindrical shape, vertical orientation, and diameter of the solution pipes are indicative of repeated episodes of wetting by stemflow (Herwitz, 1993). Stemflow from successive generations of trees were argued to form the solution pipes by influencing the spatial patterning of subsurface rock weathering (Herwitz, 1993).

8.4. Evaluation

Considerable progress has been made toward our understanding of how the spatially concentrated nature of stemflow influences the hydrologic and nutrient cycles in forests as well as geomorphic processes. Further work is needed to understand the role of flow path obstructions in the development of drip points and their influence on the spatial patterning of soil solution chemistry and decreases in stemflow. Aphid infestations on *Picea abies* have been documented to spatially concentrate carbon throughfall concentrations under infested trees, resulting in 'hot spots' of dramatically enriched throughfall inputs (Stadler and Michalzik, 1998; Stadler et al., 1998). No known studies have examined any influence of insect infestations of tree bark on stemflow chemistry.

Research that links canopy structure variables and the spatial inputs of stemflow would also be useful. In particular, the influences of specific branching angles and the presence of epiphytes should be examined in relation to the spatial dimension of stemflow inputs. The extent to which total woody surface area and orthogonally projected branch area influence the funneling of stemflow should also be examined more closely. Could a tree with a larger total woody surface area but smaller orthogonally projected branch area be a more efficient at funneling stemflow to the tree base than a tree with a much greater orthogonally projected branch area but less total woody surface area?

9. Pollutants and stemflow in forest nutrient cycles

9.1. Stemflow chemistry and pollutants

Tree canopies are aerodynamically rough surfaces that are efficient at scavenging aerosols, atmospheric pollutants, and occult deposition. In urban environments that tend to have higher levels of airborne sulfate (Radzi Abas et al., 1992; HouBao et al., 1999) and nitrate (Radzi Abas et al., 1992; Takagi et al., 1997; HouBao et al., 1999) due to industrial and automobile emissions, stemflow chemistry may be altered significantly. The pH of stemflow was reported

to be lower than the incident bulk precipitation for forests in central Bohemia exposed to heavy loads of atmospheric pollutants (Skřivan et al., 1995). For urban forests in Kuala Lumpur, Malaysia, Radzi Abas et al. (1992) ascribed the lower pH of stemflow compared to the bulk precipitation to anthropogenic sources within the city that released sulfate and nitrogen oxides to the atmosphere. In contrast, Takagi et al. (1997) reported that the annual mean pH of stemflow was higher than that of the incident bulk precipitation for urban street trees in Japan. The higher pH of stemflow was likely the result of acid neutralization due to the extraordinarily high concentrations of base cations measured in stemflow (Takagi et al., 1997). The concentrations of K^+ and Ca^{2+} reported by Takagi et al. (1997) exceeded those of Radzi Abas et al. (1992) by a factor of 10.6 and 23.1, respectively. The high stemflow concentrations of cations measured by Takagi et al. (1997) may be attributed to the leaching of excess atmospheric anions that were deposited and adsorbed to tree surfaces.

Upland forests that receive higher inputs of atmospherically wet deposited sulfate may be more prone to acidification than other forests (Farmer et al., 1991) due to differences in stemflow chemistry. Seatoller Wood, an upland forested site in northwestern Britain, was observed to have lower cation stemflow concentrations, bark pH, and bark cation exchange capacity than two other forested sites (Farmer et al., 1991). The other two forested sites, Loch Sunart and Glenlee, that received lower wet acidic inputs may be less susceptible to acidification since stemflow pH was greater than the incident bulk precipitation and the soil cation exchange capacity was greater (Farmer et al., 1991).

Forests have also been documented to enhance the atmospheric inputs of beryllium (Neal et al., 1992) and polycyclic aromatic hydrocarbons (Howsam et al., 2000) because of high interception efficiencies of dry and occult deposition by the aerodynamically rough forest canopy (Howsam et al., 2000) and concentration effects of interception losses (Soulsby and Reynolds, 1994). Stemflow may have the greatest potential to buffer pollutants deposited and adsorbed to the tree surface because of its increased contact time with the bark surface.

9.2. Stemflow and acidic deposition

The effects of forests on the buffering of acid deposition has been studied extensively (e.g. Lovett et al., 1985; Foster and Nicholson, 1988; Mahendrappa, 1990; Neary and Gizyn, 1994; Matsuura et al., 2001; Nakanishi et al., 2001). Deciduous forests have been found to be able to buffer acidic inputs more effectively than coniferous forests (Mahendrappa, 1990; Neary and Gizyn, 1994; Kim et al., 2001; Silva and Rodreiguez, 2001). Proton buffering at canopy exchange sites is a primary mechanism to reduce acidity (Lovett et al., 1985; Neary and Gizyn, 1994), representing 40–60% of total cation leaching (Lovett et al., 1985). There is, however, no discernible trend for stemflow pH that emerges between areas prone and not prone to acidic deposition (Table 3), indicating the importance of site-specific characteristics and species. In southern Ontario, Canada, deciduous canopies were able to neutralize acidic inputs year round but coniferous canopies only during summer (Neary and Gizyn, 1994). Since cations are leached mainly from the stem during dormancy (Neary and Gizyn, 1994), stemflow leaching may be responsible for the neutralization of acid deposition at deciduous sites during winter. The importance of cation leaching from the tree stem was highlighted by Neary and Gizyn (1994) since it may explain why the deciduous site was able to buffer acid deposition throughout the year and why the base cation supply was too low to buffer acidic inputs at the coniferous site during dormancy. Another reason why the broadleaved trees may be able to buffer acidic inputs throughout the year, and in particular during winter, is the lower aerosol scavenging efficiency of leafless trees compared to conifers. An anion deficiency has been reported to result from stemflow leaching associated with acid deposition (Foster and Nicholson, 1988). The balance of charge was attributed to bicarbonate and carboxylic acids in the forest soil (Foster and Nicholson, 1988).

9.3. Evaluation

Further research needs to be conducted on beryllium cycling through forests. A closer examination of beryllium stemflow inputs and flow paths in forest and agricultural soils and groundwater is

Table 3
Acidic deposition and mean pH of incident bulk precipitation and stemflow

Area	Species	pH		Reference
		Bulk precipitation	Stemflow	
Southeastern Australia[a]	*Pinus radiata*	5.30	4.24	Crockford et al. (1996a,b)
Northern Australia[a]	*Ceratopelatum virchowii*	5.42	4.48	Herwitz (1991)
Northeastern Mexico[a]	*Quercus* spp.	6.59	6.06	Silva and Rodriguez (2001)
Central Nova Scotia[b]	*Acer saccharum*	4.3	5.7	Freedman and Prager (1986)
Central Bohemia[b]	*Fagus sylvatica*	4.15	4.00	Skřivan et al. (1995)
Western Japan[b]	*Ilex rotunda*	5.2	5.7	Takagi et al. (1997)
Southeastern China[b]	*Cunninghamia lanceolata*	6.31	4.14	HouBao et al. (1999)
Northern Bavaria[b]	*Fagus sylvatica*	4.65	4.60	Chang and Matzner (2000)

[a] Site not exposed to significant acidic deposition.
[b] Site exposed to significant acidic deposition.

warranted given its potential deleterious environmental effects. The use of isotopic tracers may be useful in better understanding the interaction between beryllium stemflow inputs and their potential influence on groundwater quality.

Species-specific work should be conducted that gives insights into the ability of stemflow to buffer acidic inputs, particularly during winter. Although Neary and Gizyn (1994) have studied stemflow chemistry and acid neutralization during winter, they did not distinguish between the role of individual species in the buffering process. Relationships between stand age and acid buffering may also reveal useful information for forest managers. Since standing dead trees leach significant quantities of nutrients from their stems (Watters and Price, 1988), a study investigating the ability of dead trees to neutralize acidic inputs is also recommended.

10. Stemflow modeling

10.1. Stemflow modeling studies

The rationale for stemflow models is a more efficient management of water resources for municipal, agricultural, and industrial uses. Although there are studies that have modeled stemflow in conjunction with interception, many of these do not focus solely on stemflow and are therefore beyond the scope of this review (e.g. Helvey and Patric, 1965; Helvey, 1967; Masukata et al., 1990; Loustau et al., 1992b; Davie and Durocher, 1997a; Davie and Durocher, 1997b; Návar et al., 1999; Xiao et al., 2000b). There are a few studies, however, that have modeled stemflow as an isolated process.

Concerned with the pedogenetic effects of stemflow, De Ploey (1984) modeled stemflow quantity generated by two grass species (*Molinia coerulea* L. and *Arrhenatherum elatius* L.), a liliaceous plant (*Chlorophytum comosum* L.), and a birch tree. The model parameters were mean length and mean slope angle of stems and leaves, basal internodal surface, total 'impluvium' beneath the canopy, total vertically projected area of stems and leaves (De Ploey, 1984). The parameters for the birch tree stemflow model were angle of gross incident rainfall, mean trunk diameter, tree height, morphometric characteristics of sampled subset of the crown (branch angle and length), and the multiplicator (M) which equals the total volume of the tree divided by the volume of the sampled subset (De Ploey, 1984). The multiplicator is visually estimated and is used to extrapolate the results of the portion of the crown that was sampled. Despite the large error that is likely associated with the visual estimation of the multiplicator, the model demonstrates a good correlation ($r = 0.936$) between measured and observed stemflow volumes (De Ploey, 1984). The model implies that a maximization of stemflow yields in dry agricultural areas may optimize crop harvests (De Ploey, 1984).

Employing a laboratory-based rainfall simulator and field experiments, stemflow production from

maize was modeled as a function of leaf angle (Van Elewijck, 1989b). Parameters of the multiple regression stemflow model included rainfall intensity, storm duration, mean slope angle and width of leaf, surface area of funnel collecting stemflow, and length of leaf outside funnel collection area (Van Elewijck, 1989b). The experimentally derived model indicated that maize generated the greatest stemflow yields at low slope angles of 5–20° (Van Elewijck, 1989b). Testing the model derived by Van Elewijck (1989b) for both maize and sorghum, Bui and Box (1992) found that the model routinely overestimated stemflow quantities.

Statistical modeling and extrapolation were used to determine stemflow depth equivalent for an entire forested ecosystem (Hanchi and Rapp, 1997). Stemflow depth equivalents were obtained by the following procedure for each stand: (1) correlations were established between stemflow volume and tree diameter at breast height (dbh) for a low number of trees; (2) the distribution of trees relative to their dbh classes was calculated, stemflow volumes from step #1 were converted to depth equivalents and summed; and (3) stemflow depths are determined for trees in a stand based on the depth of incident gross precipitation for a particular period of time (Hanchi and Rapp, 1997). The stemflow depth equivalent for the forest can then be determined by summing the stemflow depth for each stand. The stemflow model devised by Hanchi and Rapp (1997) may be practical and useful for preliminary estimations of stemflow yield given its ease of application. However, based on the finding that there was a poor correlation between trunk diameter and stemflow yield in a homogeneous conifer plantation (Ford and Deans, 1978) and the great variability of stemflow generation between species reviewed earlier in this paper, the model proposed by Hanchi and Rapp (1997) may lead to a poor estimation of stemflow yield.

Annual stemflow volumes were determined with a multiple linear regression model for a laurel forest using projected crown area, the total summed height of neighboring tree crowns above the top of the sample tree, and a bark roughness index (Aboal et al., 1999). The model accounted for 66% of the variation ($r^2 = 0.66$; $F = 0.0000$) and showed that trees with the smoothest bark, the largest crown

area, and that were more prominent than their neighbors generated the greatest stemflow quantities (Aboal et al., 1999). They also found that the most accurate estimates of stemflow yield were determined by applying the annual regression equation to basal area classes and species on a stand by stand basis (Aboal et al., 1999). Aboal et al. (1999) concluded that the inclusion of a species-specific criterion (e.g. bark roughness), canopy structural properties (e.g. crown size and neighboring trees), and the relative proportion of each species per unit trunk basal area in a stand is the most valid method to estimate stemflow yield. The sum of species stemflow for each basal area size class for each stand yields total stemflow yield for the laurel forest (Aboal et al., 1999).

10.2. Evaluation

The stemflow modeling studies reviewed have examined stemflow production during rain events. To improve water resource management in areas with a strong seasonal moisture regime, stemflow infiltration and groundwater recharge into unfrozen ground during dormant season snow and mixed precipitation events should be modeled. Models that examine stemflow nutrient inputs as function of meteorological conditions, seasonality, canopy structure, and species should also be developed to permit better management of forests and farmland to optimize yields. On the basis of the modeling studies reviewed, it seems those similar to Aboal et al. (1999) which link species differences and canopy structure may be most accurate and useful. Once again, we would like to emphasize that accurate modeling of stemflow is a difficult and complex process involving a multitude of variables ranging from species, branch angle, and bark roughness to wind speed, rain drop size, and rainfall intensity. Despite the shortcomings of the models reviewed, it is argued that further field research will lead to the development of more sophisticated models that may be able to better predict stemflow volumes and chemistry that may be of use to forest hydrologists, agricultural hydrologists, and watershed managers.

11. Conclusion

Stemflow is a hydrological process that effects the biogeochemical cycling of nutrients within and through forests. As a spatially localized point input of water and nutrients at plant stems, it has been documented to significantly influence soil solution chemistry, soil nutrient status, soil moisture and groundwater recharge, and hillslope processes. Stemflow may also have a considerable effect on plant productivity and yield because of its capacity to leach fertilizers near the plant stem. Stemflow yield and chemistry are the result of the interaction of many complex variables, including meteorological conditions, seasonality, species-specific traits, and canopy structure. By analyzing each separately, it may be possible to isolate their individual affects on stemflow production and chemistry. A comprehensive understanding of each influencing factor may result in accurate modeling of stemflow water and nutrient inputs into agricultural and forest soils. Modeling and scaling of stemflow for an array of watershed sizes is of critical importance because reliable management decisions must be based on the relative dominance of each interacting factor influencing stemflow production and chemistry. Black (1998) argued that hydrologists can contribute to sound environmental management practices by scaling hydrological processes to appropriate levels and better understanding the relative dominance and interaction among hydrological processes at the watershed scale.

Acknowledgements

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