THE QUANTITATIVE IMPORTANCE OF STEMFLOW:

AN EVALUATION OF PAST RESEARCH AND RESULTS FROM A STUDY IN LODGEPOLE PINE (*PINUS CONTORTA* VAR. *LATIFOLIA*) STANDS IN SOUTHERN BRITISH COLUMBIA

by

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ABSTRACT

Stemflow is a focused point source input of precipitation and nutrients at the base of a tree or plant, and can have a significant impact on site hydrology. A review paper examining the quantitative importance of stemflow, and a stemflow modelling paper focused on juvenile lodgepole pine are presented in this thesis. Stemflow production information from 145 different studies is presented in table format with the addition of author-calculated funnelling ratios and plateau funnelling ratios when applicable. Plateau funnelling ratios were calculated to provide an estimation of the rainfall depth required to satisfy the storage capacity of a tree. Reference tables were used to identify inter-climatic, inter-genera, and intra-genera variations in stemflow production. Plateau funnelling ratios were used to identify shortcomings in current canopy interception models. Finally, the reference tables were used to identify areas of the stemflow literature where knowledge remains fairly weak. To date, no known studies have modelled stemflow production for juvenile lodgepole pine (*Pinus contorta* var. *latifolia*). Meteorological conditions, tree characteristics, and stemflow were sampled for two juvenile lodgepole pine stands over the course of the 2009 growing season. Step-wise multiple regression was used to assess which meteorological and tree architecture variables influenced stemflow production for each research plot. Once predictor variables were identified, models were produced for each stand and a generic model was produced that applied to both plots. A model employing precipitation depth and crown projection area successfully explained 71.3 % of the variation in stemflow production from sampled trees.

Key words: Lodgepole pine (*Pinus contorta* var. *latifolia*), stemflow, stemflow funnelling ratio, plateau funnelling ratio, forest hydrology

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LIST OF SYMBOLS

#Brch – Number of branches

$\overline{D}$ – Average horizontal distance

$\overline{H}$ – Average height

A – Agroforestry

A – Canopy area

a – Slope

$Angle_{2/3}$ – Branching angle at two thirds the height of the tree

$Angle_{bottom}$ – Branching angle at the bottom of the tree

b – Y-intercept

BA – Basal area

C – Temperate coniferous and boreal

CBH – Circumference at breast height

CPA – Crown projection area

D – Temperate deciduous

D – Tree diameter at the base

DBH – Diameter at breast height

Density – Tree density

Diam. – Tree or shrub diameter

F – Funnelling ratio

H – Tree height

I – Rainfall intensity

LAI – Leaf area index

M – Mediterranean

M – Proximity metric

n – Number of samples

n_{stems} – Number of stems

P – Precipitation

P'_g – Rainfall depth required for canopy saturation

$\mathrm{P_A}$ – Annual rainfall

Pg – Rainfall

$\mathrm{P_S}$ – Study period rainfall

S – Semi-arid and arid

SF – Stemflow

T – Tropical

TF - Throughfall

V – Canopy volume

X – Mixed deciduous and coniferous stands

$\beta 1$ – Regression coefficient

$\beta 2$ – Regression coefficient

CHAPTER 1

INTRODUCTION

Rainfall intercepted by vegetation cover either passes through or drips from the canopy as throughfall, moves down the bole or stem of the vegetation and reaches the ground as stemflow, or remains on the vegetation canopy and is subsequently evaporated. Of the aforementioned components, stemflow has received the least attention in the hydrologic literature (Park and Hattori, 2002; Levia and Frost, 2003; Llorens and Domingo, 2007). This is likely due to stemflow being volumetrically insignificant when compared to throughfall and evaporation; however, its importance is far from irrelevant. The first research examining the movement of intercepted rainfall down a tree's bole was conducted in the late 19th and early 20th centuries by Hoppe (1896) and Horton (1919). This process was later termed "stemflow", and is the focus of this thesis.

Despite a lower volume of water when compared to the other components of the canopy water balance, stemflow is of hydrologic importance due to it being a focused point source input of water at the base of a tree or plant (Herwitz, 1986). A principle focus of this thesis deals with the stemflow funnelling ratio. The stemflow funnelling ratio was first introduced in 1986 by Herwitz (1986) as a measure of how efficient a tree or bush is at producing stemflow. The ratio is one that expresses the amount of water directed to the base of a tree or plant during a rainfall event relative to the volume of rainfall that would have been captured by an unobstructed rain gauge with a receiving area equal to that of the tree / plant basal area. The stemflow funnelling ratio is calculated as:

$$F = SF/(Pg \cdot BA) \tag{1.1}$$

where F is the funnelling ratio (dimensionless), SF is stemflow volume (L), Pg is rainfall (mm), and BA is the basal area of the tree's truck or shrub's stem (m^2).

Stemflow research has been conducted worldwide focusing on a large variety of species under varying climatic and hydrologic regimes. Findings have shown that stemflow can be of hydrologic and biogeochemical significance, at least in certain environments. Stemflow is an important source of moisture for plant growth and ground water recharge as highlighted by a number of studies (Voigt, 1960; Tanaka *et al*., 1996; Taniguchi *et al*., 1996; Whitford *et al*., 1997). For a *Pinus densiflora* (Japanese red pine) forest in Japan, Taniguchi *et al*. (1996) found that stemflow was responsible for 20 % of the groundwater recharge rate. Along with deriving the stemflow funnelling ratio, Herwitz (1986) found that large volumes of stemflow could overwhelm the infiltration capacity of soil and result in Hortonian overland flow and subsequently cause surface erosion. Once thought to only occur under rainfall conditions, Herwitz and Levia (1997) found that stemflow was also produced under winter conditions, with increased stemflow volumes associated with mixed precipitation. Stemflow has been found to be a concentrated source of nutrients and, in some cases, pollutants (Brinson *et al*., 1980; Chang and Matzner, 2000; Schroth *et al*., 2001; Johnson and Lehmann 2006). Brinson *et al*. (1980) found that stemflow contained high levels of organic carbon and phosphorus, 20.2 % and 16.8 %, respectively, of the total amount of organic carbon and phosphorus reaching the forest floor. Stemflow can be important not only for the producer, but also for surrounding vegetation. Stemflow and the nutrients contained within have been found to create a “fertile island” effect, resulting in vegetation growth around a stemflow producing tree or bush (Whitford *et al*., 1997). Stemflow models developed to date include a variety of different predictor variables and have been produced for a number of different tree and plant species. Depending on tree architecture and geographic location of the tree(s) studied, a number of different predictor variables were employed by each study. Branching angle (Herwitz, 1987; Návar, 1993; Martínez-Meza and Whitford, 1996), number of branches (Návar, 1993), tree height (Brown and Baker, 1970), storm duration and intensity (Brown and Baker, 1970; Crockford and Richardson, 2000), crown projection area (Brown and Baker, 1970; Aboal *et al*., 1999; Park and Hattori, 2001; Pressland, 1973), and bark roughness (Horton, 1919; Aboal *et al*., 1999), are just some of the variables that have been found to influence stemflow production across a number of different species. Due to the variety of variables included in models produced to date, it is difficult to transfer models between species. Also, when producing a model, it is important to consider a large array of predictor variables. The stemflow production ability of different species from around the globe, and the modelling of stemflow production for juvenile lodgepole pine are the foci of this thesis.

Chapter 2 is a comprehensive review paper of stemflow production information for research published prior to June 30, 2010. The goal of this paper was to compile information relating to stemflow production for as many tree and plant species as possible. Once compiled, this information was organized alphabetically by species within seven different climate and vegetation classifications for ease of reference. This information was then used to identify inter-climatic, inter-genera, and intra-genera variations in stemflow production. Stemflow funnelling ratios were calculated for studies that did not contain these metrics ratios, but contained the required information for their calculation. Plateau funnelling ratios, the point at which funnelling ratios plateau, and the associated rainfall depth, were calculated for entries that provided the necessary information. This comprehensive review of stemflow production information will aid future researchers and improve our understanding of inter- and intraspecific variations in stemflow production. Past reviews have been conducted that provided stemflow production information in table format, however, these tables simply summarized stemflow production information related to the author(s)' research or focused on a particular region.

Chapter 3 is a stemflow modelling paper based on original field observations conducted on the Bonaparte Plateau, north of Kamloops, British Columbia, Canada. The goal of this chapter was to model stemflow production for juvenile lodgepole pine. Two research plots were used to model stemflow production for trees with crown projected areas ranging from 0.1 to 3.5 m^3. The generic model produced explained 71.3 % of the variation in stemflow production for individual lodgepole pines, or for entire stands fitting the model criteria. In addition to the generic model, models for the individual research plots are also presented, along with the findings that canopy structure in combination with rainfall depth accurately explained variations in stemflow production for juvenile lodgepole pine.

The rationale for Chapter 3 was the lack of knowledge concerning juvenile lodgepole pine stemflow production, and the current mountain pine beetle (*Dendroctonus ponderosae*) epidemic impacting British Columbia. The mountain pine beetle epidemic is expected to kill 77 % of all merchantable pine in the Province by 2014 (BC Ministry of Water, Land and Air Protection, 2004; Walton *et al*., 2007). The landscape of the Interior of British Columbia will not only be changed visually for decades to come, site hydrology will also change drastically as mature stands are replaced by juvenile stands at various stages of regrowth. Past research has shown that mature lodgepole pine are inefficient stemflow produces and do not produce large volumes, however little is known about the stemflow production of juvenile lodgepole pines (Spittlehouse, 1998; McKee and Carlyle-Moses, 2010). Due to the shift in stand composition that will occur over the coming years, understanding how stands of juvenile lodgepole pine partition rainfall is important as this may have impacts on streamflow production and thus potentially impact water resource supplies and aquatic ecosystem health.

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CHAPTER 2

A SYNTHESIS AND EVALUATION OF PAST RESEARCH ON THE QUANTITATIVE IMPORTANCE OF STEMFLOW

INTRODUCTION

The first notable research examining the manner in which tree canopies partition rainfall was conducted in the late 19th and early 20th centuries by Hoppe (1896) and Horton (1919). These papers identified that a portion of intercepted rainfall was diverted down the trunk of the vegetation in question, a process later termed "stemflow". Despite recent studies and reviews that have highlighted the hydrologic importance of stemflow, it has received relatively little attention in the hydrologic literature when compared to the two other canopy water balance components: throughfall and canopy interception loss (Park and Hattori, 2002; Levia and Frost, 2003; Llorens and Domingo, 2007). Due to its delivery being concentrated at the base of vegetation, stemflow has been found to be an important point source input of water for soil moisture and groundwater recharge (Voigt, 1960; Tang, 1996; Taniguchi *et al*., 1996), a cause of Hortonian overland flow in certain environments (Herwitz, 1986), and a significant source of nutrients and pollutants (Brinson *et al*., 1980; Price and Watters, 1989; Chang and Matzner, 2000; Johnson and Lehmann, 2006). The ability of vegetation to concentrate stemflow at their bases can be expressed quantitatively using the stemflow funnelling ratio (Herwitz, 1986):

$$F = SF/(Pg \cdot BA) \qquad (2.1)$$

where F is the funnelling ratio (dimensionless), SF is stemflow volume (L), Pg is rainfall (mm), and BA represents the tree basal area (m^2).

Carlyle-Moses and Price (2006), in a northern hardwood stand in southern Ontario under growing season conditions, found that stemflow funnelling ratios increased with increasing rainfall depth until a peak was reached with funnelling ratios declining with greater rainfalls. Similar results have been found for semi-arid shrubs in China (Li *et al*., 2008) and in tropical tree plantations in Panama (Carlyle-Moses *et al*., 2010).

Carlyle-Moses and Price (2006) suggest that the peak funnelling ratio is reached once the canopy becomes saturated and all areas capable of producing stemflow are doing so at their maximum capacity. At greater rainfall depths the funnelling ratios should be expected to decline since the numerator in Eq. 2.1 will be limited by the contributing area of the canopy, while the denominator will increase in a linear fashion. Thus, the derivation of stemflow funnelling ratios is not only of importance with regards to determining the quantitative significance of stemflow as a point source of water for soil moisture, groundwater and plant growth, but may also be used to determine the rainfall depth required for the complete saturation of vegetation canopies and thus can aid in canopy interception loss process and modelling studies (e.g. Carlyle-Moses *et al*., 2010).

A number of stemflow review papers have been published to date. Levia and Frost (2003) provided a comprehensive overview of stemflow research by summarizing and evaluating the different aspects of stemflow research. Levia and Frost (2003) also provided recommendations for future research by drawing attention to areas where further study is required and highlighting those areas that have already received considerable attention. Other review papers and studies containing reviews have taken a more focused approach, examining specific regions, climates, or species. Llorens and Domingo (2007), for example, provided an in-depth review of stemflow research conducted in the Mediterranean. Wei *et al*. (2005) reviewed a number of stemflow studies conducted in China, while Johnson and Lehmann (2006) provided a review of several different species under differing environmental conditions. Zinke (1967) reviewed studies examining canopy interception in the United States, which included stemflow production information for a number of different species. Barbier *et al*. (2009) reviewed the canopy water balance differences between coniferous and broadleaved species. All of these reviews provided valuable information regarding stemflow production; however, none provided a comprehensive summary of stemflow production data. Llorens and Domingo (2007) provided vast amounts of data for the Mediterranean; however, they do not employ the stemflow funnelling ratio in their paper. A comprehensive stemflow production review utilizing both stemflow as a percentage of rainfall and stemflow funnelling ratios has not been undertaken to date and would therefore be a valuable addition to the current knowledge base concerning this canopy water balance component.

It was the goal of this review to provide a reference that summarizes the ability of different tree species to produce stemflow. The purpose of this review was fourfold: (1) to review the stemflow literature for papers containing information regarding stemflow production; (2) to develop stemflow equations if the information was provided and the author(s) had not already done so; (3) to calculate season-long funnelling ratios and plateau funnelling ratios if the required information was provided by the author(s); (4) to compile information relevant to a species' ability to produce stemflow into table format. It is my objective that a stemflow reference guide will be used by future researchers not only to save time when conducting research, but also to aid in identifying inter- and intraspecific variations in stemflow production by comparing studies of similar species.

METHODS

The Web of Science database by ISI Web of Knowledge and Google Scholar were searched using the terms "stemflow", "stem flow", "funnelling ratio", and "funneling ratio". Over 600 publications containing one or more of the above terms were identified. Just over 100 of these publications published prior to June 30, 2010 were included in this review. The reference sections of the publications found in the aforementioned databases were then inspected for relevant studies not found in the academic database search. Prior to their inclusion in this review, publications were scrutinized to ensure that the data contained within was suitable for comparison with other studies. In total, 145 studies containing stemflow data for a variety of species were included in this review. Publications were examined for stemflow production information, specifically: stemflow equations (relating stemflow to another variable), stemflow funnelling ratios, the percentage of rainfall that became stemflow, and the information required to produce a stemflow equation or stemflow funnelling ratio. If a publication contained at least one of the aforementioned pieces of information it was included in the reference table along with relevant stand, meteorological, and geographic information including: tree species, geographic location, climate, tree diameter, tree density, basal area, annual precipitation, study period precipitation, and, finally, the citation. Information originally published in imperial units was converted to metric units before being entered into the reference table; any data that underwent conversion was followed by a superscript “con”.

If a stemflow equation was not provided by the author(s) of a specific study one was calculated if individual event rainfall depth and accompanying stemflow measurements were provided. Any calculated stemflow equations were followed by a superscript “calc” in the reference tables provided in the Results section of this review. For the purpose of inter- and intraspecific comparisons, stemflow funnelling ratios were calculated when possible if the author(s) of a specific study did not provide them. Calculated funnelling ratios were followed by a superscript “calc” in the reference tables. Stemflow funnelling ratios were calculated in two ways depending on the data provided by the author(s): if study period rainfall depth, percentage of rainfall that became stemflow, and stand basal area were provided, then a stand level funnelling ratio for the entire research period was calculated using Eq. 2.1 (e.g. 64.3^{calc}); if a stemflow equation relating stemflow volume or depth to rainfall depth was provided in conjunction with the basal area for a stand or individual tree then a range of funnelling ratios were calculated using rainfall depth values starting at 1 mm and increasing by 1 mm rainfall increments until the funnelling ratios “plateaued”. For the purposes of this review the point at which funnelling ratios plateaued occurred when the funnelling ratio value increased by < 1 % compared to its previously calculated value at a rainfall depth 1 mm less. Once the plateau was identified, the corresponding funnelling ratio and rainfall depth were recorded in the reference table (e.g. 48.6 at 35 mm^{calc}). Based on the results of Carlyle-Moses and Price (2006), these plateau values and associated rainfall depths are assumed to be the maximum funnelling ratios produced when the canopy reaches full saturation and the required rainfall to saturate the canopy, respectively.

Some entries in the reference tables contained more than one species; this is because certain studies only provided multi-species stand scale stemflow production data. For linear equations with a positive y-intercept, plateau values were not calculated because a positive y-intercept implies that a tree has no storage capacity. If the information required to calculate both the season-long and plateau funnelling ratios was provided, both were included in the reference tables.

Special attention was paid to the methodology and results sections of selected papers to determine if the stemflow information presented was at the individual or stand scale level. Studies that provided stemflow information for an individual tree had “Lone” entered under the tree density column of the reference tables and studies that provided stemflow information for multiple individuals but with no reference to the entire stand were identified as “Lone trees” or “Lone shrubs”. All other entries not marked as either “Lone”, “Lone trees”, or “Lone shrubs” focused on the stand scale. In addition to the percentage of rainfall that became stemflow for the study period or a range of values if the author(s) did not provide a study period value, other information can be found in the SF (%) column. The percentage of rainfall that became stemflow for specific periods or stand conditions was provided for some studies, for example, leaved and leafless or growing and dormant season periods, unlogged and logged, or summer and winter conditions. In addition to season-long funnelling ratios and plateau funnelling ratios, the funnelling ratio (F) column contains additional information for some studies. The event high funnelling ratio, representing the maximum funnelling ratio observed for an individual tree/shrub for a single event, was recorded for some entries. If multiple stemflow percentages, funnelling ratios, or formulae are contained within one entry this is because the entry contains information for multiple trees of the same species or data for multiple years.

Once the comprehensive reference table was compiled, the information it contained was organized by climate and vegetation type. Seven classifications were used to organize the 326 entries: temperate deciduous (D), temperature coniferous and boreal (C), mixed deciduous and coniferous stands (X), tropical (T), Mediterranean (M), semi-arid and arid (S), and agroforestry (A). For each climate/vegetation classification two tables were produced: one table containing stand information along with author(s); the other containing stemflow production and meteorological data. Entries were sorted alphabetically by species and given a code for ease of referencing and comparison between tables. Within the seven categories, average, median, and a range of values were calculated for stemflow and funnelling ratio values and compared at the genera and category levels. If a single entry contained multiple years of data an average was produced across those years for comparison with other entries. If a single entry contained only a range of stemflow data it was not included in comparative analyses.

RESULTS

1. Temperate deciduous

From the available literature, stand-scale stemflow was found to average 5.1 % (median = 3.9 %, *n* = 34) of growing-season or annual rainfall in temperate deciduous forests, ranging from < 0.5 % in a *Crataegus sativa – Acer campestre* stand in southwest England (Herbst *et al*., 2006, D10) to 17.1 % in an evergreen-broadleaf forest in Osaka, Japan (Masukata *et al*., 1990, D11). Mean stemflow as a percentage of growing-season or annual rainfall from nine studies conducted in *Quercus* genera dominated stands was 6.0 % (median = 4.0 %, range = 0.5 – 15.5 %), while it accounted for an average of 5.0 % (median = 5.0 %, range = 2.0 – 9.6 %, *n* = 5) in *Fagus* forests. A notably high annual stemflow value of 26 % was reported for a lone *Stewartia monadelpha* in Japan (Liang *et al*., 2009, D63). Additional stemflow percentage values for other genera dominated and mixed deciduous stands are presented in Table 2.1 and Table 2.2 found in this chapter's appendix.

The proportion of rainfall that contributes to stemflow typically increases under leafless periods compared to leafed periods. For example, in a *Q. alba – Q. velutina* forest in Rhode Island stemflow increased from 3.9 % of rainfall during the growing season to 4.8 % under dormant conditions (Brown and Barker, 1970, D48). Similar results were also found in a *Nyssa aquatic - Taxodium distichum - Fraxinus caroliniana* stand in North Carolina, where stemflow averaged 2.5 % of the 639 mm of rainfall under leafed-conditions and 4.5 % of the 466 mm of rainfall during the leafless period of the study (Brinson *et al*., 1980, D 42). Calculated stand-scale funnelling ratios for the latter stand increased from 3.6 during the leaved period to 6.5 during the leafless period.

Calculated and author-provided stand-scale growing season or annual funnelling ratios in temperate deciduous forests averaged 26.6 (median = 15.6, *n* = 12), ranging from 2.3 in a *F. orientalis* forest in Nowshahr, Iran (Ahmadi *et al*., 2009, D21) to 64.3 in a *Alnus glutinosa* forest in Lancaster, England (Cape *et al*., 1991, D05). Growing season or annual funnelling ratios for *Quercus* stands averaged 36.8 (median = 50, *n* = 5), ranging from 7.6 to 61.3. A study examining individual *Q. rubra* reported season-long funnelling ratios averaging 8.8 (median = 7.6, *n* = 7), with a range of 6.1 to 13.7 (Carlyle-Moses and Price, 2006). Growing season funnelling ratios averaged 12.1 (median = 8.6, range = 2.3 – 25.4, *n* = 3) for *Fagus* stands, and 32.7 (median = 32.4, range = 15.8 – 47.2, *n* = 9) for individual trees. An entry for *Acer saccharum* (Carlyle-Moses and Price, 2006, D03) had a notably high season-long funnelling ratio of 108.6 for an individual tree, however the average season-long funnelling ratio for all *A. saccharum* trees included in the study averaged 31.6 (median = 21.6, *n* = 7).

For temperature deciduous stands, calculated plateau funnelling ratios for the growing season averaged 23.4 at 17 mm (median = 17.6 at 15 mm, *n* = 4) with a range of 9.0 at 12 mm for a mixed deciduous forest in Ontario, Canada (Price and Carlyle-Moses, 2003, D39), to 48.6 at 35 mm for a stand of *A. glutinosa* in Lancaster, England (Cape *et al*., 1991, D05). Calculated plateau funnelling ratios for individual trees during the growing season were much higher than those for stands. Plateau funnelling ratios averaged 40.2 at 15 mm (median = 38.7 at 13 mm, *n* = 9), ranging from 1.6 at 27 mm for a lone *Liriodendron tulipifera* in Maryland (Levia *et al*., 2010, D30) to 91.5 at 7 mm for a lone *Q. suber* in California (Xiao *et al*., 2000, D62). Growing season plateau funnelling ratios were calculated for three studies that examined individual *Fagus* which averaged 55.0 at 13 mm (median = 50.0 at 13 mm, *n* = 4), ranging from 42.1 at 16 mm (Staelens *et al*., 2008, D27) to 82.3 at 13 mm (André *et al*., 2008, D23) for two *F. sylvatica* studies.

Quercus and *Fagus* are the two genera in temperate deciduous forests that have received the greatest study in regards to stemflow with 16 entries each (Table 2.1; Table 2.2). *Liriodendron*, *Acer*, *Nothofagus*, *Populus*, and *Betula* also have multiple entries, albeit less than *Quercus* and *Fagus*, while other genera, including *Alnus* and *Stewartia* have only one entry. Some studies included a mix of genera with no discernable means of separating the results in a genera specific fashion.

2. Temperate coniferous and boreal

For studies conducted in temperate coniferous and boreal stands, study period stand scale stemflow averaged 5.0 % (median = 3.7 %, *n* = 50) of rainfall, with a range of < 0.1 % for a stand of *Larix cajanderi* in Siberia, Russia (Toba and Ohta, 2005, C11) to 27 % for a stand of *Picea sitchensis* in Dumfriesshire, Scotland (Ford and Deans, 1978, C21). Mean stemflow as a percentage of rainfall from 19 studies conducted in *Pinus* dominated stands was 4.2 % (median = 2.7 %, range = < 0.1 – 15 %, *n* = 23). Studies examining *Picea* and *Larix* reported season averages above and below *Pinus*, respectively. Average stemflow as a percentage of rainfall from nine studies of *Picea* dominated stands was 8.8 % (median = 6.4 %, range = 0.5 – 27 %, *n* = 9), while it accounted for 2.0 % (median = 1.6 %, range = < 0.1 – 4 %, *n* = 5) for four studies of *Larix* dominated stands. The two highest average annual stemflow values of 27.0 % (Ford and Deans, 1978, C21) and 16.7 % (Teklehaimanot *et al*., 1991, C24) were reported from *P. sitchensis* dominated stands in Scotland. Additional stemflow percentage values for other genera dominated and mixed temperate coniferous stands are presented in Tables 2.3 and 2.4.

Calculated and study provided stand-scale growing season or annual funnelling ratios in temperature coniferous and boreal forests averaged 22.1 (median = 14.4, *n* = 12), ranging from 0.9 for a stand of *P. abies* in Vosges, France (Viville *et al*., 1993, C16) to 69.8 for a stand of *Ilex pedunculosa* in Kyoto, Japan (Park and Hattori, 2002, C09). In comparison to temperate deciduous stands, little stemflow funnelling ratio data has been reported for temperate coniferous and boreal forests. Two studies (Cape *et al*., 1991;

McKee and Carlyle-Moses, 2010) reported season-long funnelling ratio averages for *Pinus* of 19.7 (median = 17.2, range = 14.9 – 34.1, *n* = 4) and two studies (Cape *et al*., 1991; Viville *et al*., 1993) for *Picea* averaging 16.1 (median = 10.4, range = 0.9 – 37.1, *n* = 3). A nine year old stand of *Chamaecyparis obtuse* (Murakami, 2009, C05) had a notably high season-long funnelling ratio of 81.3, however, over the next three years of stand growth the season-long funnelling ratio dropped to 29.0.

Calculated plateau funnelling ratios for temperate coniferous and boreal stands during the growing season averaged 12.4 at 51 mm (median = 8.8 at 47 mm, *n* = 7), ranging from 0.8 at 59 mm for a stand of *L. decidua* (Cape *et al*., 1991, C13) to 26.1 at 39 mm for a stand of *P. sylvestris* (Cape *et al*., 1991, C47). Three stands of *P. sylvestris* had average growing season plateau funnelling ratios of 15.8 at 51 mm (median = 13.7 at 39 mm, *n* = 3) and average winter plateau funnelling ratios of 22.6 at 35 mm (median = 19.2 at 37 mm, *n* = 3).

Pinus was found to be the dominant genus studied within the temperate coniferous and boreal stands examined, followed by *Picea* (Table 2.3; Table 2.4). *Larix*, *Pseudotsuga*, and *Abies* all had multiple entries; however they received far less attention when compared to *Pinus*.

3. Mixed deciduous and coniferous stands

Studies that presented stemflow values for mixed coniferous and deciduous stands were rare, with most studies providing data for individual species if the study stand contained both coniferous and broadleaf species. Studies that did not separate data for individual species within a mixed stand were assigned to this category. Stemflow as a percentage of annual rainfall for four studies averaged 2.6 % (median = 2.5 %, range = 0.5 – 7 %, *n* = 5). A study in a coastal redwood forest in California (Reid and Lewis, 2009, X05) reported the only study period funnelling ratio in this category of 2.6. Supplementary information for the presented stemflow data can be found in Tables 2.5 and 2.6.

4. Tropical

For interception studies conducted in tropical climates, annual stemflow values at the stand level averaged 4.0 % (median = 1.6 %, *n* = 46), ranging from < 0.1 % for a tropical montane rainforest in Columbia (Veneklass and Van Ek, 1990 as cited in Levia and Frost, 2003, T57) to 30.5 % for a subtropical forest in Okinawa, Japan (Xu *et al*., 2005, T05). Study period stemflow values from studies that examined individual trees averaged 8.2 % (median = 2.7 %, *n* = 17), ranging from 0.01 % for a lone *Cecropia peltata* in Puerto Rico (Holwerda *et al*., 2006, T06) to 39.7 for a lone *Elaeocarpus foveolatus* in Queensland, Australia (Herwitz, 1986, T15). Additional stemflow percentage values for other genera dominated and mixed tropical stands are presented in Tables 2.7 and 2.8.

Calculated and published study period stemflow funnelling ratios at the stand level averaged 18.7 (median = 12.4, *n* = 8) with a range of 0.8 for a natural montane forest in Central Sulawesi, Indonesia (Dietz *et al*., 2006, T32) to 53.0 for a subtropical forest in Okinawa, Japan (Xu *et al*., 2005, T05). Study period funnelling ratios for individual trees averaged 41.2 (median = 11.0, *n* = 35), ranging from 0.5 for a *Dacryodes excelsa* in Puerto Rico (Holwerda *et al*., 2006, T15) to 275.7 for a *Prestoea montana* in Puerto Rico (Holwerda *et al*., 2006, T44).

At the stand scale only two plateau funnelling ratios could be calculated, 3.1 at 24 mm for a terra firme rainforest in Manus, Brazil (Cuartas *et al*., 2007, T58) and 8.7 at 22 mm for a lowland tropical forest in Sarawak, Malaysia (Manfroi *et al*., 2004; Manfroi *et al*., 2006). At the individual level, plateau funnelling ratios averaged 46.8 at 23 mm (median = 11.2 at 19 mm, *n* = 27), ranging from 0.7 at 34 mm for a *D. excelsa* in Puerto Rico (Holwerda *et al*., 2006, T11) to 272.8 at 2 mm for a *P. montana* in Puerto Rico (Holwerda *et al*., 2006, T40).

5. Mediterranean

Studies conducted in regions with Mediterranean climates reported annual stand scale stemflow values that averaged 4.4 % (median = 3.0 %, *n* = 77), ranging from 0.2 %

for a stand of *Eucalyptus melliodora* in Canberra, Australia (Crockford *et al*., 1996, M09) to 22.0 % for a stand of *Juniperus oxycedrus* in El Ardal, Spain (Belmonte, 1997; Belmonte and Romero, 1998 as cited by Llorens and Domingo, 2007, M25). Study period stemflow values for individual trees averaged 11.6 % (median = 4.8 %, *n* = 10), ranging from 0.6 % for a *Q. pyrenaica* in Villasrubias, Spain (Moreno *et al*., 2001 as cited by Llorens and Domingo, 2007, M84) to 42.5 % for a *Rosmarinus officinalis* in El Ardal, Spain (Belmonte, 1997; Belmonte and Romero, 1998 as cited by Llorens and Domingo, 2007, M86). Annual stemflow values for stands of *Pinus* averaged 4.4 % (median = 3.0 %, range = 0.3 – 22.0 %, *n* = 29), while stands of *Quercus* averaged 3.5 % (median = 2.8 %, range = 0.3 – 12.5 %, *n* = 16). Stemflow values from four studies of *Eucalyptus* averaged 2.2 % (median = 2.9 %, range = 0.2 – 4.0 %, *n* = 12), while five studies of *Fagus* averaged 7.9 % (median = 6.5 %, range = 1.1 – 20.4 %, *n* = 8). Additional stemflow percentage values for other genera dominated and mixed Mediterranean stands are presented in Tables 2.9 and 2.10.

Calculated and previously published stand scale season-long funnelling ratios for Mediterranean stands averaged 14.8 (median = 14.7, *n* = 51), ranging from 1.7 for *P. sylvestris* stand in the Sierra de la Demanda (Santa Regina and Tarazona, 2001, M63) to 41.1 for *Q. cerris* in south-western Spain (Moreno *et al*., 2001 as cited by Llorens and Domingo, 2007, M68). Individual trees averaged 47.8 (median = 34, *n* = 13), ranging from 16.7 to 137 for two *Q. ilex* individuals (Bellot and Escarré, 1998, M70). Season-long funnelling ratios for *Pinus* dominated stands averaged 16.1 (median = 15.4, range = 1.7 – 32, *n* = 18), while stands of *Quercus* averaged 13.6 (median = 11.3, range = 3.1 – 41.1, *n* = 11). In contrast to the aforementioned *Quercus* stands, individual *Quercus* had average study period funnelling ratios of 42.5 (median = 30.5, range = 16.7 – 137, *n* = 10). Study period stand scale funnelling ratios from *Eucalyptus* averaged 13.6 (median = 13.1, range = 4 – 21, *n* = 10), while *Fagus* stands averaged 16.4 (median = 11.9, range = 2.7 – 39.1, *n* = 4).

For Mediterranean vegetation at the stand level, only three plateau funnelling ratios were calculated averaging 21.9 at 15 mm. Plateau funnelling ratios for individual trees averaged 62.4 at 26 mm (median = 47.9 at 29, *n* = 17), ranging from 16.4 at 29 mm for *Q. ilex rotundifolia* (Bellot and Escarré, 1998, M70) to 137.9 at 17 mm for *E. globulus* (Bellot and Escarré, 1998, M01). Plateau funnelling ratios for individual *Phyllirea media* averaged 76.1 at 27 mm (median = 77.6 at 30 mm, range = 19.9 at 22 – 118.1 at 9 mm, *n* = 5), while individual *Quercus* averaged 43.3 at 27 mm (median = 27.9 at 29 mm, range = 16.4 at 29 – 129.6 at 9 mm, *n* = 9). Forests comprised predominantly of *Pinus* are the most studied in Mediterranean climates (30 entries in total, Table 2.9; Table 2.10). *Quercus*, *Eucalyptus*, and *Fagus* are also well represented in this category with 18, 11, and 8 entries, respectively.

6. Arid and semi-arid environments

Stemflow values for arid and semi-arid communities averaged 5.9 % (median = 5.9 %, *n* = 18), ranging from 0.7 % for *Grevillea robusta* in Machakos, Kenya (Jackson, 2000, S16) to 18.0 % for *Acacia aneura* in Queensland, Australia (Pressland, 1973, S01). Individual plants had higher values averaging 7.7 % (median = 6.3 %, *n* = 10), ranging from 0.6 % for a *Prosopis laevigata* in Nuevo Leon, Mexico (Návar, 1993; Návar and Bryan, 1990, S28) to 20 % for a *Anthyllis cytisoides* in Almería, Spain (Domingo *et al*., 1994; Llorens and Domingo, 2007, S05). Additional stemflow percentage values for other genera dominated and mixed arid or semi-arid communities are presented in Tables 2.11 and 2.12.

Calculated and previously published season-long funnelling ratios at the community level averaged 61.3 (median = 51.0, *n* = 8) with a range of 21.1 for a matorral community of the Sierra Madre Oriental , Mexico (Carlyle-Moses, 2004, S22) to 153.5 for *Caragana korshinskii* in Gaolan, China (Li *et al*., 2008, S08). Only three entries provided funnelling ratio data for individual plants, averaging 28.7 (median = 16.8, *n* = 3) and ranging from 11.7 for a *A. farnesiana* in Nuevo Leon, Mexico (Návar, 1993; Návar and Bryan, 1990, S02) to 57.7 for a *D. texana* in Nuevo Leon, Mexico (Návar, 1993; Návar and Bryan, 1990, S13). One plateau funnelling ratio was calculated for a tree in an arid or semi-arid climate. A lone *Ficus benjamina* in an urban setting (Queretaro City, Mexico) had a plateau funnelling ratio of 16.8 at 5 mm (Guevara-Escobar *et al*., 2007, S14).

7. Agroforestry

Eight studies that examined a variety of crop species reported an average study period stemflow value of 7.3 % (median = 1.5 %, *n* = 14) with a range of 0.6 % for a plot of *Zea mays* and *Grevillea robusta* in Kenya, Africa (Jackson, 2000, A12) to 24.7 % for a plantation of *Bactris gasipaes* in Manaus, Brazil (Schroth *et al*., 1999; Schroth *et al*., 2001, A02). Calculated or previously published study period funnelling ratios for three studies averaged 10.8 (median = 8.1, *n* = 5), ranging from 3.8 for an agroforest in Central Sulawesi, Indonesia (Dietz *et al*., 2006, A01) to 25.3 for a *Musa* sp. plantation in Guadeloupe (Cattan *et al*., 2007, A08). Supplementary information for the presented stemflow data can be found in Tables 2.13 and 2.14.

DISCUSSION

Carlyle-Moses and Price (2006) were the first to note that stemflow funnelling ratios could be used to determine the depth of rainfall required to satisfy the storage capacity of a tree. Once the canopy of a tree has reached complete saturation, the stemflow funnelling ratio will plateau and decrease if rainfall continues. The rainfall depth that corresponds to the funnelling ratio plateau indicates the point at which the canopy has reached complete saturation. Calculated plateau funnelling ratios are only as accurate as the linear equations on which they are based; therefore, the rainfall depth provided with each plateau funnelling ratio is an estimation of the point at which complete canopy saturation occurred. Holwerda *et al*. (2006, T40) provided a linear equation that produced a plateau funnelling ratio of 272.8 at 2 mm. Such a small storage capacity is either due to large amounts of scatter not reflected in the linear equation, or the plant in question had a much lower storage capacity compared to similar plants included in the study. The limitations of using a linear equation to determine funnelling ratio plateaus can be seen in some table entries where the author provided season-long funnelling ratios that were higher than calculated plateau values. Bellot and Escarré (1998) provided season-long funnelling ratios for *Q. ilex* (M70) which in some instances were up to 7 times higher than the plateau funnelling ratio. Calculated plateau values may in reality be higher or lower due to scatter that is not reflected in a linear equation but is observed when values are graphed.

The use of plateau funnelling ratios to identify the rainfall depth required to satisfy the storage capacity of a tree has implications for canopy water balance modelling. Current canopy water balance models underestimate the amount of rainfall required to reach complete canopy saturation (Carlyle-Moses and Price, 2007). Carlyle-Moses *et al.* (2010) suggested that stemflow funnelling ratios could be used to provide a more accurate estimation of the rainfall depth required to saturate the canopy (P'_g). Using the improved Gash model, Carlyle-Moses *et al.* (2010) produced P'_g values for five species in a tropical forest in Panama. Calculated P'_g values for *A. mangium*, *G. sepium*, *G. ulmifolia*, *O. pyramidale*, and *P. quinata* were 1.33 mm, 1.10 mm, 1.18 mm, 0.93 mm, and 1.00 mm, respectively, however, author calculated funnelling ratios plateaued at rainfall depths of 14.5 mm, 18.3 mm, 18.8 mm, 14.8 mm, and 26.8 mm, respectively. The calculated plateau funnelling ratios and the accompanying rainfall depths found in this paper further support the initial findings by Carlyle-Moses and Price (2006) that stemflow funnelling ratios increase until a threshold rainfall depth is reached, subsequently identifying the rainfall depth required for canopy saturation.

Based on the available data, genera comparisons between climate classes were only possible for *Quercus*, *Fagus*, and *Pinus*. Intra-genera analyses showed that there was no statistical difference for *Quercus* ($p = 0.23$), *Fagus* ($p = 0.28$), and *Pinus* ($p = 0.77$) between the different climate/vegetation classifications. *Quercus* in the temperate deciduous class had stemflow values that averaged 5.7 % (median = 4.0 %) while *Quercus* in the Mediterranean class averaged 3.5 % (median = 2.8 %). Ranges reported in both classes were similar at 0.5 – 15.5 % and 0.3 – 12.5 %, respectively. *Fagus* in the temperate deciduous class averaged 5.0 % (median = 5.0 %) while Mediterranean *Fagus* values averaged 7.9 % (median = 6.5 %). Values for *Fagus* were reported at 2.0 – 9.6 %

for temperate deciduous and 1.1 – 20.4 % for Mediterranean. In keeping with the findings for broadleaved genera, *Pinus* varied only slightly between classes. Temperate coniferous *Pinus* had stemflow values that averaged 4.1 % (median = 2.7 %) while Mediterranean values averaged 4.4 % (median = 3.0 %). Reported temperate coniferous and Mediterranean *Pinus* values had ranges of < 0.1 – 14.0 % and 0.3 – 22.0 %, respectively.

Inter-climatic variation between stemflow values did not vary as greatly as expected and no statistical difference was observed between climate/vegetation classifications. Average stemflow values for climate classes ranged from 2.6 % for mixed stands to 7.3 % for agroforestry, while median values ranged from 1.5 % for agroforestry to 5.9 % for semi-arid and arid environments. Excluding the classes with limited entries (agroforestry and mixed stands) average stemflow values ranged only 1.9 %, from 4.0 % for Tropical to 5.9 % for arid and semi-arid communities; however, median values had a range of 4.3 %. Values for temperate deciduous stands were expected to differ from temperate coniferous and boreal stands; however, as previously stated, no statistical difference was observed (p = 0.90). Both categories had similar reported stemflow values, averaging 5.1 % (median = 3.9 %) and 5.0 % (median = 3.7 %), respectively. Reported stemflow funnelling ratios for these two classes were also very similar with an average of 26.6 (median = 15.6) for temperate deciduous stands and 22.1 (median = 14.4) for temperate coniferous and boreal stands. These findings are not in keeping with those of Barbier *et al*. (2009) that found broadleaved species to have higher stemflow values when compared to coniferous species. Similar average values for temperate deciduous and temperate coniferous and boreal stands presented in this review may be due in part to an inherent bias. Only publications containing measured stemflow data were included, therefore those that stated stemflow was insignificant or used findings from a previous study were given no weight. From the available literature it appears that the majority of water balance studies that do not measure stemflow do so for coniferous stands (Baker *et al*., 1985; Fenn *et al*., 2000; Gholz *et al*., 1985; Johannes *et al*., 1986; Lankreijer *et al*., 1999; Pypker *et al*., 2005). This trend is due to the generalization that all mature conifers have low stemflow production, and because some studies employ data from previous studies due to similarities in location or vegetation.

CONCLUSION

Stemflow production data for a multitude of tree and shrub species was organized into table format totalling 326 entries. Information was sorted alphabetically by species and given a reference code within seven different climate and vegetation classifications. Reference tables were designed in such a way that future researchers will be able to quickly access information of interest to aid in comparisons between differing studies and species. Stemflow production was found to be highly variable for categories with a large number of entries; these findings are in keeping with the findings of Llorens and Domingo (2007) for studies conducted in the Mediterranean.

As noted by Llorens and Domingo (2007) a lack of standardization makes combining and comparing information in a comprehensive review difficult. Specifically, the way in which stemflow production is reported yields problems because stemflow as a percentage of rainfall cannot be compared directly to a funnelling ratio. The funnelling ratio is the superior method for reporting stemflow production when compared to reporting stemflow as a percentage of gross rainfall, however, stemflow as a percentage of gross rainfall is a more widely used method. This is partly due to the fact that the funnelling ratio was not introduced until 1986 (Herwitz, 1986). It is paramount that authors report detailed stand characteristics and stemflow funnelling ratios along with percentages of rainfall that became stemflow. Detailed stand characteristics allow for more accurate comparisons between studies and take up little space in one’s publication. Stemflow funnelling ratios should be reported because they aid in comparisons between individual trees or stands. The stemflow funnelling ratio allows for the assessment of stemflow production efficiency across species due to the inclusion of basal area in the funnelling ratio calculation.

A review of the information contained within the reference tables highlighted several areas of stemflow research that remain understudied. As noted by Levia and Frost

(2003), knowledge regarding winter stemflow generation for both deciduous and coniferous species remains weak to date. In temperate coniferous climates, our knowledge of stemflow production for genera other than *Picea*, *Pinus*, *Pseudotsuga*, *Larix*, and *Abies* is limited. Studies of deciduous species focused heavily on *Quercus* and *Fagus*, therefore future research involving different deciduous genera would add new information to the existing stemflow literature. Due to the species diversity found in tropical forests these ecosystems require more attention to further our understanding of interspecific variation in stemflow production. However, it is understandable that tropical forests with high species diversity have received less attention when compared to other forest types due to the logistical challenges of accurately sampling stemflow in these diverse forests.

Stemflow can be beneficial or detrimental to agriculture depending on differing circumstances, therefore, the further examination of rainfall portioning for agroforests and crop species is recommended. For many tree and bush species found in the Interior of British Columbia the stemflow literature is lacking. Particularly abundant, the sagebrush (*Artemisia tridentata*) has received no attention in the stemflow literature; however, other members of the genera have been examined in China (Yang *et al*., 2008). Pine species found in the Interior of British Columbia have also received little attention when compared to other species in the genera. Due to the hydrologic importance of stemflow it is paramount that we continue to enhance the stemflow literature by examining species and aspects of stemflow production that have received little or no attention.

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APPENDIX – REFERENCE TABLES

Table 2.1. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for temperate deciduous studies.

Code	Species	Location	Diam. (cm)	Density (Trees/ha)	BA (m^2/ha)	Author
D01	*Acer rubrum*	New Brunswick, Canada	23.0	2470	-	Mahendrappa (1974)
D02	*Acer rubrum*	Eastern Kentucky, USA	22.2 ± 0.6	403	1.1	Alexander and Arthur (2010)
D03	*Acer saccharum*	Mississauga, Ontario, Canada	-	Lone trees	8.9	Carlyle-Moses and Price (2006)
D04	*Aesculus californica* *Ceanothus cuneatus*	California, USA	-	-	-	Rowe (1948) (Zinke, 1967)
D05	*Alnus glutinosa*	Lancaster, England	-	2510	14	Cape *et al*. (1991)
D06	*Betula papyrifera*	New Brunswick, Canada	15.0	4303	-	Mahendrappa (1974)
D07	*Betula platyphylla*	Mao'er Shan, China	-	-	-	Wei & Zhou (1991) (Wei *et al*., 2005)
D08	Broad-leaved deciduous forest	Massachusetts, USA	-	Lone trees	-	Levia (2004)
D09	*Castanea sativa* *Quercus rubra*	Bristol, UK	-	632	-	Davie and Durocher (1997)
D10	*Crataegus monogyna* *Acer campestre*	Swindon, U.K.	-	-	-	Herbst *et al*. (2006)
D11	Evergreen-broadleaf forest	Osaka, Japan	10 - 20	767	-	Masukata *et al*. (1990)
D12	*Fagus grandifolia*	Mississauga, Ontario, Canada	-	Lone trees	3.3	Carlyle-Moses and Price (2006)
D13	*Fagus grandifolia*	Maryland, USA	74.9	Lone	-	Levia *et al*. (2010)
D14	*Fagus grandifolia*	Maryland, USA	10.3	Lone	-	Levia *et al*. (2010)
D15	*Fagus grandifolia*	New Haven, Connecticut	15.2	-	-	Voigt (1960)
D16	*Fagus grandifolia*	Maryland, USA	14.4	Lone	-	Van Stan and Levia (2010)
D17	*Fagus grandifolia*	Maryland, USA	29.6	Lone	-	Van Stan and Levia (2010)
D18	*Fagus grandifolia*	Maryland, USA	48.6	Lone	-	Van Stan and Levia (2010)
D19	*Fagus grandifolia*	Maryland, USA	-	Lone	-	Van Stan and Levia (2010)

D20	*Fagus grandifolia* *Acer saccharum* *Betula alleghaniensis*	New Hampshire, USA	-	1651^{con} 1458^{con} 1789^{con}	32.8^{con} 30.3^{con} 29.6^{con}	Leonard (1961)
D21	*Fagus orientalis*	Nowshahr, Iran	49.5	112	86.2	Ahmadi *et al*. (2009)
D22	*Fagus sylvatica*	Chimay, Belgium	-	-	-	André *et al*. (2008)
D23	*Fagus sylvatica*	Chimay, Belgium	17.8 29.3	Lone trees	-	André *et al*. (2008)
D24	*Fagus sylvatica*	Steigerwald, Germany	-	286	20.5	Chang and Matzner (2000)
D25	*Fagus sylvatica*	Thuringia, Germany	37	228	36	Krämer and Hölsher (2009)
D26	*Fagus sylvatica*	Hampshire, UK	-	-	-	Neal *et al*. (1991); Neal *et al*. (1993)
D27	*Fagus sylvatica*	Ghent, Belgium	68	Lone	-	Staelens *et al*. (2008)
D28	Hardwood forest	Georgia, USA	5 - 23	1200 1150 975	-	Bryant *et al*. (2005)
D29	*Liriodendron tulipifera*	Maryland, USA	73.1	Lone	-	Levia *et al*. (2010)
D30	*Liriodendron tulipifera*	Maryland, USA	71.1	Lone	-	Levia *et al*. (2010)
D31	*Liriodendron tulipifera*	Maryland, USA	33.7	Lone	-	Levia *et al*. (2010)
D32	*Liriodendron tulipifera*	Maryland, USA	16.5	Lone	-	Van Stan and Levia (2010)
D33	*Liriodendron tulipifera*	Maryland, USA	27.3	Lone	-	Van Stan and Levia (2010)
D34	*Liriodendron tulipifera*	Maryland, USA	67.5	Lone	-	Van Stan and Levia (2010)
D35	*Liriodendron tulipifera*	Maryland, USA	-	Lone	-	Van Stan and Levia (2010)
D36	*Lithocarpus-Castanopsis* association with bryophytes	China	-	-	-	Liu *et al*. (2002) (Johnson and Lehmann, 2006)
D37	*Lithocarpus-Castanopsis* association with bryophytes	China	-	-	-	Liu *et al*. (2003) (Johnson and Lehmann, 2006)
D38	Mixed beech-podocarp-hardwood stand	Reefton, New Zealand	-	-	-	Rowe (1979)
D39	Mixed deciduous forest *Quercus rubra* *Acer saccharum* *Fagus grandifolia* *Acer rubrum*	Mississauga, Ontario, Canada	-	442	38.5	Price and Carlyle-Moses (2003)

D40	*Nothofagus betuloides*	Chile	-	-	-	Oyarzún *et al*. (2004) (Johnson and Lehmann, 2006)
D41	*Nothofagus pumilio*	Chile	-	-	-	Godoy *et al*. (1999) (Johnson and Lehmann, 2006)
D42	*Nyssa aquatica* *Taxodium distichum* *Fraxinus caroliniana*	Pitt County, North Carolina, USA	> 2.5 < 2.5	2730 2681	69	Brinson *et al*. (1980)
D43	*Populus grandidentata*	New Braintree, Massachusetts, USA	37.0 37.5 35.0 34.8 32.0	Lone trees	-	Herwitz and Levia (1997)
D44	*Populus grandidentata*	New Brunswick, Canada	16.0	5649	-	Mahendrappa (1974)
D45	*Populus* sp.	Colorado, USA	-	-	-	Dunford and Niederhof (1944)
D46	*Pyrus calleryana*	California, USA	22	Lone	-	Xiao *et al*. (2000)
D47	*Quercus acutissima*	Nagoya, Japan		350	-	Toba and Ohta (2005)
D48	*Quercus alba* *Quercus velutina*	Rhode Island, USA	Stand 1a: 7.1 1b: 7.4 1c: 7.4 2a: 11.2 2b: 10.9 2c: 16.8 3a: 9.7 3b: 9.1 3c: 7.4	2595 2916 2520 1087 1236 840 1507 1804 2150	11.8 14.7 13.4 16.0 19.6 22.3 22.4 24.0 19.9	Brown and Barker (1970)
D49	*Quercus coccinea*	Eastern Kentucky, USA	27.7 ± 0.5	-	-	Alexander and Arthur (2010)
D50	*Quercus mongolica*	Mao'er Shan, China	-	-	-	Wei and Zhou (1991) (Wei *et al*., 2005)
D51	*Quercus montana*	Eastern Kentucky, USA	26.1 ± 0.6	-	-	Alexander and Arthur (2010)
D52	*Quercus petraea*	Chimay, Belgium	-	-	-	André *et al*. (2008)
D53	*Quercus petraea*	Lancaster, England	-	5000	20	Cape *et al*. (1991)
D54	*Quercus rubra*	Mississauga, Ontario, Canada	-	Lone trees	20.7	Carlyle-Moses and Price (2006)
D55	*Quercus rubra*	-	-	-	-	Durocher (1990) (Levia and Frost, 2003)
D56	*Quercus rubra*	Massachusetts, USA	63.8	Lone	-	Levia (2004)

D57	*Quercus serrata*	Shirasaka, Japan	7.2	5070	-	Park and Hattori (2002)
D58	*Quercus serrata*	Yamashiro, Japan	6.9	3502	-	Park and Hattori (2002)
D59	*Quercus serrata*	Nagoya, Japan		2852	-	Toba and Ohta (2005)
D60	*Quercus* sp.	Miyaluo, China	-	-	-	Lei *et al*. (1994a,b) (Wei *et al*., 2005)
D61	*Quercus* spp.	Nuevo Leon, Mexico	16.1	312	-	Silva and Rodrigues (2001)
D62	*Quercus suber*	California, USA	12.5	Lone	-	Xiao *et al*. (2000)
D63	*Stewartia monadelpha*	Kyoto, Japan	S1 - 22.3 S2 - 23.7 S3 - 29.1 S4 - 21.8 S5 - 20.3 S6 - 27.9	Lone trees	-	Liang *et al*. (2009)

Table 2.2. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for temperate deciduous studies.

Code	Species	P_A (mm)	P_S (mm)	SF (%)	F	Formula(s)
D01	*Acer rubrum*	-	-	5.6	-	-
D02	*Acer rubrum*	1130	-	-	21.5	-
D03	*Acer saccharum*	785	213.80	-	$P > 4.3$ mm 21.6 7.2 30.5 108.6 16.1 22.7 14.6	$SF = 6.02 \ln P - 0.071 I - 8.9^{a\ b\ c}$ Units: SF (L) P (mm) I (mm/h)
D04	*Aesculus californica* *Ceanothus cuneatus*	-	-	14.6	-	-

D05	*Alnus glutinosa*	-	*1983/84*: 1583 *1984/85*: 1690	9 ± 2 9 ± 2	48.6 at 35 mm^{calc} 64.3^{calc} 38.6 at 37 mm^{calc} 64.3^{calc}	Summer: SF (mm) = 0.092P (mm) - 0.837 Winter: SF (mm) = 0.074P (mm) - 0.74
D06	*Betula papyrifera*	-	-	3.9	-	-
D07	*Betula platyphylla*	676	-	4.6	-	-
D08	Broad-leaved deciduous forest	1210	-	-	Winter: 6 - 21	-
D09	*Castanea sativa* *Quercus rubra*	-	31	2.4	-	-
D10	*Crataegus monogyna* *Acer campestre*	650	1350	< 0.5	-	SF (mm) = 0.0015P (mm) - 0.0118
D11	Evergreen-broadleaf forest	1467	*1976*: 1726.5 *1977/78*: 974.1	20.3 13.8	-	SF (mm) = 0.18(P (mm) - 3.6) SF (mm) = 0.145(P (mm) - 5.8)
D12	*Fagus grandifolia*	785	213.80	-	P > 4.3 mm 15.8 24.0 32.4 39.3	SF = 14.50 ln P - 0.15I - 20.8 Units: SF (L) P (mm) I (mm/h)
D13	*Fagus grandifolia*	1221	-	-	-	SF (L) = 5.82 P (mm) + 5.75^{calc}
D14	*Fagus grandifolia*	1221	-	-	57.0 at 10 mm^{calc}	SF (L) = 0.52 P (mm) - 0.45^{calc}
D15	*Fagus grandifolia*	1143	-	9.6	-	-
D16	*Fagus grandifolia*	1200	-	-	38.2	-
D17	*Fagus grandifolia*	1200	-	-	47.2	-
D18	*Fagus grandifolia*	1200	-	-	26.9	-
D19	*Fagus grandifolia*	1200	-	-	37.4	-
D20	*Fagus grandifolia* *Acer saccharum* *Betula alleghaniensis*	1270	-	5.0	15.5 at 11 mm^{calc} 16.8 at 11 mm^{calc} 17.1 at 11 mm^{calc}	SF (mm) = 0.0563P (mm) - 0.061^{con}
D21	*Fagus orientalis*	-	309.9	2.0	2.3^{calc}	SF (mm) = 0.0029$P^{1.7315}$ (mm)
D22	*Fagus sylvatica*	1044	-	-	-	Leaved: SF (L/mm) = 0.09CBH (cm) - 4.31^{d} Leafless: SF (L/mm) = 0.17CBH (cm) - 9.16

D23	*Fagus sylvatica*	1044	-	-	38.7 at 13 mm^{calc} 82.3 at 13 mm^{calc}	SF (L) = 1.09P (mm) - 1.65 SF (L) = 6.29P (mm) - 9.65
D24	*Fagus sylvatica*	750	691	5.2^{calc}	25.4^{calc}	-
D25	*Fagus sylvatica*	544 - 662	1223	3.1^{calc}	8.6^{calc}	SF (L) = 0.41 $DBH^{2.04}$ (cm)^{e}
D26	*Fagus sylvatica*	800	640	5.0	-	-
D27	*Fagus sylvatica*	755	Leafed: 769.9 Leafless: 677.9	6.4 9.5	42.1 at 16 mm^{calc} 31.7^{calc} 61.4 at 13 mm^{calc} 47.1^{calc}	SF (mm) = 0.098P (mm) - 0.209 SF (mm) = 0.140P (mm) - 0.209
D28	Hardwood forest	830	752.8	0.7	-	-
D29	*Liriodendron tulipifera*	1221	-	-	3.3 at 28 mm^{calc}	SF (L) = 1.78P (mm) - 11.19^{calc}
D30	*Liriodendron tulipifera*	1221	-	-	1.6 at 27 mm^{calc}	SF (L) = 0.81P (mm) - 4.70^{calc}
D31	*Liriodendron tulipifera*	1221	-	-	8.5 at 21 mm^{calc}	SF (L) = 0.92P (mm) - 3.47^{calc}
D32	*Liriodendron tulipifera*	1200	-	-	19.2	-
D33	*Liriodendron tulipifera*	1200	-	-	14.4	-
D34	*Liriodendron tulipifera*	1200	-	-	3.1	-
D35	*Liriodendron tulipifera*	1200	-	-	12.2	-
D36	*Lithocarpus-Castanopsis* association with bryophytes	2165	-	2.8	-	-
D37	*Lithocarpus-Castanopsis* association with bryophytes	2165	-	2.0	-	-
D38	Mixed beech-podocarp-hardwood stand	1950	6220	1.5	-	-
D39	Mixed deciduous forest *Quercus rubra* *Acer saccharum* *Fagus grandifolia* *Acer rubrum*	785	259.3	3.7 ± 0.9	9.0 at 12 mm^{calc} 9.6^{calc}	SF (mm) = 0.039P (mm) - 0.005
D40	*Nothofagus betuloides*	7111	-	1.4	-	-
D41	*Nothofagus pumilio*	5332	-	9.0	-	-

D42	*Nyssa aquatica* *Taxodium distichum* *Fraxinus caroliniana*	-	466 639	Leafless: 4.5 Leaved: 2.5 3.3	6.5^{calc} 3.6^{calc} 4.8^{calc}	Leafless: SF (L) = 6.287DBH (cm) - 2.421 Leaves: SF (L) = 0.864DBH (cm) - 50.512
D43	*Populus grandidentata*	1190	-	5.4 9.0 9.9 7.8 8.4	5.2 12.0 8.5 9.9 14.7	-
D44	*Populus grandidentata*	-	-	6.1	-	-
D45	*Populus* sp.	599.4	487.7	1.1	-	-
D46	*Pyrus calleryana*	446	-	8	37.2 at 1 mm^{calc}	SF (mm) = 0.0794P (mm) - 0.0012
D47	*Quercus acutissima*	-	428	2.5	-	-
D48	*Quercus alba* *Quercus velutina*	1119.38	-	Growing: 3.9 Dormant: 4.8	18.8 at 19 mm^{calc} 36.7 at 16 mm^{calc} 21.0 at 20 mm^{calc} 30.2 at 15 mm^{calc}	Growing all: SF = 0.041P - 0.127 Dormant S1: SF = 0.057P - 0.127 Dormant S2: SF = 0.048P - 0.152 Dormant S3: SF = 0.077P - 0.152 All units in mm
D49	*Quercus coccinea*	1130	-	-	9.5	-
D50	*Quercus mongolica*	450 - 550	-	15.5	-	-
D51	*Quercus montana*	1130	-	-	7.6	-
D52	*Quercus petraea*	1044	-	-	-	Leaved: SF (L/mm) = 0.08CBH (cm) - 4.62 Leafless: SF = 0.16CBH (cm) - 10.20
D53	*Quercus petraea*	-	*1983/84*: 1583 *1984/85*: 1690	10 ± 2 10 ± 2	50^{calc} 43.2 at 28 mm^{calc} 50^{calc}	Summer: nd Winter: SF (mm) = 0.11P (mm) - 0.66
D54	*Quercus rubra*	785	213.80	-	P > 4.3 mm 10.4 7.4 7.6 7.0 9.3 6.1 13.7	SF = 25.55 ln$P$ - 0.50I - 38.6 Units: SF (L) P (mm) I (mm/h)

D55	*Quercus rubra*	-	-	4.0	-	-
D56	*Quercus rubra*	1210	-	-	Event high: 70.0	-
D57	*Quercus serrata*	-	4187.9	9.9	61.3	SF (mm) = $(0.0124(DBH\ (\text{cm}))^{1.455})$ Pg - $(0.018(DBH\ (\text{cm}))^{1.825})$
D58	*Quercus serrata*	-	2955.5	5.0	55.6	SF (mm) = $(0.0077(DBH\ (\text{cm}))^{1.500})$ P (mm) - $(0.0195(DBH\ (\text{cm}))^{2.031})$
D59	*Quercus serrata*	-	735.4	3.0	-	-
D60	*Quercus* sp.	700 - 1000	-	2.3	-	-
D61	*Quercus* spp.	639	974	0.5	-	-
D62	*Quercus suber*	446	-	15	91.5 at 7 mm$^{\text{calc}}$	SF (mm) = 0.148P (mm) - 0.0589
D63	*Stewartia monadelpha*	1523	-	S1 - nd S2 - 26.0 S3 - 10.3 S4 - 14.7 S5 - 3.3 S6 - 6.6	-	-

[a] *SF* = Stemflow

[b] *P* = Precipitation

[c] *I* = Rainfall intensity

[d] *CBH* = Circumference at breast height

[e] *DBH* = Diameter at breast height

Table 2.3. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for coniferous and boreal studies.

Code	**Species**	**Location**	**Diam. (cm)**	**Density (Trees/ha)**	**BA (m^2/ha)**	**Author**
C01	*Abies balsamea*	New Brunswick, Canada	18.0	2959	-	Mahendrappa (1974)
C02	*Abies balsamea*	New Hampshire, USA	-	-	-	Olson *et al*. (1981)
C03	*Abies lasiocarpa*	-	-	-	-	Niederhof and Wilm (1943) (Zinke, 1967)

C04	*Abies lasiocarpa* *Picea glauca* x *engelmannii*	Penticton, BC, Canada	-	1470	-	Spittlehouse (1998)
C05	*Chamaecyparis obtusa*	Honshu, Japan	*1997*: 5.8 *1999*: 7.0 *2000*: 8.1	2944	-	Murakami (2009)
C06	*Chamaecyparis obtusa*	Tokyo, Japan	21.5	932	-	Koichiro *et al*. (2001); Kuraji *et al*. (2001)
C07	*Chamaecyparis obtusa*	Tokyo, Japan	21.5	932	-	Koichiro *et al*. (2001); Kuraji *et al*. (2001)
C08	*Fitzroya cupressoides*	Cordillera de la Costa, Chile	-	-	-	Oyarzún *et al*. (1998)
C09	*Ilex pedunculosa*	Kyoto, Japan	3.5	15	-	Park and Hattori (2002)
C10	*Juniperus* sp.	Texas, USA	-	-	-	Owens *et al*. (2006)
C11	*Larix cajanderi*	Siberia, Russia	-	840	-	Toba and Ohta (2005)
C12	*Larix decidua*	Edinburgh, Scotland	-	3900	30	Cape *et al*. (1991)
C13	*Larix decidua*	Aberdeen, Scotland	-	1600	50	Cape *et al*. (1991)
C14	*Larix gmelinii*	Genhe, China	-	-	-	Zhou (2003) (Wei *et al*., 2005)
C15	*Larix laricina*	Canada	-	-	-	Lilienfein and Wilcke (2004) (Johnson and Lehmann, 2006)
C16	*Picea abies*	Vosges, France	-	575	53.3	Viville *et al*. (1993)
C17	*Picea abies*	Lancaster, England	-	3200	35	Cape *et al*. (1991)
C18	*Picea engelmannii*	-	-	-	-	Niederhof and Wilm (1943) (Zinke, 1967)
C19	*Picea glauce*	New Brunswick, Canada	17.0	3767	-	Mahendrappa (1974)
C20	*Picea rubens*	New Brunswick, Canada	16.0	4841	-	Mahendrappa (1974)
C21	*Picea sitchensis*	Dumfriesshire, Scotland	25 - 36	-	-	Ford and Deans (1978)
C22	*Picea sitchensis*	Balquhidder, Scotland	-	-	-	Johnson (1990)
C23	*Picea sitchensis*	Carnation Creek, BC, Canada	-	1500	-	Spittlehouse (1998)
C24	*Picea sitchensis*	Edinburgh, Scotland	15	156 277 625 3000	-	Teklehaimanot *et al*. (1991)

C25	*Picea sitchensis*	Aberdeen, Scotland	-	3600	125	Cape *et al*. (1991)
C26	*Pinus arandi*	Miyaluo, China	-	-	-	Lei *et al*. (1994a,b) (Wei *et al*., 2005)
C27	*Pinus contorta*	Mayson Lake, British Columbia, Canada	2.0 - 14.6	-	-	McKee and Carlyle-Moses (2010)
C28	*Pinus contorta*	Penticton, BC, Canada	-	720	-	Spittlehouse (1998)
C29	*Pinus contorta*	-	-	-	-	Wilm and Dunford (1948) (Zinke, 1967)
C30	*Pinus contorta*	Colorado, USA	-	-	-	Dunford and Niederhof (1944)
C31	*Pinus densiflora*	Tsukuba, Japan	20.4 19.8	2300 1700	-	Taniguchi *et al*. (1996)
C32	*Pinus densiflora*	Northern Japan	-	1444	-	Toba and Ohta (2005)
C33	*Pinus densiflora*	Northern Japan	-	1678	-	Toba and Ohta (2005)
C34	*Pinus densiflora*	Northern Japan	-	355	-	Toba and Ohta (2005)
C35	*Pinus elliottii*	Guangzhou, China	30	400	-	Tang (1996)
C36	*Pinus koraiensis*	Mao'er Shan, China	-	-	-	Zhou *et al*. (1994) (Wei *et al*., 2005)
C37	*Pinus palustri*	Georgia, USA	10	2050	-	Bryant *et al*. (2005)
C38	*Pinus pseudostrobus*	Nuevo Leon, Mexico	32.4	246	-	Silva and Rodrigues (2001)
C39	*Pinus radiata* plantation	-	-	-	-	Crockford and Khanna (1997) (Levia and Frost, 2003)
C40	*Pinus radiata*	-	-	-	-	Crockford and Richardson (1990) (Levia and Frost, 2003)
C41	*Pinus resinosa*	New Brunswick, Canada	22.0	1882	-	Mahendrappa (1974)
C42	*Pinus resinosa*	New Haven, Connecticut	20.3	500	-	Voigt (1960)
C43	*Pinus strobus*	New Brunswick, Canada	21.0	2151	-	Mahendrappa (1974)
C44	*Pinus strobus*	North Carolina, USA	-	-	-	Helvey (1967)
C45	*Pinus sylvestris*	Siberia, Russia	-	1492	-	Toba and Ohta (2005)
C46	*Pinus sylvestris*	Lancaster, England	-	2270	36	Cape *et al*. (1991)
C47	*Pinus sylvestris*	Edinburgh, Scotland	-	3900	44	Cape *et al*. (1991)
C48	*Pinus sylvestris*	Aberdeen, Scotland	-	2700	95	Cape *et al*. (1991)

C49	*Pinus tabulaeformis*	Miyaluo, China	-	-	-	Lei *et al*. (1994a,b) (Wei *et al*., 2005)
C50	*Pinus taeda*	-	-	-	-	Hoover (1953) (Zinke, 1967)
C51	*Pinus taeda* *Pinus palustris*	Georgia, USA	14 - 21	556 367 189	-	Bryant *et al*. (2005)
C52	*Pinus wallichiana*	Himachal Pradesh, India	-	1200	29	Singh (1987)
C53	*Pseudotsuga menziesii*	Malalcahuello, Chile	25.9	1143	60.3	Iroumé and Huber (2002)
C54	*Pseudotsuga menziesii*	Oregon, USA	-	-	-	Rothacher (1963) (Zinke, 1967)
C55	*Pseudotsuga menziesii*	Cowichan Lake, BC, Canada	-	1050	-	Spittlehouse (1998)
C56	*Pseudotsuga menziesii*	Cowichan Lake, BC, Canada	-	1090	-	Spittlehouse (1998)
C57	*Tsuga canadensis*	New Haven, Connecticut	24.1	-	-	Voigt (1960)
C58	*Tsuga heterophylla*	Carnation Creek, BC, Canada	-	480	-	Spittlehouse (1998)

Table 2.4. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for coniferous and boreal studies.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
C01	*Abies balsamea*	-		3.5	-	-
C02	*Abies balsamea*	-	389	3 - 8	-	-
C03	*Abies lasiocarpa*	-	-	-	-	SF (L) = 2.312P (mm) - 6.342^{con}
C04	*Abies lasiocarpa* *Picea glauca* x *engelmannii*	3316	454	< 0.5	-	-

C05	*Chamaecyparis obtusa*	1467.7	*1997*: 1259.7 *1998*: 1509.4 *1999*: 1673.2 *2000*: 1431.2	5.9 2.8 3.8 4.3	81.3 30 31.4 29	-
C06	*Chamaecyparis obtusa*	2279	2156.4	12.0	-	-
C07	*Chamaecyparis obtusa*	2279	1862.9	12.0	-	-
C08	*Fitzroya cupressoides*	4000	4098	2.0	-	-
C09	*Ilex pedunculosa*	-	-	-	69.8	SF (mm) = (0.0047(*DBH* (cm))$^{2.174}$) *Pg* - (0.0428(*DBH*(cm))$^{1.150}$)
C10	*Juniperus* sp.	600 - 900	1176 - 3209	5.0	-	*SF* (mm) = 3.5 x (1 - e$^{-0.103 \text{ x } P}$) (mm)
C11	*Larix cajanderi*	-	59.13	0.0	-	Slope = 0.62 x 10^{-4}
C12	*Larix decidua*	-	*1984/85*: 783 *1985/86*: 1053	4 ± 1 3 ± 1	8.5 at 63 mm^{calc} 13.3^{calc} 15.3 at 52 mm^{calc} 10.0^{calc}	Summer: *SF* (mm) = 0.041*P* (mm) - 0.984 Winter: *SF* (mm) = 0.07*P* (mm) - 1.26
C13	*Larix decidua*	-	*1984/85*: 1023 *1985/86*: 986	1 ± 0 0.4 ± 0.1	0.8 at 59 mm^{calc} 2.0^{calc} 3.2 at 72 mm^{calc} 0.8^{calc}	Summer: *SF* (mm) = 0.006*P* (mm) - 0.132 Winter: *SF* (mm) = 0.027*P* (mm) - 0.81
C14	*Larix gmelinii*	-	-	3.3	-	-
C15	*Larix laricina*	-	-	1.6	-	-
C16	*Picea abies*	1400	1710.6	0.5	0.9^{calc}	-
C17	*Picea abies*	-	*1983/84*: 1583 *1984/85*: 1690	13 ± 3 14 ± 3	21.1 at 47 mm^{calc} 37.1^{calc} 34.6 at 33 mm^{calc} 40^{calc}	Summer: *SF* (mm) = 0.16*P* (mm) - 2.4 Winter: *SF* (mm) = 0.16*P* (mm) - 1.28
C18	*Picea engelmannii*	-	-	-	-	*SF* (L) = 0.668*P* (mm) - 4.933^{con}
C19	*Picea glauce*	-		6.4	-	-
C20	*Picea rubens*	-		2.3	-	-
C21	*Picea sitchensis*		1639	27.0	-	-
C22	*Picea sitchensis*	2130		3.0	-	-
C23	*Picea sitchensis*	3316	454	9.0	-	-
C24	*Picea sitchensis*	1000	441.78	0.5 1.0 2.9 16.7	-	-

C25	*Picea sitchensis*	-	*1984/85*: 1023 *1985/86*: 986	13 ± 3 14 ± 3	8.8 at 37 mm^{calc} 10.4^{calc} 10.4 at 15 mm^{calc} 11.2^{calc}	Summer: *SF* (mm) = 0.15*P* (mm) - 1.5 Winter: *SF* (mm) = 0.15*P* (mm) - 0.3
C26	*Pinus arandi*	700 - 1000	-	5.0	-	-
C27	*Pinus contorta*	600	52.3	-	14.9	-
C28	*Pinus contorta*	3316	454	< 0.5	-	-
C29	*Pinus contorta*	-	-	-	-	-
C30	*Pinus contorta*	599.4	396	1.5	-	-
C31	*Pinus densiflora*	1222	1291	0.5 1.2	-	*SF* (mm) = 0.0136*P* (mm) – 0.0896 *SF* (mm) = 0.0061*P* (mm) – 0.0729
C32	*Pinus densiflora*	-	152.2	5.2	-	slope = 0.16
C33	*Pinus densiflora*	-	269	2.7	-	-
C34	*Pinus densiflora*	-	174.6	3.3	-	-
C35	*Pinus elliottii*	1500	-	9.4	-	*SF* (mm) = 0.088*P* (mm) – 0.432
C36	*Pinus koraiensis*	676	-	3.8	-	-
C37	*Pinus palustri*	830	724.8	2.0	-	-
C38	*Pinus pseudostrobus*	639	974	0.6	-	-
C39	*Pinus radiata* plantation	-	-	3.1 - 3.9	-	-
C40	*Pinus radiata* plantation	-	-	11.2	-	-
C41	*Pinus resinosa*	-	-	0.7	-	-
C42	*Pinus resinosa*	1143	-	1.2	-	-
C43	*Pinus strobus*	-	-	5.3	-	-
C44	*Pinus strobus*	-	-	8.8 4.3 2.3	-	10 yrs old - *SF* = 0.00 + 0.09P^{con} 35 yrs old - *SF* = -0.254 + 0.06P^{con} 60 yrs old - *SF* = -0.254+ 0.03P^{con} All units (mm)
C45	*Pinus sylvestris*	-	49.75	0.0	-	Slope = 0.31 x 10^{-3}
C46	*Pinus sylvestris*	-	*1983/84*: 1583 *1984/85*: 1690	7 ± 1 6 ± 1	13.7 at 76 mm^{calc} 19.4^{calc} 19.2 at 28 mm^{calc} 16.7^{calc}	Summer: *SF* (mm) = 0.087*P* (mm) - 2.871 Winter: *SF* (mm) = 0.088*P* (mm) - 0.528
C47	*Pinus sylvestris*	-	*1984/85*: 783 *1985/86*: 1053	15 ± 3 13 ± 3	26.1 at 39 mm^{calc} 34.1^{calc} 38.6 at 41 mm^{calc} 29.5^{calc}	Summer: *SF* (mm) = 0.16*P* (mm) - 1.76 Winter: *SF* (mm) = 0.24*P* (mm) - 2.88

C48	*Pinus sylvestris*	-	*1984/85*: 1023 *1985/86*: 986	10 ± 2 8 ± 2	7.5 at 37 mm^{calc} 10.5^{calc} 10.0 at 37 mm^{calc} 8.4^{calc}	Summer: SF (mm) = 0.098P (mm) - 0.98 Winter: SF (mm) = 0.13P (mm) - 1.3
C49	*Pinus tabulaeformis*	700 - 1000	-	2.6	-	-
C50	*Pinus taeda*	-	-	-	-	SF (mm) = 0.222 P (mm) - 0.457^{con}
C51	*Pinus taeda* *Pinus palustris*	830	752.8	0.5	-	-
C52	*Pinus wallichiana*	-	-	2.7	-	-
C53	*Pseudotsuga menziesii*	2341	3805	6.0	9.3 at 15 mm^{calc} 10^{calc}	SF (mm) = 0.065P (mm) - 0.131
C54	*Pseudotsuga menziesii*	-	-	0.3	-	-
C55	*Pseudotsuga menziesii*	3316	454	9.0	-	-
C56	*Pseudotsuga menziesii*	3316	454	4.0	-	-
C57	*Tsuga canadensis*	1143	-	5.9	-	-
C58	*Tsuga heterophylla*	3316	454	1.0	-	-

Table 2.5. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for mixed deciduous and coniferous stands.

Code	**Species**	**Location**	**Diam. (cm)**	**Density (Trees/ha)**	**BA (m^2/ha)**	**Author**
X01	Dry sclerophyll forest	-	-	-	-	Crockford and Richardson (1990) (Levia and Frost, 2003)
X02	*Pinus densiflora* *Quercus myrsinaefolia* *Eurya japonica*	Ibaraki, Japan	-	-	-	Iida *et al*. (2005)
X03	*Quercus alba* *Pinus taeda*	Georgia, USA	16 - 18	711	-	Bryant *et al*. (2005)
X04	*Quercus berberidifolia* *Pinus palustris*	Georgia, USA	14 60	1411	-	Bryant *et al*. (2005)
X05	*Sequoia sempervirens* *Pseudotsuga menziesii* *Lithocarpus densiflorus*	Fort Bragg, California, USA	-	341 108 89	61 31 5.5	Reid and Lewis (2009)

Table 2.6. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for mixed deciduous and coniferous stands.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
X01	Dry sclerophyll forest	-	-	4.8	-	-
X02	*Pinus densiflora* *Quercus myrsinaefolia* *Eurya japonica*	1207	*1984/1985*: 1213 *2001/2002*: 1246	1.2 8.5	-	SF (mm) = 0.0186P (mm) – 0.119 SF (mm) = 0.101P (mm) – 0.297
X03	*Quercus alba* *Pinus taeda*	830	684.9	0.5	-	-
X04	*Quercus berberidifolia* *Pinus palustris*	830	724.8	0.5	-	-
X05	*Sequoia sempervirens* *Pseudotsuga menziesii* *Lithocarpus densiflorus*	1285	1316	2.5	2.6^{calc}	-

Table 2.7. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for tropical studies.

Code	**Species**	**Location**	**Diam. (cm)**	**Density (Trees/ha)**	**BA (m^2/ha)**	**Author**
T01	*Acacia mangium*	Soberania, Panama	-	Lone	-	Park and Cameron (2008); Carlyle-Moses *et al.* (2010)
T02	Amazonian terra firme rainforest	Manaus, Amazonas, Brazil	-	3000	-	Lloyd *et al.* (1988)
T03	*Balanops australiana*	Northeast Queensland, Australia	27.9 39.1	Lone trees	-	Herwitz (1986)
T04	*Cardwellia sublimis*	Northeast Queensland, Australia	40.2	Lone	-	Herwitz (1986)

T05	*Castanopsis sieboldii*, *Schima wallichii*, and *Rapanea neriifolia* dominated stand	Ryukyus, Japan	> 3.0	6625	57.5^{calc}	Xu *et al*. (2005)
T06	*Cecropia peltata*	Luquillo Mountains, Puerto Rico	21 24 19 18	Lone trees	-	Holwerda *et al*. (2006)
T07	*Cecropia peltata*	Rio Piedras, Puerto Rico	-	-	-	Scatena (1990)
T08	*Ceratopetalum virchowii*	Northeast Queensland, Australia	25.0 46.1 43.3	Lone trees	-	Herwitz (1986)
T09	Cerrado (native savanna)	Brazil	-	-	-	Lilienfein and Wilcke (2004) (Johnson and Lehmann, 2006)
T10	*Cunningshamia lanceolata* plantation	Huitong, China	-	-	-	Tian *et al*. (1994) (Wei *et al*., 2005)
T11	*Dacryodes excelsa*	Luquillo Mountains, Puerto Rico	32 54 49 32 41 59	Lone trees	-	Holwerda *et al*. (2006)
T12	*Dacryodes excelsa*	Rio Piedras, Puerto Rico	-	-	-	Scatena (1990)
T13	*Dimorphandra macrostachya* and *Euceraea nitida*	Canaima, Venezuela	> 10 < 10	950 4530	29.7 9.2	Dezzeo and Chacón (2006)
T14	*Dimorphandra macrostachya* and *Euterpe* sp.	Canaima, Venezuela	> 10 < 10	1060 3400	40 7	Dezzeo and Chacón (2006)
T15	*Elaeocarpus foveolatus*	Northeast Queensland, Australia	48.1	Lone	-	Herwitz (1986)
T16	*Elaeocarpus* sp.	Northeast Queensland, Australia	45.0	Lone	-	Herwitz (1986)

T17	*Eschweilera* spp.	Manaus, Brazil	21.0	-	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
T18	*Eucalyptus melanophloia*	Australia	-	-	-	Prebble and Stirk (1980) (Johnson and Lehmann, 2006)
T19	Eucalyptus mixed cross	Congo	-	-	-	Laclau *et al*. (2003) (Johnson and Lehmann, 2006)
T20	*Eucommia ulmoides*	Hunan Province, China	4.5 ± 1.1	6478	-	Cao *et al*. (2008)
T21	Evergreen montane forest	Zamora-Chinchipe, Ecuador	-	-	-	Fleischbein *et al*. (2005, 2006)
T22	*Gliricidia sepium*	Soberania, Panama	-	Lone	-	Park and Cameron (2008); Carlyle-Moses *et al*. (2010)
T23	*Guazuma ulmifolia*	Soberania, Panama	-	Lone	-	Park and Cameron (2008); Carlyle-Moses *et al*. (2010)
T24	Large timber extraction forest	Central Sulawesi, Indonesia	-	5495 3740 4052	41.1 53.6 34.6	Dietz *et al*. (2006)
T25	Lowland dipterocarp forest	Malaysia	-	-	-	Manokaran (1979)
T26	Lowland evergreen rain forest	Central Kalimantan, Indonesia	> 10	-	-	Vernimmen *et al*. (2007)
T27	Lowland tropical forest	Kalimantan, Indonesia	-	Unlogged: 581 Logged: 278	38.6 13.8	Asdak *et al*. (1998)
T28	Lowland tropical forest	Sarawak, Malaysia	-	6856	43.3	Manfroi *et al*. (2004); Manfroi *et al*. (2006)
T29	Mixed pine broadleaf	Dinghushan, China	-	-	-	Yan *et al*. (2003) (Wei *et al*., 2005)
T30	Monsoon evergreen broadleaf	Dinghushan, China	-	-	-	Yan *et al*. (2003) (Wei *et al*. 2005)
T31	Monsoon pine forest	Dinghushan, China	-	-	-	Yan *et al*. (2003) (Wei *et al*. 2005)
T32	Natural montane forest	Central Sulawesi, Indonesia	-	2272 1806 3455	68.6 50 51.1	Dietz *et al*. (2006)
T33	*Nectandra* sp.	La Mancha, Veracruz, Mexico	-	-	-	Kellman and Roulet (1990)

T34	*Nectandra* sp.	La Mancha, Veracruz, Mexico	-	-	-	Kellman and Roulet (1990)
T35	*Ochroma pyramidale*	Soberania, Panama	-	Lone	-	Park and Cameron (2008); Carlyle-Moses *et al*. (2010)
T36	*Oenocarpus bacaba*	Manaus, Brazil	15.5	-	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
T37	*Pachira quinata*	Soberania, Panama	-	Lone	-	Park and Cameron (2008); Carlyle-Moses *et al*. (2010)
T38	*Pinus canariensis*		-	-	-	Kittredge *et al*. (1941) (Zinke, 1967)
T39	*Pinus massoniana*	Hunan Province, China	9.2 ± 3.4	2628		Cao *et al*. (2008)
T40	*Prestoea montana*	Luquillo Mountains, Puerto Rico	15 16 16 15 18 17 15 17	Lone trees	-	Holwerda *et al*. (2006)
T41	*Quercus copeyensis*	Costa Rica	-	-	-	Hölscher *et al*. (2003) (Johnson & Lehmann, 2006)
T42	*Quercus copeyensis*	Costa Rica	-	-	-	Hölscher *et al*. (2003) (Johnson & Lehmann
T43	*Quercus copeyensis*	Costa Rica	-	-	-	Hölscher *et al*. (2003) (Johnson & Lehmann
T44	Rain forest	Sabah, Malaysia	-	-	-	Sinun *et al*. (1992)
T45	Rain forest with high abundance of ectomycorrhizal trees	Korup, Cameroon	> 5	301	-	Chuyong *et al*. (2004)
T46	Rain forest with low abundance of ectomycorrhizal trees	Korup, Cameroon	> 5	303	-	Chuyong *et al*. (2004)
T47	Semi-deciduous monsoon forests	Jianfengling, China	-	-	-	Zeng (1994) (Wei *et al*., 2005)

T48	*Sloanea berteriana*	Luquillo Mountains, Puerto Rico	Lone trees	382	-	Holwerda *et al*. (2006)
T49	*Sloanea berteriana*	Rio Piedras, Puerto Rico	-	-	-	Scatena (1990)
T50	Small timber extraction forest	Central Sulawesi, Indonesia	-	2020 3855 2420	55.5 67 41.4	Dietz *et al*. (2006)
T51	Stunted heath forest	Central Kalimantan, Indonesia	> 10	-	-	Vernimmen *et al*. (2007)
T52	Stunted heath forest	Central Kalimantan, Indonesia	Small trees	-	-	Vernimmen *et al*. (2007)
T53	Tall heath forest	Central Kalimantan, Indonesia	> 10	-	-	Vernimmen *et al*. (2007)
T54	Terra firme rainforest	Manaus, Brazil	> 10	670	33.7	Cuartas *et al*. (2007)
T55	*Tristania* sp.	Central Kalimantan, Indonesia	-	-	-	Vernimmen *et al*. (2007)
T56	Tropical dry forest	La Mancha, Veracruz, Mexico	-	-	-	Kellman and Roulet (1990)
T57	Tropical montane rainforest	Columbia	-	-	-	Veneklaas and Van Ek (1990) (Levia and Frost, 2003)
T58	Tropical rain forest	Manaus, Brazil	3.8 - 52.2	3000	-	Lloyd and de Marques (1988)
T59	Tropical rain forest (228 species)	San Carlos de Rio Negro, Venezuela	-	11217	-	Jordan (1978)
T60	Tropical rain forest (100 species)	San Carlos de Rio Negro, Venezuela	-	2736	-	Jordan (1978)
T61	Tropical rainforest	Araracuara, Colombia	-	-	-	Marin *et al*. (2000)
T62	*Vernicia fordii*	Hunan Province, China	7.3 ± 2.1	2000	-	Cao *et al*. (2008)
T63	*Vismia guianensis*, *Myrcia* sp. *Clusia* sp.	Canaima, Venezuela	> 10 < 10	130 1030	2 2	Dezzeo and Chacón (2006)
T64	*Vismia* spp.	Manaus, Brazil	3.5	19500		Schroth *et al*. (1999); Schroth *et al*. (2001)

Table 2.8. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for tropical studies.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
T01	*Acacia mangium*	2127	158.1	2.7 ± 2.0	38.7 at 14.5 mm 20.3^{calc}	-
T02	Amazonian terra firme rainforest	2391	4804	-	-	*SF* (mm) = 0.036*P* (mm) - 0.15
T03	*Balanops australiana*	6500	7800	25.2^{calc} 3.3^{calc}	112 7	-
T04	*Cardwellia sublimis*	6500	7800	3.8^{calc}	11	-
T05	*Castanopsis sieboldii* *Schima wallichii* *Rapanea neriifolia* dominated stand	2680	*1998*: 4320 *1999*: 2231 *2000*: 3424	32.1 27.6 31.7	55.8^{calc} 48.0^{calc} 55.1^{calc}	-
T06	*Cecropia peltata*	3000 - 4000	2246	0.01	1.5 at 33 mm^{calc} 1.2^{calc} 2.2 at 38 mm^{calc} 1.6^{calc} 3.5 at 30 mm^{calc} 3.0^{calc} 5.3 at 5 mm^{calc} 5.5^{calc}	*SF* (L) = 0.07*P* (mm) - 0.58 *SF* (L) = 0.14*P* (mm) - 1.49 *SF* (L) = 0.13*P* (mm) - 0.92 *SF* (L) = 0.14*P* (mm) - 0.03
T07	Cecropia peltata	-	-	9.8	-	-
T08	*Ceratopetalum virchowii*	6500	7800	18.6^{calc} 26.2^{calc} 7.7^{calc}	100 33 20	-
T09	Cerrado (native savanna)	1656	-	0.8	-	-
T10	*Cunningshamia lanceolata* plantation	1550	-	0.2	-	-
T11	*Dacryodes excelsa*	3000 - 4000	2246	0.3	3.9 at 36 mm^{calc} 2.9^{calc} 2.3 at 19 mm^{calc} 2.2^{calc} 1.8 at 30 mm^{calc} 1.5^{calc} 0.7 at 34 mm^{calc} 0.5^{calc} 1.9 at 38 mm^{calc} 1.4^{calc} 1.7 at 35 mm^{calc} 1.2^{calc}	*SF* (L) = 0.43*P* (mm) - 4.14 *SF* (L) = 0.63*P* (mm) - 1.95 *SF* (L) = 0.44*P* (mm) - 3.12 *SF* (L) = 0.08*P* (mm) - 0.69 *SF* (L) = 0.35*P* (mm) - 3.65 *SF* (L) = 0.62*P* (mm) - 5.72
T12	*Dacryodes excelsa*	-	-	1.5	-	-

T13	*Dimorphandra macrostachya* and *Euceraea nitida*	2548	2215	6.9	17.7^{calc}	-
T14	*Dimorphandra macrostachya* and *Euterpe* sp.	2548	2215	8.4	17.9^{calc}	-
T15	*Elaeocarpus foveolatus*	6500	7800	39.7^{calc}	50	-
T16	*Elaeocarpus* sp.	6500	7800	3.2^{calc}	9	-
T17	*Eschweilera* spp.	2622	2672	0.1	-	-
T18	*Eucalyptus melanophloia*	718	-	0.8	-	-
T19	Eucalyptus mixed cross	1502	-	1.6	-	-
T20	*Eucommia ulmoides*	1347.2	2086.1	7.6	-	-
T21	Evergreen montane forest	2048	2504	1.0	-	-
T22	*Gliricidia sepium*	2127	255.1	1.5 ± 0.21	74.8 at 18.3 mm 29.7^{calc}	-
T23	*Guazuma ulmifolia*	2127	264.2	2.3 ± 0.28	105.1 at 18.8 mm 37.7^{calc}	-
T24	Large timber extraction forest	2437 - 3424	220 185 259	0.7 0.7 0.6	1.7^{calc} 1.3^{calc} 1.7^{calc}	-
T25	Lowland dipterocarp forest	2030 - 3050	2381	0.6	-	SF (L/100 sq.m) = 0.008 P (x10^{2} L/100 sq.m) - 2.6797
T26	Lowland evergreen rain forest	3625 ± 560	2995	0.2	-	SF (ml/mm) = 4.2 BDH (cm) - 32.2
T27	Lowland tropical forest	2862	2199 3563	Logged: 1.4 Unlogged: 0.3	-	SF (m^{3}) = 0.008 + 0.019BA (m^{2})^{a} SF (m^{3}) = 0.002 + 0.019BA (m^{2})
T28	Lowland tropical forest	2740.5	Yr 1: 2292 Yr 2: 2439 Yr 3: 2668	3.5 2.8 3.0	8.7 at 22 mm^{calc} Year 1: 8.1^{calc} Year 2: 6.5^{calc} Year 3: 6.9^{calc}	SF (mm) = 0.046 P (mm) - 0.18 SF (ml/mm) = -11.6 + 122.4 log10(DBH (cm))
T29	Mixed pine broadleaf	1900	-	6.5	-	-
T30	Monsoon evergreen broadleaf	1900	-	8.3	-	-

T31	Monsoon pine forest	1900	-	1.9	-	-
T32	Natural montane forest	2437 - 3424	215 165 148	0.6 0.3 0.5	0.9^{calc} 0.6^{calc} 1.0^{calc}	-
T33	*Nectandra* sp.	1300	32 16	-	Event high: 111.9	-
T34	*Nectandra* sp.	130	16	-	Event high: 135.3	-
T35	*Ochroma pyramidale*	2127	269.6	0.9 ± 0.6	29.9 at 14.8 mm 10.3^{calc}	-
T36	*Oenocarpus bacaba*	2622	2672	0.7	-	-
T37	*Pachira quinata*	2127	232.6	1.3 ± 0.3	29.8 at 26.8 mm 12.2^{calc}	-
T38	*Pinus canariensis*			0.03 - 13		SF (mm) = 0.03P (mm) - 0.508^{con}
T39	*Pinus massoniana*	1347.2	2086.1	2.4	-	-
T40	*Prestoea montana*	3000 - 4000	2246	2.7	206.9 at 10 mm^{calc} 214.0^{calc} 132.5 at 14 mm^{calc} 133.9^{calc} 63.3 at 15 mm^{calc} 63.2^{calc} 115.3 at 19 mm^{calc} 110.7^{calc} 11.2 at 23 mm^{calc} 10.3^{calc} 73.5 at 6 mm^{calc} 76.0^{calc} 272.8 at 2 mm^{calc} 275.7^{calc} 53.1 at 7 mm^{calc} 55.1^{calc}	SF (L) = 4.05P (mm) - 3.94 SF (L) = 3.03P (mm) - 5.11 SF (L) = 1.47P (mm) - 2.95 SF (L) = 2.41P (mm) - 7.09 SF (L) = 0.35P (mm) - 1.49 SF (L) = 1.76P (mm) - 0.55 SF (L) = 4.87P (mm) - 0.10 SF (L) = 1.30P (mm) - 0.67
T41	*Quercus copeyensis*	2830	-	2.2	-	-
T42	*Quercus copeyensis*	2900	-	16.1	-	-
T43	*Quercus copeyensis*	2900	-	16.6	-	-
T44	Rain forest	-	3627	1.9	-	-
T45	Rain forest with high abundance of ectomycorrhizal trees	5011	5370	2.2	-	-
T46	Rain forest with low abundance of ectomycorrhizal trees	5011	5370	1.5	-	-
T47	Semi-deciduous monsoon forests	1650 - 2650	-	3.0	-	-

T48	*Sloanea berteriana*	3000 - 4000	2246	0.6	9.7 at 33 mm^{calc} 7.7^{calc} 6.3 at 35 mm^{calc} 4.7^{calc} 14.4 at 27 mm^{calc} 12.6^{calc} 2.1 at 36 mm^{calc} 1.6^{calc}	*SF* (L) = 0.29*P* (mm) - 2.31 *SF* (L) = 0.27*P* (mm) - 2.48 *SF* (L) = 0.28*P* (mm) - 1.57 *SF* (L) = 0.13*P* (mm) - 1.25
T49	*Sloanea berteriana*	-	-	1.0	-	-
T50	Small timber extraction forest	2437 - 3424	480 315 300	0.7 0.9 0.6	1.3^{calc} 1.3^{calc} 1.4^{calc}	-
T51	Stunted heath forest	3625 ± 560	2995	0.4	-	*SF* (ml/mm) = 3.2*DBH* (cm) - 10.0
T52	Stunted heath forest	3625 ± 560	2995	1.0	-	*SF* (ml/mm) = 49.0*DBH* (cm) + 2.6
T53	Tall heath forest	3625 ± 560	2995	0.8	-	*SF* (ml/mm) = 1.1*DBH* (cm) + 6.53 *SF* (ml/mm) = 3.3*DBH* (cm) + 13.74
T54	Terra firme rainforest	2442	3064.2	0.7	3.1 at 24 mm^{calc}	*SF* (mm) = 0.013*P* (mm)- 0.06
T55	*Tristania* sp.	3625 ± 560	2995	0.6	-	*SF* (ml/mm) = 35.4*DBH* (cm) - 27.6
T56	Tropical dry forest	1300	304	0.7	-	-
T57	Tropical montane rainforest	-	-	< 0.1	-	-
T58	Tropical rain forest	2442	2721	1.8 ± 1	-	-
T59	Tropical rain forest (228 species)	-	2861	7.1	-	-
T60	Tropical rain forest (100 species)	-	3087	1.8	-	-
T61	Tropical rainforest	3100	3273.8 3293.0 3158.4 3120.9	0.9 0.9 1.5 1.1	-	Plot 1 - $SF = 0.0015P^{1.53}$ Plot 2 - $SF = 0.0020P^{1.467}$ Plot 3 - $SF = 0.0029P^{1.423}$ Plot 4 - $SF = 0.0031P^{1.325}$ Units: *SF*(mm) *P*(mm)
T62	*Vernicia fordii*	1347.2	2086.1	3.6	-	-
T63	*Vismia guianensis, Myrcia* sp. and *Clusia* sp.	2548	2215	2.0	50.0^{calc}	-
T64	*Vismia* spp.	2622	2672	20.3	-	*SF* (L/mm) = 0.026*DBH* (cm) - 0.03

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[a] *BA* = Basal area

Table 2.9. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for Mediterranean studies.

Code	**Species**	**Location**	**Diam. (cm)**	**Density (Trees/ha)**	**BA (m^2/ha)**	**Author**
M01	*Arbutus unedo*	Tarragona, Spain	2.8 3.2 5.4 7.0 10.5	Lone trees	-	Bellot and Escarré (1998)
M02	*Castanea sativa*	Argemil, Tras-os-Montes, Portugal	41.2 39.2	67	-	Portela and Pires (1995) (Llorens and Domingo, 2007)
M03	*Eucalyptus globulus*	Pousadas, Agueda basin, Portugal	13.5	1792	25	Ferreira (1992, 1996) (Llorens and Domingo, 2007)
M04	*Eucalyptus globulus*	Cabeço Cão, Agueda basin, Portugal	12.7	1760	24.6	Ferreira (1992)
M05	*Eucalyptus globulus*	Serra de Cima, Agueda basin, Portugal	7.3	1664	17.3	Ferreira (1992)
M06	*Eucalyptus globulus*	Herdade da Espira, Portugal	14.2	1010	-	Valente *et al*. (1997)
M07	*Eucalyptus macrorhyncha*	Canberra, Austalia	23	292	7.3	Crockford *et al*. (1996)
M08	*Eucalyptus mannifera*	Canberra, Austalia	23	433	10.8	Crockford *et al*. (1996)
M09	*Eucalyptus melliodora*	Canberra, Austalia	15	100	1.4	Crockford *et al*. (1996)
M10	*Eucalyptus nitens*	Collipulli, Chile	-	1560	29.6	Huber and Iroumé (2001)
M11	*Eucalyptus nitens*	Collipulli, Chile	-	850	19.5	Huber and Iroumé (2001)
M12	*Eucalyptus nitens*	Collipulli, Chile	-	633	15.9	Huber and Iroumé (2001)
M13	*Eucalyptus rossii*	Canberra, Austalia	21	700	14.6	Crockford *et al*. (1996)
M14	*Fagus moesiaca*	Pindous MTS, Greece	-	-	-	Michopoulos *et al*. (2001) (Llorens and Domingo, 2007)

M15	*Fagus sylvatica*	Mont Lozère, Lozère, France	10.2	4270	52.2	Didon-Lescot (1996, 1998) (Llorens and Domingo, 2007)
M16	*Fagus sylvatica*	Toscana, Italy	28.5 28.5	-	-	Giacomin and Trucchi (1992)
M17	*Fagus sylvatica*	Selva Piana, Abruzo, Italy	24.3	889	41.2	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M18	*Fagus sylvatica*	Piano Nuda, Campanioa, Italy	39.7	327	40.3	Moreno *et al*. (2001) (Llorens and Domingo
M19	*Fagus sylvatica*	Brasimone, Emilia-Romagna, Italy	10.3	4356	35.15	Moreno *et al*. (2001) (Llorens and Domingo
M20	*Fagus sylvatica*	Pian Cansiglio, Veneto, Italy	36.2	345	35.46	Moreno *et al*. (2001) (Llorens and Domingo
M21	*Fagus sylvatica*	Burgos-Logroño, Spain	4 - 20	526	-	Tarazona *et al*. (1996)
M22	*Fitzroya cupressoides*	Hueicolla, Chile	-	1100	58	Huber and Iroumé (2001)
M23	*Fraxinus ornus* *Quercus pubescentis*	Istrian Peninsula, Slovenia	-	3100	-	Šraj *et al*. (2008)
M24	Holm-oak forest	Tarragona, Spain	-	9178	37.9	Bellot and Escarré (1998); Bellot *et al*. (1999)
M25	*Juniperus oxycedrus*	El Ardal, Murcia, Spain	-	Lone	-	Belmonte (1997); Belmonte and Romero (1998) (Llorens and Domingo, 2007)
M26	Laurel forest	Agua Garcia Mountains, Tenerife	> 6	1693	33.7	Aboal *et al*. (1999); Aboal *et al*. (2002)
M27	Mixed broadleaved	Hueicolla, Chile	-	530	99.6	Huber and Iroumé (2001)
M28	Mixed broadleaved	Mariquina, Chile	-	335	-	Huber and Iroumé (2001)
M29	Mixed broadleaved	Malalcahuello, Chile	-	367	47	Huber and Iroumé (2001)
M30	*Nothofagus dombeyi*	Chile	-	-	-	Uyttendaele and Iroumé (2002) (Johnson and Lehmann, 2006)
M31	*Nothofagus obliqua*	Nacimiento, Chile	-	3500	-	Huber and Iroumé (2001)
M32	*Nothofagus alpina* *Nothofagus dombeyi*	Malalcahuello, Chile	37.6 43.4	133 200	14.8 29.6	Iroumé and Huber (2002)
M33	*Olea europaea*	Coraba, Spain	26 26 26	Lone trees	-	Gomez *et al*. (2002)

M34	*Phyllirea media*	Tarragona, Spain	3.2 3.8 6.5 7.0 13.7	Lone trees	-	Bellot and Escarré (1998)
M35	*Picea abies*	Lozère, France	27	395	22	Didon-Lescot (1996); Didon-Lescot (1998) (Llorens and Domingo, 2007)
M36	*Pinus hapepensis*	El Ardal, Murcia, Spain	-	Lone	-	Belmonte (1997); Belmonte and Romero (1998) (Llorens and Domingo, 2007)
M37	*Pinus nigra* L.	Don Bruno, Sila Greca, Italy	23.1 25.7	1533 867	64.5 44.9	Iovino *et al*. (1998) (Llorens and Domingo, 2007)
M38	*Pinus pinaster*	Barrosa, Agudea Basin, Portugal	32.1	400	32.8	Ferreira (1992, 1996) (Llorens and Domingo, 2007)
M39	*Pinus pinaster*	Bordeaux, France	9 - 15	800	-	Loustau *et al*. (1992)
M40	*Pinus pinaster*	Herdade da Espira, Portugal	33.7	312	-	Valente *et al*. (1997)
M41	*Pinus pinea*	Petit-Saint-Jean, Delta Rhone, France	-	800	-	Ibrahim *et al*. (1982) (Llorens and Domingo, 2007)
M42	*Pinus pinea*	Languedoc, France	20.2	800	33.9	Rapp and Ibrahim (1978) (Llorens and Domingo, 2007)
M43	*Pinus radiata*	Valdivia, Chile	-	733	60	Huber and Iroumé (2001)
M44	*Pinus radiata*	Valdivia, Chile	-	973	65.9	Huber and Iroumé (2001)
M45	*Pinus radiata*	Valdivia, Chile	-	467	51.6	Huber and Iroumé (2001)
M46	*Pinus radiata*	Valdivia, Chile	-	194	34.9	Huber and Iroumé (2001)
M47	*Pinus radiata*	Nacimiento, Chile	-	2000	-	Huber and Iroumé (2001)
M48	*Pinus radiata*	Nacimiento, Chile	-	443	-	Huber and Iroumé (2001)
M49	*Pinus radiata*	Collipulli, Chile	-	460	19.5	Huber and Iroumé (2001)
M50	*Pinus radiata*	Collipulli, Chile	-	220	12	Huber and Iroumé (2001)
M51	*Pinus radiata*	Collipulli, Chile	-	833	13.4	Huber and Iroumé (2001)
M52	*Pinus radiata*	Collipulli, Chile	-	395	6.8	Huber and Iroumé (2001)
M53	*Pinus radiata*	San Ignacio, Chile	-	1206	27.1	Huber and Iroumé (2001)

M54	*Pinus radiata*	San Ignacio, Chile	-	549	13.7	Huber and Iroumé (2001)
M55	*Pinus radiata*	San Ignacio, Chile	-	1143	22.1	Huber and Iroumé (2001)
M56	*Pinus radiata*	San Ignacio, Chile	-	417	8.8	Huber and Iroumé (2001)
M57	*Pinus radiata*	Laja, Chile	-	926	11	Huber and Iroumé (2001)
M58	*Pinus radiata*	Laja, Chile	-	1087	16.5	Huber and Iroumé (2001)
M59	*Pinus radiata*	Canberra, Australia	18	1708	35.1	Crockford *et al*. (1996)
M60	*Pinus radiata*	Chile	-	-	-	Uyttendaele and Iroumé (2002) (Johnson andLehmann, 2006)
M61	*Pinus sylvestris*	S.J. Pena, Aragón, Spain	18.6	1080	52.3	Alvera (1976) (Llorens and Domingo, 2007)
M62	*Pinus sylvestris*	Mediterranean	-	2400	39	Llorens (1997) (Llorens and Domingo, 2007)
M63	*Pinus sylvestris*	Sierra de la Demanda, Spain	-	581	29.6	Santa Regina and Tarazona (2001)
M64	*Pinus sylvestris*	Salamanca, Spain	19.8	1700	-	Santa Regina (1995) (Llorens and Domingo, 2007)
M65	*Pinus sylvestris*	Burgos-Logroño, Spain	30 - 40	581	-	Tarazona *et al*. (1996)
M66	*Pseudotsuga menziesii*	Malalcahuello, Chile	-	1143	97	Huber and Iroumé (2001)
M67	*Quercus cerris*	Carrega, Emigia-Romagna, Italy	12.5	2131	25.9	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M68	*Quercus cerris*	Monte Rufeno, Lazio, Italy	14.1	1623	25.3	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M69	*Quercus cerris*	Monteromano, Lazio, Italy	-	2375	-	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M70	*Quercus ilex*	Tarragona, Spain	1.9 4.1 4.6 6.0 6.2 11.7 12.6 15.1 19.1 23.4	Lone trees	-	Bellot and Escarré (1998)

M71	*Quercus ilex*	Montpellier, France	4 - 12	6885		Limousin *et al*. (2008)
M72	*Quercus ilex*	Colognole, Toscana, Italy	12.7	2366	30.2	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M73	*Quercus ilex*	La Castanya, Montseny Range, Spain	11.3	2127	26.5	Rodrigo and Avila (2001)
M74	*Quercus ilex*	St Pere Vilamajor, Montseny Range, Spain	12	1753	22.3	Rodrigo and Avila (2001)
M75	*Quercus ilex rotundifolia*	Évora, Portugal	0.5 ± 0.11	35 - 45	-	David *et al*. (2006)
M76	*Quercus ilex rotundifolia*	Munovela, Salamanca, Spain	24.9	Lone	-	Calabuig *et al*. (1978) (Llorens and Domingo, 2007)
M77	*Quercus ilex rotundifolia*	Guadalperón, Cáceres, Spain	25.5	Lone	-	Mateos (2001); Mateos and Schnabel (1998) (Llorens and Domingo, 2007)
M78	*Quercus petraea*	Carrega, Emigia-Romagna, Italy	12.5	2131	25.9	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M79	*Quercus pubescens*	Settimo, Crati, Italy	2.2	3250	1.8	Iovino *et al*. (1998) (Llorens and Domingo, 2007)
M80	*Quercus pubescentis Carpinus orientalis croaticus*	Istrian Peninsula, Slovenia	-	900	-	Šraj *et al*. (2008)
M81	*Quercus pyrenaica*	Navasfrias, Salamanca, Spain	15.2	820	14.9	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M82	*Quercus pyrenaica*	El Payo, Salamanca, Spain	25.4	406	20.6	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M83	*Quercus pyrenaica*	Fuenteginaldo, Salamanca, Spain	16.5	738	15.8	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M84	*Quercus pyrenaica*	Villasrubias, Salamanca, Spain	11	1043	9.9	Moreno *et al*. (2001) (Llorens and Domingo, 2007)
M85	*Quercus suber*	Odemira, Portugal	15.8	-	-	Pereira de Almeida and Riekerk (1990)
M86	*Rosmarinus officinalis*	El Ardal, Murcia, Spain	-	Lone	-	Belmonte (1997); Belmonte and Romero (1998) (Llorens and Domingo, 2007)

M87	*Thymus vulgaris*	El Ardal, Murcia, Spain	-	Lone	-	Belmonte (1997); Belmonte and Romero (1998) (Llorens and Domingo, 2007)

Table 2.10. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for Mediterranean studies.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
M01	*Arbutus unedo*	570	1296.26	3.8	72.3 at 23 mm^{calc} 79.9 at 29 mm^{calc} 137.9 at 17 mm^{calc}	*SF* (L) = 0.096*P* (mm) + *0.060* *SF* (L) = 0.072*P* (mm) - *0.318* *SF* (L) = 0.234*P* (mm) - 1.480 *SF* (L) = 0.625*P* (mm) - 1.603 *SF* (L) = 0.425*P* (mm) + 2.276
M02	*Castanea sativa*	1133	2490	0.2	-	-
M03	*Eucalyptus globulus*	1600	156.8	2.9	11.6^{calc}	-
M04	*Eucalyptus globulus*	1600	223.4	2.9	11.8^{calc}	-
M05	*Eucalyptus globulus*	1600	335.7	2.9	16.8^{calc}	-
M06	*Eucalyptus globulus*	600	1545.80	1.7	-	-
M07	*Eucalyptus macrorhyncha*	679	805	0.3^{calc}	4	-
M08	*Eucalyptus mannifera*	679	805	1.1^{calc}	10.6	-
M09	*Eucalyptus melliodora*	679	805	0.2^{calc}	18.6	-
M10	*Eucalyptus nitens*	1540	*1996/97*: 1039 *1997/98*: 1858 *1998/99*: 734	4 4 4	13.5^{calc}	*SF* (mm) = 0.014*P* (mm) + 20.65
M11	*Eucalyptus nitens*	1540	*1996/97*: 1039 *1997/98*: 1858 *1998/99*: 735	3 3 3	15.4^{calc}	*SF* (mm) = 0.014*P* (mm) + 20.65
M12	*Eucalyptus nitens*	1540	*1996/97*: 1039	2.0	12.6^{calc}	*SF* (mm) = 0.014*P* (mm) + 20.65

M13	*Eucalyptus rossii*	679	805	3.1^{calc}	21	-
M14	*Fagus moesiaca*	-	-	8.0	-	-
M15	*Fagus sylvatica*	1900	1537.5	20.4	39.1^{calc}	-
M16	*Fagus sylvatica*	2027	-	13.8 15.0	-	-
M17	*Fagus sylvatica*	1300	-	4.1	-	-
M18	*Fagus sylvatica*	1500	1552.5	1.1	2.7^{calc}	-
M19	*Fagus sylvatica*	1800	1139	6.4	18.2^{calc}	-
M20	*Fagus sylvatica*	1900	1366.5	2.0	5.6^{calc}	-
M21	*Fagus sylvatica*	895	*1986*: 812.8 *1987*: 1669.8 *1988*: 1911	6.0 5.6 8.3	-	-
M22	*Fitzroya cupressoides*	3500	*1982/83*: 4603	9.0	15.5^{calc}	-
M23	*Fraxinus ornus* *Quercus pubescentis*	1000 - 1300	1318	4.5 ± 0.8	-	-
M24	Holm-oak forest	570	1296.26	12.1	30.4 at 16 mm^{calc} 31.9^{calc}	*SF* (mm) = 0.133*P* (mm) - 0.285
M25	*Juniperus oxycedrus*	228	89.7	22.0	-	-
M26	Laurel forest	733	626	6.9	19.2 at 11 mm^{calc} 20.5^{calc}	*SF* (mm) = 0.0719*P* (mm) – 0.0805
M27	Mixed broadleaved	2500	*1982/83*: 3563	4.0	4.0^{calc}	*SF* (mm) = 0.014*P* (mm) + 20.65
M28	Mixed broadleaved	2400	*1986*: 2973 *1987*: 2268 *1988*: 1538 *1989*: 1643 *1990*: 2287 *1991*: 2355 *1993/94*: 2690 *1994/95*: 2066	2 1 1 7 1 1 1 1	-	*SF* (mm) = 0.014*P* (mm) + 20.65
M29	Mixed broadleaved	2350	*1998/99*: 1347	8.0	17.0^{calc}	*SF* (mm) = 0.014*P* (mm) + 20.65

M30	*Nothofagus dombeyi*	1982	-	2.0	-	-
M31	*Nothofagus obliqua*	1200	*1991/92*: 1973	3.0	-	SF (mm) = 0.014P (mm) + 20.65
M32	*Nothofagus alpina* *Nothofagus dombeyi*	2341	3805	7.0	16.0 at 19 mm^{calc} 15.8^{calc}	SF (mm) = 0.085P (mm) - 0.263
M33	*Olea europaea*	606	180.17	3.9 7.9 5.4	51 85 60	SF (mm) = 0.0509P (mm) - 0.1814^{calc} SF (mm) = 0.1055P (mm) - 0.3962^{calc} SF (mm) = 0.0606P (mm) - 0.1012^{calc}
M34	*Phyllirea media*	570	1296.26	1.6	77.6 at 39 mm^{calc} 117.1 at 33 mm^{calc} 118.1 at 9 mm^{calc} 47.9 at 30 mm^{calc} 19.9 at 22 mm^{calc}	SF (L) = 0.087P (mm) - 0.958 SF (L) = 0.175P (mm) - 1.393 SF (L) = 0.428P (mm) - *0.324* SF (L) = 0.239P (mm) - 1.643 SF (L) = 0.361P (mm) - 1.477
M35	*Picea abies*	1900	1537.5	0.7	3.2^{calc}	-
M36	*Pinus hapepensis*	228	217.8	1.7	-	-
M37	*Pinus nigra* L.	1179		0.7 0.8	-	-
M38	*Pinus pinaster*	1600	990.1	1.1	3.4^{calc}	-
M39	*Pinus pinaster*	920	*1987*: 139.4 *1988*: 97.5 *1988*: 190.3 *1989*: 82.5	3.4 4.9 2.7 4.2	-	-
M40	*Pinus pinaster*	600	1366.20	0.3	-	-
M41	*Pinus pinea*	494	-	2.3	-	-
M42	*Pinus pinea*	648	769	2.3	6.8^{calc}	-
M43	*Pinus radiata*	2150	*1982*: 2389 *1983*: 1628 *1984*: 2059 *1985*: 2295 *1986*: 2341 *1987*: 1841	13 12 12 11 10 9	21.7^{calc} 20.0^{calc} 20.0^{calc} 18.3^{calc} 16.8^{calc} 15.0^{calc}	SF (mm) = 0.106P (mm) - 72.29
M44	*Pinus radiata*	2150	*1992/93*: 2925 *1993/94*: 2075	10 9	15.2^{calc} 13.7^{calc}	SF (mm) = 0.106P (mm) - 72.29

M45	*Pinus radiata*	2150	*1992/93*: 2925 *1993/94*: 2075 *1994/95*: 2394 *1996/97*: 2574 *1997/98*: 1676	8 8 8 8 8	15.5^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M46	*Pinus radiata*	2150	*1992/93*: 2925 *1993/94*: 2075 *1994/95*: 2394 *1996/97*: 2574 *1997/98*: 1676	6 5 5 5 6	17.2^{calc} 14.3^{calc} 14.3^{calc} 14.3^{calc} 17.2^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M47	*Pinus radiata*	1200	*1991/92*: 1971	5.0	-	*SF* (mm) = 0.106*P* (mm) - 72.29
M48	*Pinus radiata*	1200	*1991/92*: 1972	3.0	-	*SF* (mm) = 0.106*P* (mm) - 72.29
M49	*Pinus radiata*	1540	*1996/97*: 1039 *1997/98*: 1858	3 3	15.4^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M50	*Pinus radiata*	1540	*1996/97*: 1039 *1997/98*: 1858	1 2	8.3^{calc} 16.7^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M51	*Pinus radiata*	1540	*1996/97*: 1039 *1997/98*: 1858 *1998/99*: 734	2 2 2	14.9^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M52	*Pinus radiata*	1540	*1996/97*: 1039	1.0	14.7^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M53	*Pinus radiata*	1000	*1998/99*: 1005	5.0	18.5^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M54	*Pinus radiata*	1000	*1998/99*: 1005	4.0	29.2^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M55	*Pinus radiata*	1000	*1998/99*: 1005	6.0	27.1^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M56	*Pinus radiata*	1000	*1998/99*: 1005	2.0	22.7^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M57	*Pinus radiata*	1000	*1998/99*: 1038	1.0	9.1^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M58	*Pinus radiata*	1000	*1998/99*: 1038	3.0	18.2^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M59	*Pinus radiata*	679	824	11.2^{calc}	32	-
M60	*Pinus radiate*	1982	-	22.0	-	-
M61	*Pinus sylvestris*	931	858	0.8	-	-
M62	*Pinus sylvestris*	850	-	1.3	-	-
M63	*Pinus sylvestris*	886	1254	0.5	1.7^{calc}	-
M64	*Pinus sylvestris*	985	1021	10.8	-	-

M65	*Pinus sylvestris*	895	*1986*: 600.7 *1987*: 1281.4 *1988*: 1678.7	0.35 0.5 0.4	-	-
M66	*Pseudotsuga menziesii*	2350	*1998/99*: 1346	6.0	6.2^{calc}	*SF* (mm) = 0.106*P* (mm) - 72.29
M67	*Quercus cerris*	1200	748	3.1	12.0^{calc}	-
M68	*Quercus cerris*	1000	991.5	10.4	41.1^{calc}	-
M69	*Quercus cerris*	-	-	6.3	-	-
M70	*Quercus ilex*	570	1296.3	6.6	62.8 at 35 mm^{calc} 60.9	*SF* (L) = 0.024*P* (mm) - *0.217*
					37.9 at 34 mm^{calc} 32.0	*SF* (L) = 0.072*P* (mm) - *0.944*
					46.8 at 36 mm^{calc} 44.8	*SF* (L) = 0.106*P* (mm) - *1.015*
					34.0	*SF* (L) = 0.069*P* (mm) + *0.899*
					129.6 at 9 mm^{calc} 137.0	*SF* (L) = *0.430P* (mm) - 0.349
					20.7 at 24 mm^{calc} 21.6	*SF* (L) = 0.273*P* (mm) - 1.218
					21.5 at 29 mm^{calc} 21.8	*SF* (L) = 0.347*P* (mm) - 2.305
					27.9 at 25 mm^{calc} 29.0	*SF* (L) = 0.619*P* (mm) - 2.977
					16.4 at 29 mm^{calc} 16.7	*SF* (L) = 0.603*P* (mm) - *3.825*
					26.2 at 25 mm^{calc} 27.2	*SF* (L) = 1.393*P* (mm) - *6.703*
M71	*Quercus ilex*	908	1605	12.5	-	*SF* (mm) = 0.16*P* (mm) - 0.98
M72	*Quercus ilex*	900	861.5	3.4	11.3^{calc}	-
M73	*Quercus ilex*	876	1275.2	2.7	10.2^{calc}	-
M74	*Quercus ilex*	876	1048.2	5.3	23.8^{calc}	-
M75	*Quercus ilex rotundifolia*	665	1736.4	0.3	-	-
M76	*Quercus ilex rotundifolia*	432	-	0.6	-	-
M77	*Quercus ilex rotundifolia*	516	755	0.7	-	-
M78	*Quercus petraea*	1200	748	4.7	18.1^{calc}	-
M79	*Quercus pubescens*	1021	-	0.3	-	-
M80	*Quercus pubescentis* *Carpinus orientalis croaticus*	1000 - 1300	1318	2.9 ± 0.6	-	-
M81	*Quercus pyrenaica*	1580	1056.7	0.9	6.0^{calc}	-

M82	*Quercus pyrenaica*	1245	933.3	0.64	3.1^{calc}	-
M83	*Quercus pyrenaica*	720	624.7	0.8	5.1^{calc}	-
M84	*Quercus pyrenaica*	872	825	0.6	6.1^{calc}	-
M85	*Quercus suber*	-	-	1.3	-	-
M86	*Rosmarinus officinalis*	228	181.3	42.5	-	-
M87	*Thymus vulgaris*	228	181.3	31.2	-	-

Table 2.11. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for arid and semi-arid studies.

Code	**Species**	**Location**	**Diam. (cm)**	**Density (Trees/ha)**	**BA (m^2/ha)**	**Author**
S01	*Acacia aneura*	South-Western Queensland, Australia	-	-	-	Pressland (1973)
S02	*Acacia farnesiana*	Nuevo Leon, Mexico	12.75	Lone shrubs	-	Návar (1993); Návar and Bryan (1990)
S03	*Acacia rigidula*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)
S04	*Adenocarpus decorticans*	Filabres, Almeria, Spain	12.4	Lone	-	Domingo *et al*. (1994); Llorens and Domingo (2007)
S05	*Anthyllis cytisoides*	Almería, Spain	-	Lone	-	Domingo *et al*. (1998); Llorens and Domingo (2007)
S06	*Artemisia sphaerocephala*	Mu Us, China	-	-	-	Yang *et al*. (2008)
S07	*Bumelia celastrina*	Nuevo Leon, Mexico	-	-	-	Návar et al. (1999)
S08	*Caragana korshinskii*	Gaolan, China	-	-	-	Li *et al*. (2008)
S09	*Cistus laurifolius*	Filabres, Almeria, Spain	8.3	Lone	-	Domingo *et al*. (1994); Llorens and Domingo (2007)
S10	*Condalia hookeri*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)
S11	*Cordia boissieri*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)
S12	*Diospyros palmeri*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)

S13	*Diospyros texana*	Nuevo Leon, Mexico	9.22	Lone shrubs	-	Návar (1993); Návar and Bryan (1990)
S14	*Ficus benjamina*	Queretaro City, Mexico	22.4	Lone	-	Guevara-Escobar *et al*. (2007)
S15	*Flourensia cernua*	New Mexico, USA	-	-	-	Martínez-Meza and Whitford (1996)
S16	*Grevillea robusta*	Machakos, Kenya	-	-	-	Jackson (2000)
S17	*Hedysarum scoparium*	Shaanxi, China	-	-	-	Li *et al*. (2009)
S18	*Larrea divaricata*	Viedma, Argentina	-	-	-	Cecchi *et al*. (2006)
S19	*Larrea tridentata*	Las Cruces, New Mexico	-	-	-	Abrahams *et al*. (2003)
S20	*Larrea tridentata*	New Mexico, USA	-	-	-	Martínez-Meza and Whitford (1996)
S21	*Larrea tridentata*	Las Cruces, New Mexico	-	Lone shrubs	-	Whitford *et al*. (1997)
S22	Matorral community	Santa Rosa de Iturbide, Mexico	-	-	16.2	Carlyle-Moses (2004)
S23	*Pinus halepensis*	Yatir forest, Israel	-	360	-	Shachnovich *et al*. (2008)
S24	*Pinus nigra*	Filabres, Almeria, Spain	5.8	Lone	-	Domingo *et al*. (1994); Llorens and Domingo (2007)
S25	*Pinus pinaster*	Filabres, Almeria, Spain	12.8	-	-	Domingo *et al*. (1994); Llorens and Domingo (2007)
S26	*Pithecellobium pallens*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)
S27	*Prosopis glandulosa*	New Mexico, USA	-	-	-	Martínez-Meza and Whitford (1996)
S28	*Prosopis laevigata*	Nuevo Leon, Mexico	10.6	Lone shrubs	-	Návar (1993); Návar and Bryan (1990)
S29	*Prosopis laevigata*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)
S30	*Quercus emoryi*	Arizona, USA	11.7 - 45.9	-	-	Haworth and McPherson (1995)
S31	*Reaumuria soongorica*	Gaolan, China	-	-	-	Li *et al*. (2008)
S32	*Retama sphaerocarpa*	Almería, Spain	1.7	Lone	-	Domingo *et al*. (1994); Llorens and Domingo (2007)
S33	*Salix psammophila*	Shaanxi, China	-	-	-	Li *et al*. (2009)
S34	*Salix psammophila*	Mu Us, China	-	-	-	Yang *et al*. (2008)
S35	*Tamarix ramosissima*	Gaolan, China	-	-	-	Li *et al*. (2008)

S36	Tamaulipan thornscrub	Nuevo Leon, Mexico	2.3 - 3.9	-	-	Návar *et al*. (1999)
S37	*Zanthoxylum fragara*	Nuevo Leon, Mexico	-	-	-	Návar *et al*. (1999)

Table 2.12. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for arid and semi-arid studies.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
S01	*Acacia aneura*	-	618.55	18.0	-	BA(0-0.01): $SF = 1.446P - 0.026P^2 - 2.235$ BA(0.01-0.03): $SF = 2.198P + 0.191$ BA(0.03-0.065): $SF = 6.047P - 6.842$ BA(>0.065): $SF = 8.085P - 5.128$ P(0-6.25): $SF = 0.026BA + 1.631$ *P(6.25-12.5):* $SF = 0.076BA + 7.751$ P(12.5-25): $SF = 0.162BA + 0.369$ P(>25): $SF = 0.280BA + 13.810$ Units: P (mm) *SF* (L) *BA* (cm^2)
S02	*Acacia farnesiana*	-	230	0.6	11.7	-
S03	*Acacia rigidula*	805	489.1	-	-	SF (mm) = $0.038P$ (mm) - 0.085
S04	*Adenocarpus decorticans*	395	650	4.4	-	-
S05	*Anthyllis cytisoides*	300	-	20.0	-	-
S06	*Artemisia sphaerocephala*	395	173	2.7	41.5	SF (mm) = $0.024P$ (mm) + 0.015
S07	*Bumelia celastrina*	805	489.1	-	-	SF (mm) = $0.014P$(mm) - 0.019
S08	*Caragana korshinskii*	263	-	7.2	153.5 ± 66.2 Event high: 292	SF (mm) = $0.079P$ (mm) - 0.028 SF (mm) = $0.107P$ (mm) - $0.036I$ (mm/h) - 0.056
S09	*Cistus laurifolius*	395	650	7.2	-	-

S10	*Condalia hookeri*	805	489.1	-	-	*SF* (mm) = 0.013*P* (mm) - 0.040
S11	*Cordia boissieri*	805	489.1	-	-	*SF* (mm) = 0.027*P* (mm) - 0.066
S12	*Diospyros palmeri*	805	489.1	-	-	*SF* (mm) = 0.034*P* (mm) - 0.080
S13	*Diospyros texana*	-	230	5.6	57.7	-
S14	*Ficus benjamina*	548	152	2.4	16.8 at 5 mm[calc] 17.2[calc]	*SF* (mm) = 0.0248*P* (mm) – 0.007[calc]
S15	*Flourensia cernua*	230	-	Summer: 10.6 Winter: 10.5	-	*SF* (L) = 3·9*A* (m^2) + 4.8[a]
S16	*Grevillea robusta*	782	1583.00	0.7	-	-
S17	*Hedysarum scoparium*	395	-	3.4	77.8 Event high: 203	*SF* (mm) = 0.034*P* (mm) - 0.046
S18	*Larrea divaricata*	350	-	Disturbed: 3.6 Intact: 7.2	-	*SF* = 0.0361*P* - 0.1512 *SF* = 0.0722*P* - 0.3483 All units in mm
S19	*Larrea tridentata*	245	-	6.7	-	*SF* (cm/h) = 0.16*A* (cm^2) *P* (cm/h)
S20	*Larrea tridentata*	230	-	10	-	*SF* (L) = 17·0 + 20·5*V* (m^3)[b]
S21	*Larrea tridentata*	235	-	16.8 ± 1.9	-	-
S22	Matorral community	635 ± 145	-	8.5 ± 1.9	21.1	*SF* = [21.13(*P* x *BA*)]n_{stem}[c] Units: *SF* (L) *P* (mm) *BA* (m^2)
S23	*Pinus halepensis*	280	*2000/01*: 306 *2001/02*: 307 *2002/03*: 341.5	2.1 1.4 1.5	-	*SF* (mm) = 0.02*P* (mm) - 0.06
S24	*Pinus nigra* Ar.	395	650	12.3	-	-
S25	*Pinus pinaster*	395	650	1.5	-	-
S26	*Pithecellobium pallens*	805	489.1	-	-	*SF* (mm) = 0.037*P* (mm) - 0.068
S27	*Prosopis glandulosa*	230		Summer: 5.4 Winter: 5.3	-	*SF* (L) = 10·3*A* (m^2) + 7.6
S28	*Prosopis laevigata*		230	0.6	11.1	-
S29	*Prosopis laevigata*	805	489.1	-	-	*SF* (mm) = 0.005*P* (mm) - 0.012

S30	*Quercus emoryi*	600	-	-	-	$\ln(SF) = 8.65 + 0.036(A) - 11^{e\text{-}1.36(P)}$ Units: SF(ml) CA(m^2) P(mm)
S31	*Reaumuria soongorica*	263	-	3.7	53.2 ± 25.7 Event high: 97	SF (mm) = 0.065P (mm) - 0.13 SF (mm) = -0.103 + 0.066P (mm) - 0.019I (mm/h)
S32	*Retama sphaerocarpa*	300	-	7.0	-	-
S33	*Salix psammophila*	395	-	6.3	48.7 Event high: 117	SF (mm) = 0.063P (mm) - 0.139
S34	*Salix psammophila*	395	173	7.6	69.4	SF (mm) = 0.057P (mm) + 0.136
S35	*Tamarix ramosissima*	263	-	2.2	24.8 ± 15.3 Event high: 54	SF (mm) = 0.039P (mm) - 0.083 SF (mm) = 0.041P (mm) - 0.001I (mm/h) - 0.070
S36	Tamaulipan thornscrub	805	489.1	3.0 ± 1.9	-	-
S37	*Zanthoxylum fragara*	805	489.1	-	-	SF (mm) = 0.007P (mm) - 0.012

[a] A = Canopy area

[b] V = Canopy volume

[c] n_{stems} = Number of stems

Table 2.13. Species, location, stand information (diameter: Diam, tree density: Density, stand basal area: BA), author(s), and alphanumeric code for agroforestry studies.

Code	Species	Location	Diam. (cm)	Density (Trees/ha)	BA (m^2/ha)	Author
A01	Agroforest	Central Sulawesi, Indonesia	-	1706 2705 2612	8.6 23.7 26.5	Dietz *et al*. (2006)
A02	*Bactris gasipaes*	Manaus, Brazil	16.5 < 8	625 1875	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
A03	*Bactris gasipaes*	Manaus, Brazil	-	2500	-	Schroth *et al*. (1999); Schroth *et al*. (2001)

A04	*Bertholletia excelsa*	Manaus, Brazil	8.4	93	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
A05	*Bixa orellana*	Manaus, Brazil	-	156	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
A06	Cacao plantation	-	-	-	-	Opakunle (1989) (Levia and Frost, 2003)
A07	*Manihot esculenta* *Zea mays* *Oryza sativa*	West Java, Indonesia	-	-	-	van Dijk *et al*. (2001)
A08	*Musa* sp.	Capesterre-Belle-Eau, Guadeloupe	-	-	-	Cattan *et al*. (2007)
A09	*Musa* sp.	Roseau, St Lucia	-	-	-	Harris (1997)
A10	*Phyllostachys pubescens*	Munakata, Japan	12.4 13.4 13.7	6800	-	Onozawa *et al*. (2009)
A11	*Theobroma grandiflorum*	Manaus, Brazil	5.5	93	-	Schroth *et al*. (1999); Schroth *et al*. (2001)
A12	*Zea mays* *Grevillea robusta*	Machakos, Kenya	-	-	-	Jackson (2000)

Table 2.14. Species, meteorological data (annual rainfall: P_A, and study period rainfall: P_S), stemflow production information (funnelling ratio(s): F, and percentage of gross rainfall diverted to stemflow: SF), and stemflow formulae for agroforestry studies.

Code	**Species**	**P_A (mm)**	**P_S (mm)**	**SF (%)**	**F**	**Formula(s)**
A01	Agroforest	2437 - 3424	293 172 214	0.7 0.9 1.0	8.1^{calc} 3.8^{calc} 3.8^{calc}	-
A02	*Bactris gasipaes*	2622	2672	24.7	-	*SF* (L/mm) = 5.32 - 0.224 *DBH* (cm)
A03	*Bactris gasipaes*	2622	2672	20.6	-	*SF* (L/mm) = 0.114*DBH* (cm) - 0.09
A04	*Bertholletia excelsa*	2622	2672	0.8	-	*SF* (L/mm) = 0.303*DBH* (cm) - 2.59

A05	*Bixa orellana*	2622	2672	0.1	-	-
A06	Cacao plantation	-	-	2.0	-	-
A07	*Manihot esculenta* *Zea mays* *Oryza sativa*	2600	*1995*: 1577 *1999*: 1642	2.4 3.9	-	*SF* (L/m^2)= 0.054*TF* (mm)[a]
A08	*Musa* sp.	3850	Vegetative: 164 Flowering: 158 Bunch: 151	25.6 24.1 17.9	Ve: 20 Fl: 28 Bu: 28	*F* = 11.2*LAI*[b c]
A09	*Musa* sp.	-	-	10.0	13	-
A10	*Phyllostachys pubescens*	1697	2105	15.3	-	-
A11	*Theobroma grandiflorum*	2622	2672	0.1	-	-
A12	*Zea mays* *Grevillea robusta*	782	1583.00	0.6	-	-

[a] *TF* = Throughfall

[b] *F* = Funnelling ratio

[c] *LAI* = Leaf area index

CHAPTER 3

MODELLING STEMFLOW PRODUCTION BY JUVENILE LODGEPOLE PINE (*PINUS CONTORTA* VAR. *LATIFOLIA*) TREES IN SOUTHERN BRITISH COLUMBIA, CANADA

INTRODUCTION

Stemflow is rainfall that has been intercepted by vegetation cover and subsequently directed down the stem or trunk of the plant or tree to its base. The ability of vegetation to produce stemflow can be described quantitatively using the stemflow funnelling ratio (Herwitz, 1986), which represents the ratio between the stemflow volume collected at the base of the plant's stem or tree's bole to the volume of rainfall that would have been collected by a rain gauge having an area equal to that of the base of the plant stem / tree bole in the absence of vegetation cover. The stemflow funnelling ratio is calculated as (Herwitz, 1986):

$$F = SF/(Pg \cdot BA) \tag{3.1}$$

where F is the funnelling ratio (dimensionless), SF is stemflow volume (L), Pg is rainfall depth (mm), and BA is the basal area of the plant's stem or tree's bole (m^2).

Stemflow has received relatively little attention in the hydrologic literature due to its volumetric insignificance at the plot-scale and beyond when compared to throughfall and canopy interception loss (Levia and Frost, 2003). However, stemflow may still be of hydrological and biogeochemical importance since it is a focused point source of water at the base of a plant or tree (Herwitz, 1986; Levia and Frost, 2003). The importance of stemflow as a source of soil moisture has been highlighted by a number of studies (Voigt, 1960; Tanaka *et al*., 1996; Taniguchi *et al*., 1996; Whitford *et al*., 1997). Taniguchi *et al*. (1996) found that 20 % of groundwater recharge within a red pine forest in Japan originated as stemflow, while in a rainforest in Queensland, Australia, Herwitz (1986) showed that large concentrations of stemflow can exceed the infiltration capacity of soil and result in Hortonian overland flow subsequently causing erosion. Stemflow has also been found to be a concentrated source of nutrients and, in some cases, pollutants

(Brinson *et al*., 1980; Chang and Matzner, 2000; Schroth *et al*., 2001; Johnson and Lehmann, 2006).

Only two studies have examined stemflow production by tree species in the Interior of British Columbia, with both of these studies being conducted within mature coniferous stands. Spittlehouse (1998) reported a stemflow fraction of < 0.5 % of a 454 mm May – October study period rainfall record for both a mature *Pinus contorta* var. *latifolia* (lodgepole pine) stand, and a mature *Picea glauca* x *engelmannii* (hybrid white spruce) - *Abies lasiocarpa* (subalpine fir) forest, while Moore *et al*. (2008) reported that stemflow comprised 0.2 % of the rainfall over two growing seasons within a mature lodgepole pine – hybrid white spruce – subalpine fir stand. The results of these studies suggest that stemflow is a minor component of the canopy water balances of mature coniferous forests in the Interior of British Columbia.

British Columbia is currently undergoing a *Dendroctonus ponderosae* (mountain pine beetle – MPB) epidemic which has been forecast to kill ~ 77 % of all merchantable pine in the province by 2014 (Walton *et al*., 2007). In addition, the frequency of wildfires in British Columbia is projected to increase as a consequence of global climatic change (BC Ministry of Water, Land and Air Protection, 2004). Due to these disturbances, many of the province’s interior watersheds will see a shift in land-cover dominated by mature conifers to stands at various stages of juvenile re-growth. This shift in stand composition brings with it many uncertainties, including the impacts on site hydrology. One aspect of the forest water balance that may be altered is the quantitative importance of stemflow. McKee and Carlyle-Moses (2010) found that juvenile lodgepole pine trees produced more stemflow compared to mature trees; however, no studies to date have examined factors influencing stemflow production from juvenile lodgepole pine.

Despite studies that have highlighted the influence of a multitude of variables on stemflow production (Levia and Frost, 2003), the majority of stemflow simulation models produced to date only utilize one independent variable, normally rainfall depth or plant / tree diameter. However, other variables have also been shown to exert a control on the quantity of stemflow produced, including, branching angle (Herwitz, 1987; Návar, 1993; Martínez-Meza and Whitford, 1996), number of branches (Návar, 1993), tree height (Brown and Baker, 1970), storm duration and intensity (Brown and Baker, 1970; Crockford and Richardson, 2000), crown projection area (Brown and Baker, 1970; Pressland 1973; Aboal *et al*., 1999; Park and Hattori, 2001), and bark roughness (Horton, 1919; Aboal *et al*., 1999). Logistically, it would be difficult to collect sufficient data to include all of the potential factors influencing stemflow production; however, the inclusion of more than one predictive variable would lead to more accurate modelling (Levia and Frost, 2003) and improve our understanding of how tree architecture and meteorological conditions influence stemflow production.

The objective of this research was threefold: (1) to identify the abiotic and biotic factors that influence stemflow production by lodgepole pine, (2) to incorporate the most influential of these factors into a predictive model of stemflow yield from this forest type, and (3) to evaluate the spatial transferability of the developed model.

MATERIALS AND METHODS

Site description

Measurements of incident rainfall and stemflow were made from 1 June, 2009 to 31 October, 2009 at the Mayson Lake Hydrological Processes Study Area (MLk) located approximately 60 km NNW of Kamloops, British Columbia on the Thompson-Bonaparte Plateau at 51^{o} 13’ N, 120^{o} 24’ W. The MLk, located at an elevation of ~1260 m a.m.s.l., is situated within the Montane Spruce Biogeoclimatic Zone (MSdm2), a zone typified by cold winters and moderately short, warm summers (Lloyd *et al*., 1990). The nearest long-term meteorological station with a comparable elevation to the study site, 1155 m a.m.s.l, is Bridge Lake 2 (Meteorological Service of Canada Climate Station ID = 1160986). This station, located approximately 41 km NNW of the study area, has a mean annual rainfall depth of approximately 600 mm (1980 – 2000) with approximately half falling during the growing-season (mid-May to September, inclusive) in the form of rain. Snow is the dominant form of precipitation during the dormant season. Mean annual temperature at the Bridge Lake 2 station is 3.7 ^{o}C with mean monthly values ranging from -7.8 ^{o}C in December to 14.2 ^{o}C in July and August.

Data were largely collected from two plots situated within juvenile lodgepole pine dominated stands. These two juvenile stands, designated Plots E and D (Figures 3.1 and 3.2, respectively), were replanted after commercial harvesting. Detailed tree and stand characteristics for Plots E and D can be found in Table 3.1. Stemflow was also measured in three additional plots: Plot A – a mature pine-spruce-fir stand of ~ 125 years of age with most pine at the MPB grey attack stage, Plot B – a pine dominated stand of ~ 27 years of age at the red / grey MPB attack stage, and Plot C – a stand of ~ 16 years of age largely comprised of healthy pine, although a few individuals were at the green or red MPB attack stage. Plots A, B, C, and E measured 72 m by 40 m in size, while Plot D measured 160 m by 24 m.

Table 3.1. Stand characteristics for Plots E and D.

		Plot E	Plot D
Stand Age (yrs)		~ 7	~ 9
Avg. Tree Diameter (cm)		2.7	3.5
Avg. Tree Height (m)		1.42	2.01
Avg. Tree CPA (m^2)		0.43	0.63
Tree density (trees ha^{-1})		8476	7974
BA (m^2 ha^{-1})		7.4	10.9
Avg. Number of branches per tree		23	32
Composition (%)	Pine	86	79
	Subalpine Fir	14	21
Relative Dominance of Pine (%)		94	89

Meteorological data

The meteorological station used for this study was situated in the centre of Plot E and was equipped with an Onset® Wind Speed and Direction Smart Sensor (product # S-WCA-M003) and an Onset® Temperature / Relative Humidity Smart Sensor (product # S-THA-M002). Measurements of wind speed, temperature and relative humidity were taken 2 m above the principal tree canopy on a 30 second time-step and averaged and

Figure 3.1. View of Plot E from the northwest corner of the plot.

Figure 3.2. View of Plot D from the centre looking south.

logged on 10 minute time-step using a Hobo® Micro Station data logger (product # H21-002). Rainfall depth and intensity measurements were taken in locations closest to each plot that allowed for unobstructed measurement. At each location rainfall was measured using an Onset ® Data Logging Rain Gauge (product # RG-3-M) with an orifice diameter of 15.4 cm and a resolution of 0.2 mm tip^{-1} as well as a cylindrical polyethylene gauge having a diameter of 29.0 cm in which the volume of collected rainfall was measured using a graduated cylinder. Rainfall measurements for Plots A, B, and C were taken in a fire break located ~ 630 m from the geographic centre of Plot A and ~ 560 and 310 m from the centres of Plots B and C, respectively. Rainfall measurements for Plots D and E were taken with both an Onset® rain gauge and a cylindrical polyethylene gauge situated in clearings no further than ~ 90 m from the centres of each of the two plots. A rain event was defined for this study as a period of rainfall bounded by periods of eight hours with no measurable rainfall, as this was the observed maximum time required for the juvenile pine canopies and boles to dry completely.

Stemflow collection

Stemflow was sampled from lodgepole pine trees only. Plots A, B, and C contained seven, seven, and five stemflow collection systems, respectively. Stemflow in these three plots was collected using stemflow collars constructed from 2.5 cm diameter corrugated flexible tubing that was cut in half lengthwise, then wrapped 360° around the tree on a downward angle and secured with nails and silicone sealant (Levia, 2004). An uncut piece of corrugated tubing running from the stemflow collar diverted the intercepted stemflow to a collection container at the base of the tree. Stemflow collection containers in these three plots ranged in capacity from 4 to 20 L depending on the expected stemflow production of each tree.

Stemflow in Plots D and E was sampled more intensely than the other plots because previous research showed that juvenile lodgepole pine trees were more efficient stemflow producers when compared to mature pine trees (McKee and Carlyle-Moses, 2010). Thirty-six and thirty-seven trees were sampled for stemflow in plots D and E, respectively. Twelve relatively small, 12 medium, and 12 large trees were sampled in Plot D in order to achieve a representative sample. The same sampling method was used in Plot E with the addition of one medium tree. Adjacent to Plot E, one small, one medium, and one large tree had their branches and trunk needles removed. Stemflow collars were attached to these trees in an attempt to further understand the influence of abiotic factors by eliminating tree architecture completely. Sample trees were located outside of Plot E on the northeast edge to insure that experiments inside the plot were not influenced by anthropogenic damage to these trees. Each stemflow collar in these two plots was constructed using fabricated plastic funnels that were cut vertically, then wrapped and sealed to the tree near the base of the bole using silicone sealant (Figure 3.3). A plastic tube with a diameter of ~ 1.0 cm connected the inner portion of the stemflow collar to a 4 L collection container for subsequent measurement. All stemflow collars in the five plots were tested weekly to determine if any leakage may have occurred due to tree growth and/or animal disturbance. If a stemflow collar had a leak it was noted and promptly repaired and any data collected since the prior test was discarded. Collected stemflow was measured after each rainfall event using a graduated cylinder.

Figure 3.3. Stemflow collar and collection container used in Plots E and D.

Tree characteristics

Stand level characteristics were recorded along with individual tree characteristics for trees associated with stemflow collection. The point-quarter method (Mueller *et al*., 1974) was used to determine tree density, species frequency, and basal area information required to determine stand scale stemflow production for Plots D and E. In order to relate stemflow production to tree architecture, tree characteristics were recorded for each plot. In Plots A, B, and C, tree diameter and height were recorded for all trees being sampled for stemflow. As the focus of this research was on juvenile trees, more detailed tree characteristics were recorded in Plots D and E. In these two plots, tree height, number of branches, canopy width, branching angle, and tree diameter (at the base just under the first branch) were recorded for each tree sampled for stemflow. North, south, east, and west facing branches were selected at the base and top of the tree, as well as at one-third and two-thirds the tree height. Branching angle where the branch met the tree bole was recorded for each of these branches, measured from the horizontal yielding a positive or negative angle. Canopy width was also derived for the four sampled levels for each tree by taking the average horizontal distance from the outermost extent of the branch projecting in a northerly direction to that projecting in a southerly direction and the outermost extent of the easterly branch to that of the branch extending westward.

A proximity metric was developed for Plots D and E to determine if sheltering by neighbouring trees had an influence on stemflow production. All trees whose canopies extended to within a 45^{o} cone of the base of a stemflow tree were recorded. The distance of each of the neighbouring trees from the tree sampled for stemflow, as well as the height of those trees, were recorded. The proximity statistic was then calculated for each stemflow tree as:

$$M = n \cdot \overline{H}/\overline{D} \tag{3.2}$$

where M is the proximity metric (dimensionless), n is the number of trees whose heights' extended to within a 45^{o} cone centred on the base of the tree sampled for stemflow, while $\overline{H}$ and $\overline{D}$ are the average height (m) and average horizontal distance (m) from the tree sampled for stemflow of the n trees.

Statistical analysis

Statistical analysis and modelling was performed using Microsoft® Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA) spreadsheet application and Minitab® 15 (Minitab Inc., State College, PA, USA) statistical software. Excel 2010 was used for data organization and graphing, while Minitab 15 was used to perform stepwise multiple regression analysis. Levels of statistical significance reported in this study were at the $p < 0.05$ level.

Modelling procedure

Park and Hattori (2002) suggested that the slope, a, and the intercept, b, associated with the linear relationship between stemflow depth (mm) and rainfall depth (mm) [i.e., Stemflow = $a \cdot$ Rainfall + b] for a single tree or an entire stand may be related to the tree / stand diameter at breast height (DBH) in the form of power relationships:

$$a = A(DBH)^{\beta 1} \tag{3.3}$$

$$b = B(DBH)^{\beta 2} \tag{3.4}$$

where A, B, $\beta 1$, and $\beta 2$ are regression coefficients, while DBH is diameter at breast height.

In contrast to Park and Hattori (2002), the slope (a) and intercept (b) values in this study were compared against a number of different abiotic and biotic factors to determine which factor(s) had a statistically significant influence on stemflow production. Biotic factors were analysed on the event basis and abiotic factors were analysed on a per tree basis. The analysis was conducted in this manner because a multiple regression could not be conducted with all independent variables versus stemflow volume due to some variables changing from tree to tree, while others only changed from event to event. This resulted in linear equations replacing Eqs. 3.3 and 3.4 containing one or more variables. Regression between event rainfall depth (mm) and associated stemflow volume (L) was conducted for each tree in order to produce a and b values. Stepwise multiple regression was then conducted to determine which variables explained variations in a and b for Plot E and for Plot D. The candidate biotic predictor variables were: total number of branches, tree height (m), tree diameter (cm), the proximity metric (dimensionless), canopy width (m) and branching angle (^{o}), at the top, two-thirds of the height, one-third of the height, and at the bottom of the tree. The candidate abiotic predictor variables were rainfall depth (mm), intensity (mm h^{-1}), storm duration (h), maximum wind gust speed (m s^{-1}), as well as storm duration (h), wind speed (m s^{-1}), and vapour pressure deficit (kPa) when rainfall intensity ≥ 0.4 mm h^{-1}.

Once Plot E and Plot D models have been produced, they will be examined to determine if common variables exist between the two, and if they do, simplified models will be produced using those variable(s). Data sets used to produce simplified models will then be combined if their slopes and intercepts are not significantly different. The regression process employing common variable(s) will then be repeated using the combined dataset to produce a generic model of stemflow prediction for these stands.

RESULTS

Funnelling ratios for lodgepole pine

For the research period, cumulative rainfall for 22 events ranged from 126.0 mm in Plot E to 135.6 mm in Plot D, with individual events ranging in size from 0.5 to 41.3 mm. Plots E and D produced a total of 102.5 and 77.1 L of stemflow, respectively, from 20 of the sampled trees in each plot whose stemflow collection systems were operational throughout the study period (~ 5.1 L $tree^{-1}$ in Plot E and 3.9 L $tree^{-1}$ in Plot D). Plot-scale stemflow for Plots E and D were estimated at 1.8 % of rainfall for both stands, assuming that the juvenile sub-alpine fir trees had similar stemflow production abilities to that of the juvenile pine. Given that crown projection area (*CPA*) represented ~ 3750 m^2 ha^{-1} in Plot E and ~ 5200 m^2 ha^{-1} in Plot D, a total of 5.1 and 3.7 % of rain falling within the crown areas was portioned into stemflow, respectively. The season-long funnelling ratio for pines within Plot E averaged 24.3, while individual trees had season-long funnelling ratios up to 69.3, with a single event maximum of 95.9 (tree diameter = 1.6 cm, rainfall = 7.0 mm). The season-long funnelling-ratio for Plot D averaged 22.2, while individual trees in this plot had season-long funnelling ratios as great as 60.4, with a single event maximum of 111.7 (tree diameter = 3.3 cm, rainfall = 17.4 mm).

The exponential decay relationship between season-long funnelling ratios and tree diameter (cm) is shown in Figure 3.4. Figure 3.4 contains only data for healthy lodgepole pine trees from which stemflow was collected over the entire study period. The largest healthy lodgepole pine sampled was 18.1 cm in diameter; however, pine at various stages of MPB attack, nine in total, ranged in size from 8.6 to 39.5 cm in diameter. These dead pine trees had an average season-long funnelling ratio of 2.3, ranging from 0.01 to 17.6, with the latter value being derived from the smallest dead tree.

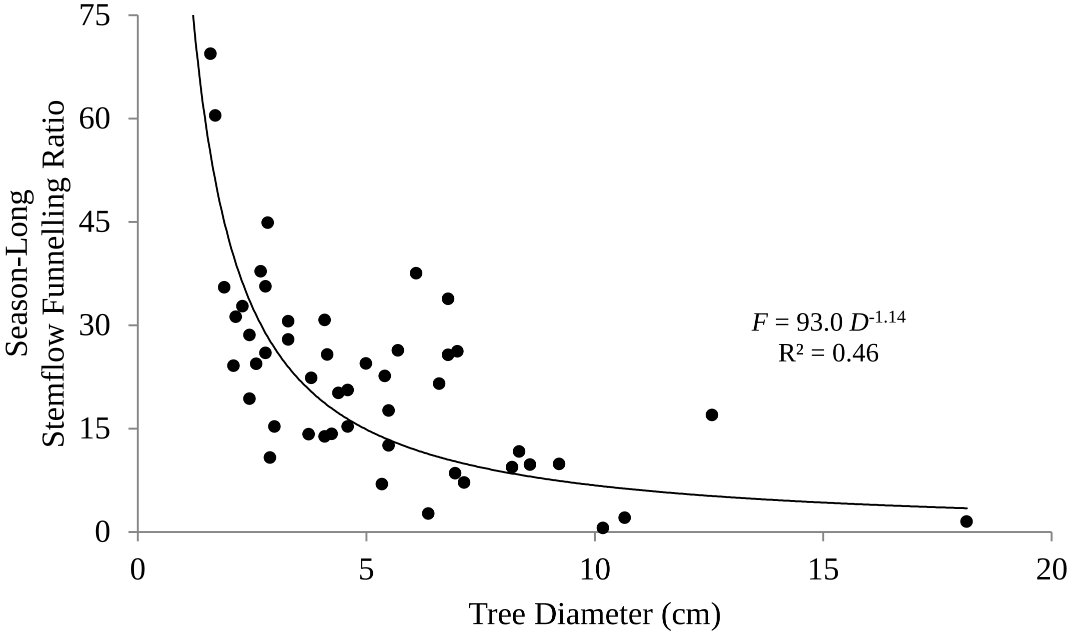

Figure 3.4. Season-long stemflow funnelling ratios versus tree diameter for all healthy lodgepole pine trees in Plots E, D, C, and B.

Abiotic and biotic influences on stemflow and the simulation of stemflow production

Multiple regression analysis, which included the linear transformations of some of the data, revealed that each of the biotic predictor variables used in this study, with the exception of proximity, had a statistically significant influence ($p < 0.05$) on stemflow volume at the individual rainfall event scale for at least one event. However, canopy width at various levels, branching angle at various levels, and diameter at the base were the most prominent. Since a multitude of variables were shown to have a statistically significant influence on stemflow production for different rainfall events, it was decided that all biotic variables, with the exception of proximity, would be included in the multiple regression for predicting the values of *a* and *b* in Eqs. 3.3 and 3.4, respectively. When examining abiotic variables, it was found that only one variable, rainfall depth ($p <$ 0.001), was consistently statistically significant throughout. Rainfall depth explained over 80 % of the variation in stemflow production for 31 of the 34 trees tested in Plot E. Trees that were influenced by a variable aside from rainfall are listed in Table 3.1. Storm duration was statistically significant for nine trees, maximum gust during the storm was significant for two trees, and duration of the storm when rainfall intensity was greater than 0.4 mm hr^{-1} was significant for one tree. Only duration explained between 5 % and 11 % of the variation in stemflow for three trees, while for the remaining trees, duration, maximum gust speed, and duration when rainfall intensity $\geq$ 0.4 mm hr^{-1} explained less than 3 % of the stemflow variation. Due to these findings, rainfall depth was the only abiotic variable selected for inclusion in the final model.

Table 3.2. Coefficient of determination (R^2) and *p*-values associated with statistically significant abiotic predictor variables of stemflow production for individual study trees.

Tree	Rainfall Depth (mm)	Duration (h)	Max. Gust (m s^{-1})	Duration while intensity $\geq$ 0.4 mm h^{-1} (h)
1	0.96 ($p < 0.001$)	0.03 ($p = 0.001$)	-	-
4	0.91 ($p < 0.001$)	0.03 ($p = 0.004$)	-	-
12	0.80 ($p < 0.001$)	0.11 ($p = 0.001$)	-	-
16	0.97 ($p < 0.001$)	-	0.01 ($p = 0.048$)	-
18	0.92 ($p < 0.001$)	0.03 ($p = 0.001$)	-	-
20	0.77 ($p < 0.001$)	0.09 ($p = 0.007$)	-	-
24	0.94 ($p < 0.001$)	0.02 ($p < 0.001$)	0.01 ($p = 0.003$)	-
26	0.93 ($p < 0.001$)	0.05 ($p < 0.001$)	-	-
28	0.97 ($p < 0.001$)	-	-	0.01 ($p = 0.016$)
34	0.97 ($p < 0.001$)	0.01 ($p = 0.008$)	-	-

Linear regression equations were developed between stemflow volume (L) and rainfall depth (mm) for individual trees in Plot E. The derived slope (*a*) and intercept (*b*) values were then plotted against the diameter of the individual trees sampled for stemflow. According to Park and Hattori (2002) *a* versus *DBH* and *b* versus *DBH* should produce power relationships. Although *a* versus tree diameter (cm) was found to follow a power relationship, *b* versus tree diameter (cm) did not (Figures 3.5 and 3.6, respectively).

In this study, since all of the biotic variables with the exception of proximity, and not just diameter, had a statistically significant influence on stemflow production for at least one event, and because the relationship between plotted *b* values and diameter was found to be weak, stepwise multiple regression using *a* and *b* as dependent variables was conducted to determine which biotic factors best explained variation in slope and intercept values.

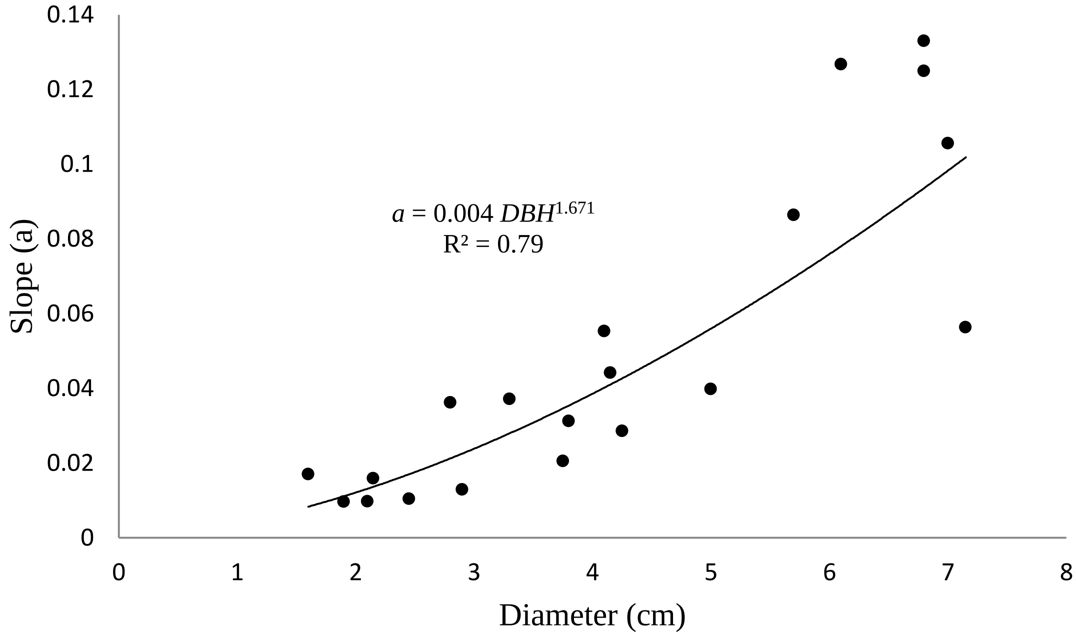

Figure 3.5. Power relationship between slope values and tree diameter for healthy lodgepole pine trees.

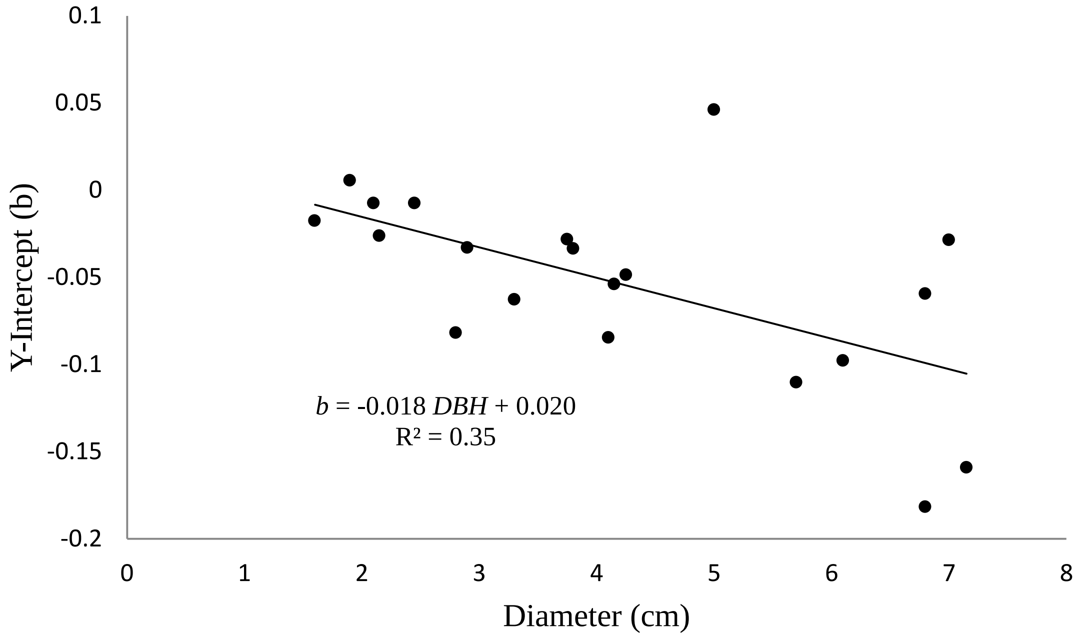

Figure 3.6. Intercept values versus diameter showing a weak linear relationship and not the power relationship shown by Park and Hattori (2002).

Upon performing the regression analysis multicollinearity was observed. Tree diameter at the base, height, number of branches, and canopy width at differing levels were highly correlated, resulting in the removal of diameter when performing analyses on slope and intercept values. The result passed the multicollinearity test, however correlation between independent variables remained fairly high. This was resolved by replacing the four separate canopy width measurements with one variable, *CPA*. Crown projection area solved all multicollinearity problems and also increased the accuracy of the model. Crown projection area ($p < 0.001$) and branching angle at two-thirds the height of the tree ($Angle_{2/3}$) ($p = 0.001$) explained 76.8 % of the variation in *a*. Branching angle at the bottom of the tree ($Angle_{bottom}$) ($p = 0.004$) and *CPA* ($p < 0.001$) explained 55.2 % of the variation in *b*. Following are the two equations that were used in conjunction with Eq. 3.7 to produce a predictor model of stemflow volume as a function of biotic and abiotic factors in Plot E:

$$a = 0.04\, CPA + 0.001\, Angle_{2/3} - 0.008 \qquad (3.5)$$

$$b = -\ 0.06\ CPA + 0.003\ Angle_{bottom} -\ 0.0007 \quad (3.6)$$

$$SF = a\ Pg + b \quad (3.7)$$

where SF is stemflow volume (L) and Pg is rainfall depth (mm).

The next stage of the analysis was to determine the performance of the stemflow model in simulating observed versus predicted stemflow volumes within Plot E, the plot in which the model was developed (Piñeiro *et al.*, 2008). The model was successful in predicting 83.0 % of the variation in stemflow production for Plot E (Figure 3.7). Total predicted stemflow volume was 147.3 L and observed stemflow volume totalled 144.0 L, an overprediction of only 2.3 %. Analysis of the slope and intercept associated with the linear equation of observed versus predicted values found that they did not differ significantly from one and zero, respectively.

In order to assess the spatial transferability of the Plot E model, it was applied to Plot D data. The above procedure was repeated to determine the performance of the model when applied to a different plot. The model was found to explain 74.1 % of the variations in observed data; however, for large rainfall events the model greatly overestimated the amount of stemflow produced (Figure 3.8). Although the intercept of predicted versus observed stemflow (L) was not significantly different from zero, the slope was found to be significantly different from one.

In an attempt to understand why the Plot E model greatly overestimated stemflow production when applied to Plot D, Plot D stemflow was modeled in the same manner as Plot E using stepwise multiple regression. This was to determine if other variables aside from the ones highlighted during the Plot E analysis were important for predicting stemflow production in Plot D. Crown projection area ($p = 0.006$), number of branches (*#Brch*) ($p = 0.038$), and branching angle at the bottom of the tree ($p = 0.036$) explained 46.6 % of the variation in a. Number of branches ($p = 0.013$) explained 17.4 % of the variation in b. Following are the two equations that were used in conjunction with Eq. 3.7 for Plot D:

$$a = 0.02\ CPA + 0.001\ Angle_{bottom} + 0.001\ \#Brch + 0.006 \quad (3.8)$$

$$b = -\ 0.002\ \#Brch -\ 0.008 \quad (3.9)$$

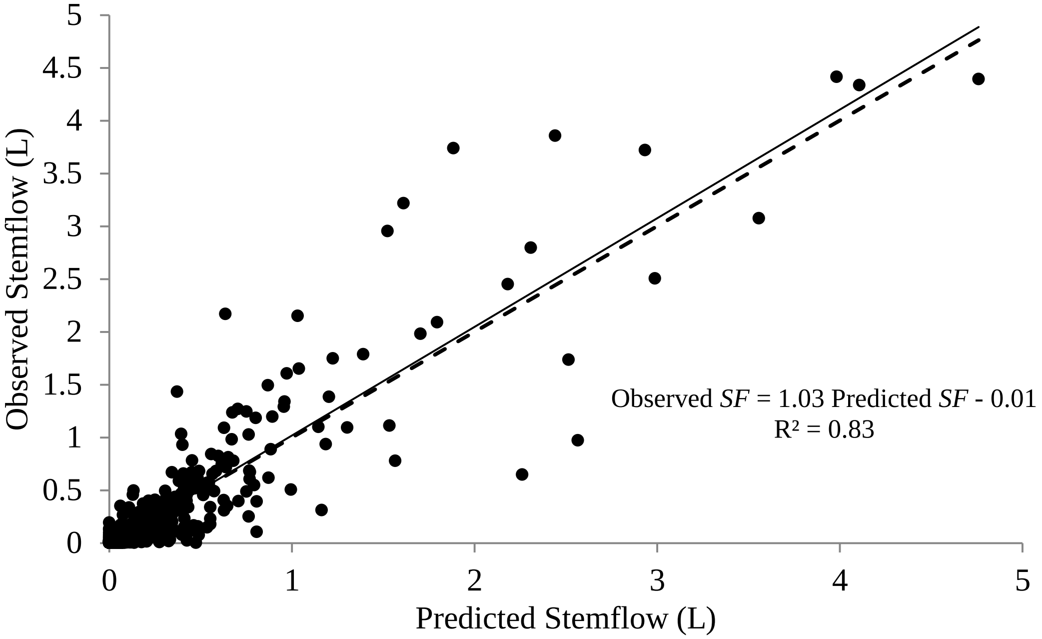

Figure 3.7. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for Plot E (——) and the 1:1 line (------).

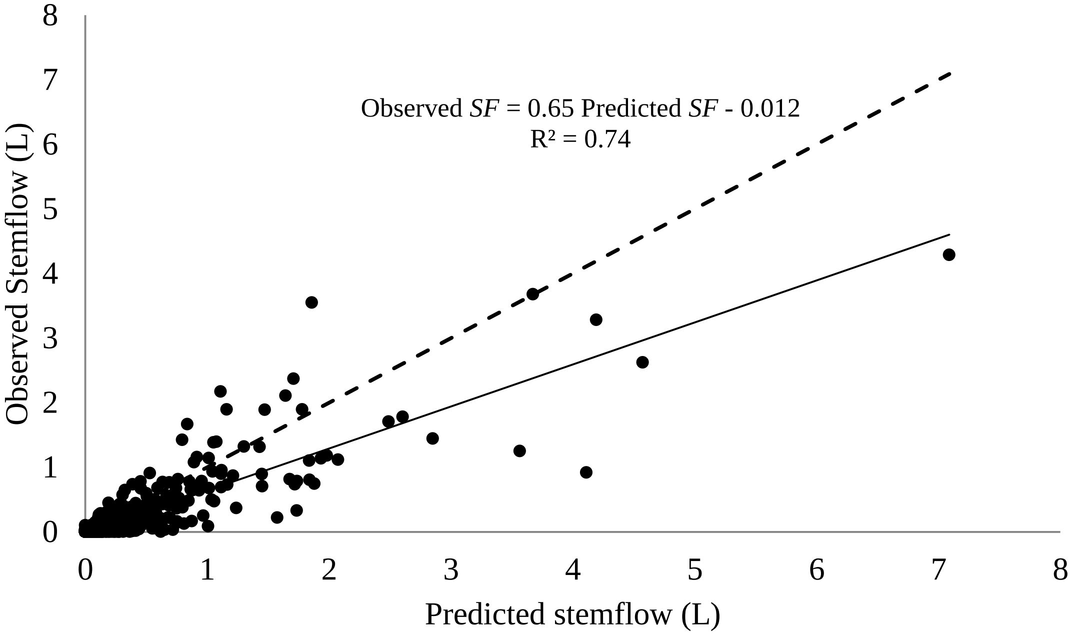

Figure 3.8. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for Plot D employing the Plot E model (——) and the 1:1 line (------).

The process used in Plot E to test the performance of the model was repeated for Plot D. The resulting Plot D model predicted 78.1 % of the variation in stemflow production (Figure 3.9).

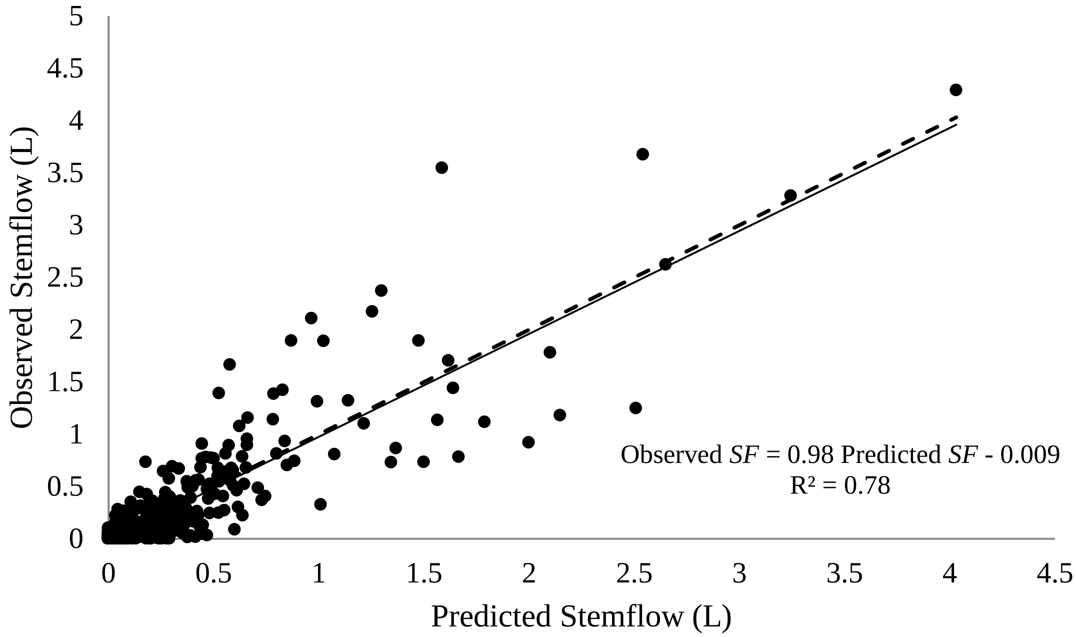

Figure 3.9. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for Plot D (——) and the 1:1 line (------).

Total predicted stemflow volume was 127.9 L and observed stemflow volume totalled 119.6 L, an overprediction of 6.9 %. Analysis of the slope and intercept found that they did not differ significantly from one and zero, respectively.

Both the Plot E and Plot D models successfully modelled stemflow production, however for the most part they employed different variables to do so. Due to the variety of variables used in each model, a simplified model was also developed. In an attempt to produce a generic model, stemflow was re-modelled for both plots using only *CPA*, which was the most influential variable common to both of the more complex models. Crown projection area explained 65.8 % of the variation in a ($p < 0.001$) for Plot E and 31.8 % for Plot D ($p < 0.001$), along with 40.5 % of the variation in b ($p < 0.001$) for

Plot E and 16.7 % for Plot D (p = 0.015). Equations 3.10 and 3.11 were used in conjunction with Eq. 3.7 to produce the simplified Plot E model (Figure 3.10):

$$a = 0.05\ \mathit{CPA} + 0.003 \tag{3.10}$$

$$b = -0.07\ \mathit{CPA} - 0.005 \tag{3.11}$$

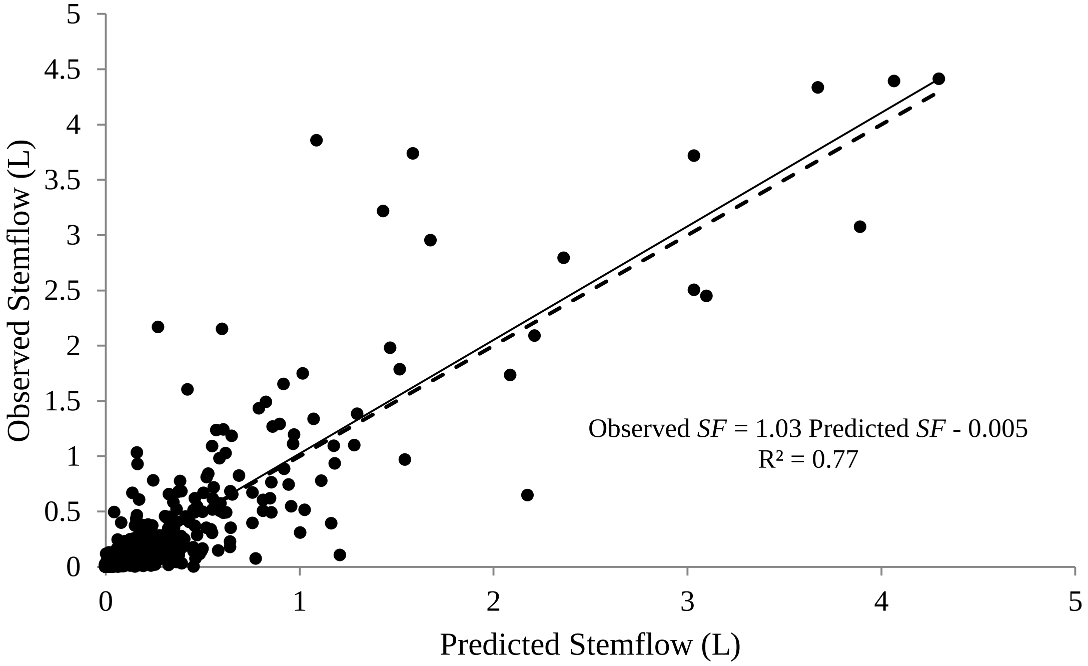

Figure 3.10. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for Plot E employing the simplified model (——) and the 1:1 line (------).

Equations 3.12 and 3.13 were used in conjunction with Eq. 3.7 to produce the simplified Plot D model (Figure 3.11):

$$a = 0.02\ \mathit{CPA} + 0.019 \tag{3.12}$$

$$b = -0.04\ \mathit{CPA} - 0.038 \tag{3.13}$$

The process previously used to access model performance was repeated for both the simplified Plot E and Plot D models. The Plot E model explained 77.3 % of the variation in cumulative stemflow production by individual trees, while predicting an all sample tree production of 143.5 L compared to the observed 144.0 L, an underprediction of 0.3 %. The Plot D model explained 74.3 % of the variation in cumulative stemflow production by individual trees, while predicting an all-sample tree production of 130.0 L compared to 119.6 L, an overprediction of 8.7 %.

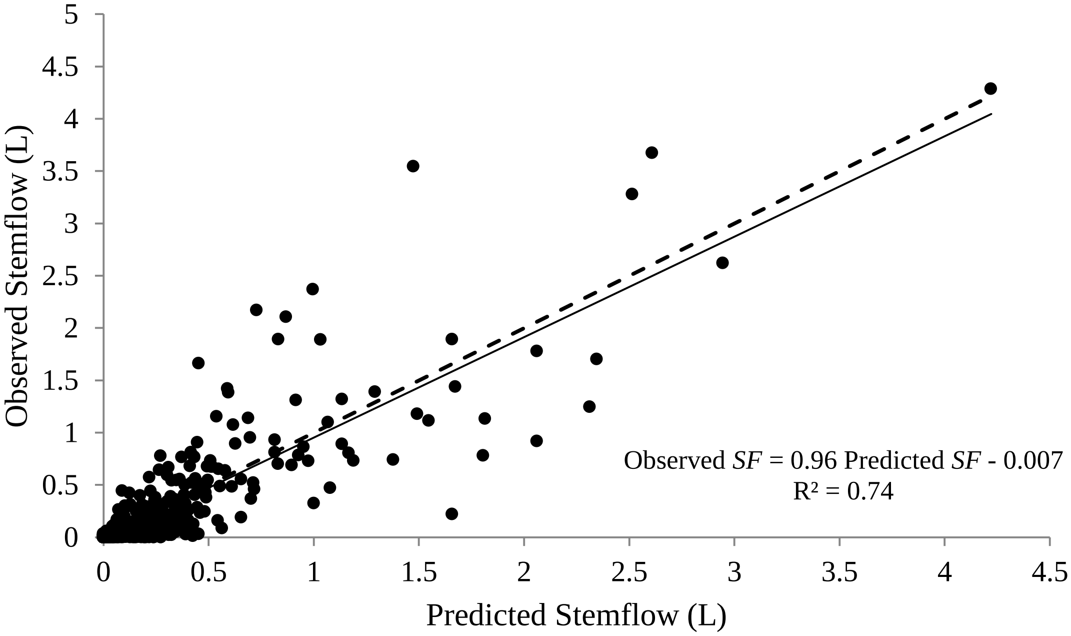

Figure 3.11. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for Plot D employing the simplified model (——) and the 1:1 line (------).

The culmination of the modelling process was the production of a generic model that could be used to determine stemflow production for both Plot E and Plot D. Slope (*a*) and intercept (*b*) values were produced in the same manner as the previous models. Slope and intercept values for Plot E and Plot D did not differ significantly and were combined for the regression analysis culminating in one model which was applicable to both stands, resulting in Eqs. 3.14 ($p < 0.001$) and 3.15 ($p < 0.001$). This model applies to individual trees or stands with trees having *CPA*s in the range of 0.01 to 3.5 m^3. Trees with this *CPA* range had associated diameters ranging from 1.6 cm to 8.8 cm ($CPA = 0.078\ D^{1.55}$, $R^2 = 0.81$) and tree heights (*H*) ranging from 0.85 m to 4.89 m ($CPA = 0.201\ H^{1.58}$, $R^2 = 0.77$). The model can be seen in Figure 3.12 and was produced using Eqs. 3.14 and 3.15, in conjunction with Eq. 3.7:

$a = 0.03\ CPA + 0.015$ (3.14)

$b = -\ 0.05\ CPA - 0.023$ (3.15)

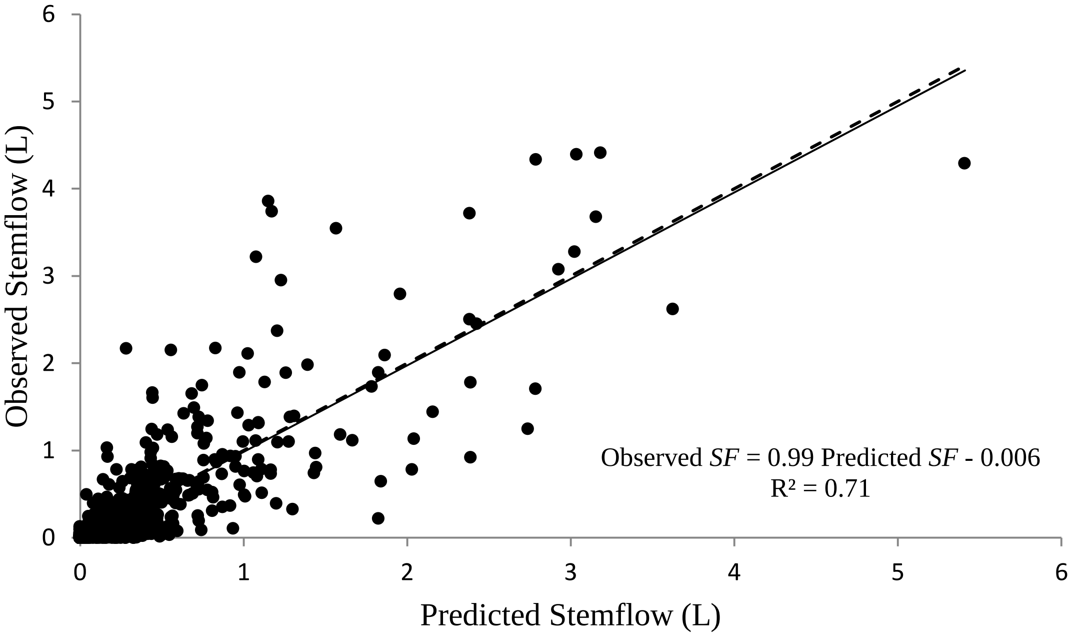

Figure 3.12. Observed stemflow volume versus predicted stemflow volume derived from Eq. 3.7 for lodgepole pines in Plots E and D employing the generic model (——) and the 1:1 line (------).

The generic model explained 71.3 % of the variation in stemflow production for juvenile lodgepole pine stands, while predicting an all sample tree production of 274 L compared to the observed 264 L, an over prediction of 3.8 %. The slope did not differ significantly from one nor did the intercept differ significantly from zero. Equations 3.14 and 3.15 were used in conjunction with the relationship between *CPA* and *D* and applied to tree frequency data for each stand to generate stand scale estimates of stemflow volume and percentage of rainfall portioned into stemflow (Figure 3.13). The relationship between the percentage of rainfall that became stemflow and rainfall depth also highlights the point at which stemflow production commences: 1.6 mm of rainfall for both Plots E and D.

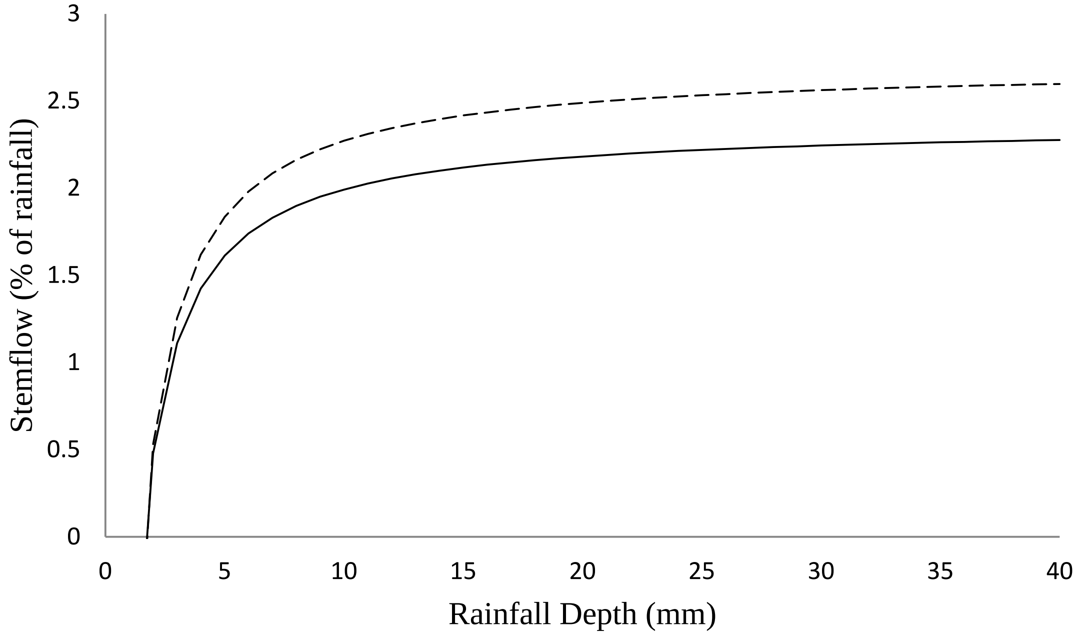

Figure 3.13. The percentage of rainfall that became stemflow versus rainfall depth at the stand scale for Plot E (——) and Plot D (------), highlighting the rainfall depth required for the commencement of stemflow production (1.6 mm).

Stemflow produced by a branchless tree

Three branchless trees were sampled for stemflow in an attempt to further understand the influence of abiotic factors on stemflow production. However, these trees suffered very high data loss due to leaking stemflow collars. As a result, only the large tree had a complete dataset and the incomplete data sets of the small and medium trees were discarded. Stepwise multiple regression was conducted using stemflow volume as the dependent variable and only meteorological conditions as independent variables. The result of the analysis was Eq. 3.16 which explained 94.8 % of the variation in stemflow production. Stemflow production for a tree with no canopy was influenced by the amount of rainfall and the duration of the storm. Stemflow increased as the amount of rainfall increased but decreased as the duration of a storm increased. The decrease due to increased storm length is most likely due to evaporation from the trunk, including evaporation during breaks in the storm.

$$SF = 37.9\, Pg - 5.2\, Dur - 63.8 \tag{3.16}$$

A tree lacking a canopy was expected to have minimal stemflow production and be an inefficient stemflow producer. However, this was not the case for this lone branchless tree, as it had an average season-long funnelling ratio of 10.9 and an event high funnelling ratio of 19.8.

DISCUSSION

The results show that juvenile lodgepole pine trees are far more efficient stemflow producers than their mature counterparts due to differences in tree morphology. It is therefore not surprising that in comparison to other canopy water balance studies, with a sampling emphasis on mature lodgepole pine, we have observed much higher stemflow production. Juvenile lodgepole pine dominated stands partitioned up to ~ 2 % of incoming rainfall into stemflow and individual trees are highly efficient producers, with event funnelling ratios as high as 111.7. In contrast to our findings, Moore *et al*. (2008) in a mature pine – hybrid white spruce – subalpine fir stand at the Mayson Lake study site, found that stemflow represented ~ 0.2 % of season-long rainfall, while Spittlehouse (1998) calculated that < 0.5 % of rainfall became stemflow for a mature lodgepole pine stand in Penticton, BC. A comparison between the results of this present study and those presented by Moore *et al*. (2008) suggest that within the study area, juvenile lodgepole pine stands divert ~ 10 times more rainfall to stemflow than do mature coniferous stands. Dunford and Niederhof (1944), however, reported higher values of 1.5 % of rainfall becoming stemflow for a lodgepole pine stand in Colorado. Unfortunately, very few stand characteristics necessary for accurate comparisons were provided by these authors. Dunford and Niederhof (1944) provided the average canopy area (3.25 m^2), which is just over four times larger than the average canopy area observed in Plot E. Thus, although it is evident that the Dunford and Niederhof (1994) study took place in an older stand, it is not clear if it was a mature stand or one at the pole-stage. Spittlehouse (1998) listed tree heights ranging from 22 – 26 m, much taller than the 0.85 – 3.48 m observed in Plot E. As one can see, these studies both examine trees that are considerably larger than those examined in this study, highlighting the lack of attention juvenile lodgepole pine canopy water balances have received in the hydrologic literature.

Lodgepole pine stemflow production

The stand-scale funnelling ratios for Plots E and D were 24.3 and 22.2, respectively, while the highest observed season-long funnelling ratio for an individual tree was 69.3, and the single event lone tree maximum was 111.7. These findings suggest that during the study period the base of these trees received an average stemflow input having an equivalent depth of 3060 and 3010 mm, respectively – some 5 times the average annual precipitation depth. Unfortunately, no other studies have provided funnelling ratios for pine, let alone lodgepole pine, making comparisons with other pine stands impossible. Only one other study has derived funnelling ratios for a coniferous species. Murakami (2009) derived funnelling ratios for *Chamaecyparis obtuse* (Japanese cypress) over a four year period, and found that funnelling ratios decreased from 81.3 to 29 with increasing stand age (9 – 12 yrs of age). The funnelling ratios derived in this study compare well with findings in other forest environments. Herwitz (1987), for example, observed a maximum season-long funnelling ratio from a lone *Balanops australiana* of 112 in a tropical rainforest, while Van Stan and Levia (2010) found that season-long funnelling ratios varied from 3.1 to 19.2 and 26.9 to 47.2 for lone *Liriodendron tulipifera* (yellow poplar) and *Fagus grandifolia* (American beech) trees, respectively. Návar (1993) recorded a season-long high funnelling ratio of 128 for a single *Diospyros texana*; however, he also recorded a large variation in season-long funnelling ratios ranging from 13 to 128 over 15 sampled shrubs. Season-long funnelling ratios in this present study also varied by an order of magnitude (6.9 to 69.3). Juvenile lodgepole pines are efficient stemflow producers, however, the large variation observed at the individual tree scale highlights the impact tree characteristics can have on the amount of rainfall partitioned into stemflow.

Model assessment

In addition to rainfall depth, a number of tree characteristics allowed for the accurate modelling of stemflow production from juvenile lodgepole pine. The identification of rainfall depth as the only prominent abiotic factor that influenced stemflow production is in keeping with the findings of Cape *et al*. (1991). Tree characteristics were used to explain variation in the slope and intercept values of the regression between stemflow volume and rainfall depth. The slope of the regression represents stemflow production and the intercept value represents the storage capacity of the tree. The use of multiple predictor variables resulted in increased model accuracy when compared to using only one variable like tree diameter (Park and Hattori, 2002). It is important to note that the usefulness of adding additional variables to increase model accuracy will vary depending on the species of study. Comparing our findings with those of Park and Hattori (2002) is a perfect example of the differences that occur when modelling species or specimens with differing morphology.

Stemflow production for the Plot E model increased as crown projection area and the branching angle at two-thirds the tree height increased. A tree with a wider canopy will produce more stemflow as it is able to capture more rainfall, while increasing the upward branch inclination will result in more efficient flow along those branches (Herwitz, 1987). However, a tree with a wider canopy will have a larger storage capacity, and as the angle of the lower branches of the tree becomes more negative, more water will drip from that canopy, contributing to throughfall rather than stemflow. The model incorrectly assumed that canopy drip was becoming storage and thus the intercept of the model should be viewed as representing both canopy + trunk storage and throughfall in the form of canopy drip. The application of the Plot E model (Eqs. 3.5 and 3.6) to Plot D resulted in a gross overestimate of the amount of stemflow produced. The poor performance of Eqs. 3.5 and 3.6 when applied to Plot D was believed to be the result of a variable that was highly influential in Plot E but not in Plot D. In an attempt to identify this variable, a new stemflow model was produced for Plot D using the same methodology as Plot E. The Plot D model (Eqs. 3.8 and 3.9) identified that stemflow production increased as crown projection area and number of branches increased, but decreased as the inclination of the bottom branches of the tree became more negative. The storage capacity of trees in Plot D was dependent upon the number of branches: as the number of branches increased, the storage capacity of the tree increased. Both Plot E and Plot D models identified *CPA* as the prominent variable; however, both models also contained other variables not common to both. The Plot D model included number of branches, highlighting that more rainfall will be intercepted by a denser canopy. Upon analysis of the variables contained in the Plot E and Plot D models, it was found that $Angle_{2/3}$ and *#Brch* were statistically different between the two plots, $p = 0.035$ and $p = 0.056$, respectively. Therefore, this was the likely cause of the overestimation of stemflow production observed when applying the Plot E model to Plot D resulted in an incorrect estimation of stemflow production. Our findings that branching angle (Herwitz, 1987; Návar, 1993; Martínez-Meza and Whitford, 1996; Aboal *et al*., 1999), canopy area (Ford and Deans, 1978; Martínez-Meza and Whitford, 1996), and number of branches or canopy density (Martínez-Meza and Whitford, 1996) have a significant influence on stemflow production for trees sampled in this study are consistent with past studies.

As *CPA* was the only common and most influential variable between the models produced for each plot, new simplified models were produced using only *CPA* as a predictor of stemflow production and storage capacity. Our finding that *CPA* was the most influential biotic predictor of stemflow production for both plots is in keeping with the findings of Davie and Durocher (1997) and Aboal *et al*. (1999). The simplified models for Plot E (Eqs.3.10 and 3.11) and Plot D (Eqs. 3.12 and 3.13) explained only 5.5 % and 3.8 % less variation in stemflow production, respectively. This is most likely due to an overall decrease in the importance of canopy architecture for a lodgepole pine stand as it matures, and more of a reliance on total rainfall. The final modelling stage involved combining Plot E and D data to produce a generic equation for juvenile pine stands using *CPA*. This model explained 71.3 % of the variation in stemflow production for individual lodgepole pines or entire stands using *CPA* and gross rainfall. The model is applicable to individual trees or stands that contain trees with CPAs ranging from ~ 0.1 to 3.5 m^3.

The finding that a lone branchless tree had a season-long funnelling ratio of 10.9 suggests that meteorological conditions influence stemflow production for a tree lacking a canopy. If rain was to fall vertically then the funnelling ratio of a branchless tree would be less than one due to trunk storage. Therefore, rain must be falling on an angle and stemflow production is therefore dependent on rainfall intensity and wind speed (Herwitz and Slye, 1995; Xiao *et al*., 2000).

CONCLUSION

Field research conducted during the 2008 growing season showed that healthy juvenile lodgepole pine trees are far more efficient stemflow producers than mature individuals. Due to these findings, two stands of juvenile lodgepole pine were heavily sampled for stemflow during the 2009 growing season. Stemflow production for both juvenile stands was successfully modelled using two predictor variables: rainfall depth and crown projected area. Additional variables could be added to the individual models for each plot; however, the increase in accuracy for the sampled stands was insignificant when compared to the variation in stemflow production explained by the aforementioned variables. However, it is important to note that the identification of different biotic variables at the plot scale highlights the fact that as trees age, the biotic factors that influence stemflow production change. Therefore, modelling stemflow production is more accurate when more than one variable is employed, in contrast to using only one as the majority of studies have done to-date. However, gathering the data required for the inclusion of additional variables in one’s model is no small task. If a researcher is restrained by resources or time, crown projected area can be used in conjunction with rainfall depth to produce a generic model for juvenile lodgepole pine that, at least in this study, accurately predicted stemflow volumes.

The inclusion of detailed stand characteristics in one’s methodology is paramount for comparison with other studies. It is therefore important that future publications include detailed stand characteristics for ease of intra- and interspecific stemflow production comparisons. Due to the findings that juvenile lodgepole pine are efficient stemflow producers, further research into the hydrologic importance of the stemflow produced by these trees, including the potential impact on soil moisture and groundwater recharge, is merited.

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CHAPTER 4

CONCLUSION

In comparison to other components of the vegetation canopy water balance, stemflow has received the least attention in the hydrologic literature (Levia and Frost, 2003). Despite being volumetrically insignificant at the plot scale and beyond when compared to throughfall and interception loss, stemflow is hydrologically important because it is a focused input of precipitation at the base of a tree or plant (Herwitz, 1986). Over the course of a century of study, the important impact stemflow can have on site hydrology has been highlighted time and time again. Stemflow can have implications for groundwater recharge, erosion, and vegetation growth (Voigt 1960; Brinson *et al*., 1980; Herwitz, 1986; Tanaka *et al*., 1996; Taniguchi *et al*., 1996; Whitford *et al*., 1997; Chang and Matzner, 2000; Schroth *et al*., 2001; Johnson and Lehmann, 2006). Due to the importance of stemflow as highlighted by prior studies, it is imperative that we strive to increase our knowledge by studying different vegetation species under differing geographic and climatic conditions, as well as under different age and condition (e.g., disturbance, planting arrangement, etc.) scenarios.

Stemflow production data was compiled for studies published prior to June 30, 2010, which contained one or more of the following: a stemflow equation, percentage of rainfall that became stemflow, or stemflow funnelling ratios. The information was organized by species and partitioned into seven climate and vegetation classifications. Once organized, stemflow funnelling ratios and plateau funnelling ratios were calculated for studies that provided the necessary information. Upon table completion, the data was examined to identify inter-climatic, intra-climatic, and inter-genera relationships. Plateau funnelling ratios were used to estimate the amount of rainfall required to satisfy the storage capacity of a tree or bush. When compared to the values used in current canopy water balance models, rainfall amounts found using the plateau funnelling ratio method were much greater, highlighting a large underestimation in current models. Finally, the data contained within the reference tables was used to highlight areas where knowledge remains fairly weak, and to identify particular genera which have received the most attention to date.

After examination of the stemflow literature it was noted that stemflow knowledge for species found in the Interior of British Columbia was lacking. Due to the changes in the landscape that will occur as a result of the Mountain Pine Beetle epidemic, an examination of stemflow production for lodgepole pine was undertaken. Spittlehouse (1998) showed that stemflow production was fairly low for mature lodgepole pine, however, no studies to-date had examined juvenile lodgepole pine. Field research conducted for the 2008 growing season showed that juvenile lodgepole pine were much more efficient stemflow producers when compared to mature trees (McKee and Carlyle-Moses, 2010). Due to these findings, two stands of juvenile lodgepole pine were heavily sampled over the 2009 growing season with the goal of identifying the meteorological conditions and tree characteristics that influence stemflow production. The dataset gathered for this thesis further supports the findings of McKee and Carlyle-Moses (2010) that juvenile lodgepole pine produce significant volumes of stemflow. Analysis of the dataset resulted in the successful production of three stemflow models, one for each individual research plot, and a comprehensive model encompassing the entire dataset. These models employed multiple variables, highlighting the importance of considering a wide array of variables when modelling stemflow production.

Reviewing the quantitative importance of stemflow not only produced a reference guide for future researchers, it also highlighted the shortcomings of current canopy water balance models. Calculated plateau funnelling ratios were used to estimate the amount of rainfall required to satisfy the storage capacity of a tree or plant. The rainfall depths associated with the calculated plateau funnelling ratios suggest that current methods of estimating the required rainfall depth to saturate a vegetation canopy (e.g. Valente *et al*., 1997) may be erroneous. Examination of the review tables also highlighted the importance of including detailed stand characteristics which aid in inter-study comparisons.

With regards to the field study, logistics limited the number of plots used to produce the dataset required for developing the stemflow models to two. Plots E and D contained 37 and 36 samples, respectively, that were representative of their respective stands. The inclusion of more samples from other locations with differing tree architecture would have resulted in a more comprehensive model, or multiple models categorized by tree size. Despite the limitations due to sampling logistics, the final model explained 71.3 % of the variation in stemflow production for both juvenile stands. This model provides the basis for the development of a broadly applicable model that would allow hydrologists to calculate stemflow production for individual juvenile lodgepole pine or for lodgepole pine stands outside the geographic area of this study.

Based on the findings that plateau funnelling ratios can be used to estimate the amount of rainfall required to satisfy the storage capacity of a tree, and that current models greatly underestimate the storage capacity, new canopy water balance models must be produced that accurately estimate canopy storage. The use of the stemflow funnelling ratio in the stemflow literature should be expanded because it is an effective way of explaining a tree’s or stand’s ability to produce stemflow. The inclusion of detailed stand characteristics is paramount for comparison with other studies. It is therefore important that future studies include detailed stand characteristics for ease of inter- and intra-specific stemflow production comparisons.

Juvenile lodgepole pine trees are efficient stemflow producers and are capable of producing large volumes of stemflow, up to 10 times more than their mature counterparts. Based on that finding alone, more research is required to determine the hydrological and ecological implications of stemflow production from juvenile lodgepole pine. What are the implications for site hydrology? Specifically, is stemflow from juvenile lodgepole pine important for soil moisture and groundwater recharge? Is this water flux also an important source of nutrients for growth for this tree species? Further investigation into the hydrological and biogeochemical importance of stemflow from juvenile lodgepole pine is paramount due to the uncertainties surrounding the potential impacts of mountain pine beetle, wildfire, and climate change on the hydrology and ecology of British Columbia's Interior.

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