THE INFLUENCE OF TREE MORPHOLOGY ON STEMFLOW IN A REDWOOD REGION SECOND-GROWTH FOREST

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by

Elias Steinbuck

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Stemflow is the portion of rainfall which, having been intercepted by the forest canopy, reaches the ground by running down the stems of trees. Stemflow volumes from coast redwood, Douglas-fir, and tanoak were collected from January 2000 to April 2001 in the Caspar Creek Watershed in Mendocino County, California. Average funneling ratios reveal a greater contribution to stemflow from the crowns of tanoak and Douglas-fir trees than from those of redwood trees. An in situ bark texture experiment designed to isolate the stem from the crown was conducted on one tree of each species. A technique of measuring gross bark surface area was developed and applied to the study trees. Bark texture increased the gross bark surface areas by 33%, 15% and 2% in redwood, Douglas-fir, and tanoak, respectively. Gross bark surface area of the isolated

segments of stem accounted for 99% of the variation in the volume of water recovered from the three trees during the bark texture experiment. A linear regression model based on the percent of positively inclined branches, the crown projection area, and the stem surface area explained 88 percent of the variation in the stemflow volumes measured during the study period. Depth of rainfall prior to stemflow inception was estimated on one tree of each species by analyzing five discrete rainfall events. Average rainfall depth varied from 5 mm prior to the inception of stemflow from the tanoak, to 14 mm prior to the inception of stemflow from the redwood. The Douglas-fir averaged 11 mm of rainfall prior to stemflow inception.

CHAPTER I

INTRODUCTION

Precipitation falling over a forested watershed does not fall directly to the ground but rather is diverted by needles, leaves, branches, and stems. The mechanism by which water is captured by the foliage and stems of vegetation is generally termed rainfall interception. Intercepted water may be recycled to the atmosphere as evaporation. With prolonged precipitation, intercepted water can congregate on foliage and drip from the vegetation in the form of throughfall. Water has also been observed to cling to vegetation and form a very thin film of flow that can concentrate and flow down the stem to the soil as stemflow. Stemflow as a hydrologic process is often considered to be an insignificant contributor to the hydrologic budget. This is most likely because of the relatively small percentage of the gross rainfall (approximately 1%-5%, in most cases) contributed by stemflow (Zinke, 1966).

However, practical interest surrounding stemflow exists on many levels. At the watershed level, stemflow is a measurable component of rainfall interception, which is of great interest to foresters and hydrologists developing a hydrologic budget in a forest setting. Many stemflow studies have been conducted in the context of a large-scale rainfall interception budget (Rutter, 1963; Gash and Stewart, 1977; Loustau *et al*., 1992; Gash *et al*., 1995; Liu, 1997; Llorens, 1997; Klaassen *et al*., 1998). A difficulty when determining stemflow as a percentage of gross rainfall is specifying the area of effective stemflow. As with gross precipitation, an area is needed to convert stemflow volume into a unit of water depth. Matsubayashi *et al*. (1995) reported the results of a stemflow study on broadleaf trees. They determined that stemflow was concentrated in a 6-centimeter-wide band around the tree. Using this narrow area to determine the unit depth of stemflow revealed that stemflow was being delivered at a rate 22 times that of rainfall. Based on trunk projected area 1.5 meters above ground, Durocher (1990) found that rainfall input at the base of some trees was 30 to 40 times larger than the mean throughfall. Essentially, throughfall is distributed over a very large area while stemflow is not.

At the microsite level, stemflow has the ability to concentrate large quantities of water in small areas and locally recharge groundwater (Taniguchi *et al*., 1996) and soil water (Voigt, 1960; Durocher, 1990; Crabtree and Trudgill, 1985). This localized input of water can affect the timing and spatial distribution of fine root development in early spring (Ford and Deans, 1978; Herwitz and Levia Jr., 1997). Results from a study in a permeable carbonate bedrock suggest that stemflow may rapidly infiltrate and bypass the soil matrix via macropores and root channels to produce subsurface stormflow. Crabtree and Trudgill (1985) hypothesized that stemflow therefore has implications for influencing the hydrological response of a forested hillslope.

Variability in stemflow volume, which results from a variety of factors, has been investigated in many forested environments. Precipitation intensity, crown morphology, and stem morphology have all been shown to influence the variability in stemflow volume. Ford and Deans (1978) argued that medium intensity precipitation events provide optimal conditions for stemflow generation. During low intensity precipitation events, most water will evaporate from the canopy. When large intensity precipitation is generated, the canopy reaches a point where conducting channels become saturated. If no additional water can flow from a point, then water must drip or evaporate as soon as it is received. Thus, during intense precipitation there is a general tendency for throughfall percentage to increase while stemflow percentage remains constant or perhaps even decreases (Ford and Deans, 1978; Xiao *et al*., 2000).

Morphologic differences between trees have been quantified to explain stemflow variability. During precipitation, the morphology and distribution of the trees and, collectively, the forest control the fate of the water. The morphology of the vegetation can influence the quantity and distribution of water descending from the canopy to the ground surface (Schroth *et al*., 1999). Crown area is a significant factor in predicting the variability in stemflow (Lawson, 1967; Aboal *et al*., 1999). Essentially, the trees with the largest crown area have the ability to capture the most precipitation.

Another significant crown characteristic is the orientation of the branches. Clark (1985) reported that generally two types of branching habits are recognized: excurrent and decurrent. In the excurrent branching pattern, the branch generally slopes downward to the stem. This would greatly increase the likelihood of water being conducted to the stem. In the decurrent branching pattern, the upper branches may slope down to the stem but the lower branches slope away from the stem. This branching pattern can generate stemflow in the upper canopy, but the lower branches have less potential for conducting water to the stem, and may even conduct water away from the stem. The decurrent branching pattern is common in conifer trees, while the excurrent pattern common in deciduous trees. Herwitz (1987) conducted an experiment to determine the relationship between branch inclination and branchflow. Laboratory experiments were conducted on dry and wet branches at inclinations from 2.5° to 60°. A linear relationship was found between branchflow and branch inclination for dry branches. Wet branches that were subjected to the same experiment revealed that not only were wet branches more efficient at conducting water, but the relationship between branchflow and inclination was logarithmic. Herwitz theorized that as dry branches are wetted, the intercepted water on the branch surface terminates at a transient drip point where it falls from the branch. Only after sufficient water has flowed over the branch surface will the transient drip points coalesce and the branch develop conducting channels that efficiently route the water to the stem (Herwitz, 1987). Johnson (1990) worked in a 50-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr.) forest in Scotland. He found that stemflow volume decreased as trees became older. He theorized that the branching habit of mature Sitka spruce trees did not provide ideal conditions for stemflow generation. Generally speaking, as conifers age, the branches slope downward from the stem. This eliminates the pathway for intercepted water to be routed to the stem, although intercepted precipitation in the upper canopy will still contribute to stemflow. Johnson (1990) observed a general trend of increasing throughfall with distance from the stem. This can also be attributed to the downsloping branches, as the branches would likely conduct water away from the stem and eventually become throughfall at a fixed drip point. Cape *et al*. (1991) conducted a study in a pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst), Sitka spruce, larch (*Larix decidua* L.), oak (*Quercus petraea* Matt.), and alder (*Alnus glutinosa* (L.) Gaerta) forest in northern Britain. They concluded that the branching habit of each species was the main determinant of stemflow. Also noted was that the provenance of a species will affect the branching habit and, therefore, stemflow of that species. This can be quite important when quantifying the relationship between species and stemflow in a region, as those results may be quite different in a similar forest type in a nearby region.

The tree stem has also been documented to control stemflow variability (Navar, 1993; Aboal *et al*., 1999). Trees with smooth bark will conduct water to the ground more efficiently with less loss occurring in the form of stem drip. Stem drip is water that falls directly from the stem to the ground due to a localized drip point, typically on a rough textured bark surface. Quantifying bark roughness is not a trivial task. Previous researchers have taken measurements on small pieces of bark in an attempt to obtain a bark roughness index which can be used to classify the bark for a given tree (Aboal *et al*., 1999). In addition to affecting stem drip, bark roughness may influence the amount of initial storage of precipitation prior to stemflow. Durocher (1990) implemented a study in a red oak (*Quercus rubra*) and sweet chestnut (*Castenea sativa*) forest in Bristol, England. Results from the study reveal large differences in stemflow generation not only between species but also between individuals of the same species having similar stand position, shape, and dimension. High resolution stemflow recording gauges revealed that once the initial interception storage had been exceeded, stemflow timing reflected the rainfall dynamics almost perfectly. Very small quantities of stemflow were collected once precipitation ceased, indicating little water was stored. It was noted, however, that the conclusions drawn from the smooth bark trees could not necessarily be applied to rough bark types. Helvey and Patric (1965) discuss initial storage of intercepted rainfall prior to stemflow in a summary report of the many studies conducted in the eastern United States. Stemflow starts after 1.27 mm of rain on beech (*Fagus grandifolia* Ehrh.) (Voigt, 1960), but may not start on other species until 5.08 mm (Black, 1957) to 22.86 mm (Gilbert, 1953).

The purpose of this thesis was to determine if morphologic characteristics of three tree species could be used to explain stemflow variability in a redwood forest. To accomplish this, several tree morphology characteristics were quantified: diameter, height, bark thickness, crown projection area, branching habit, and stem surface area. A method of estimating total stem surface area was developed to characterize the bark texture. This method accounted for differences in bark texture at different points on the stem. Tree morphology characteristics were analyzed using a multiple linear regression model. Additionally, an in situ bark texture experiment was conducted to isolate the role of bark texture on stemflow. Electronic stemflow data collected during precipitation events was analyzed to understand the temporal differences of stemflow inception between the three species. Based on previous literature and findings herein, trees with positively inclined branches, large canopy areas, and smooth textured bark will likely intercept significantly more precipitation, and efficiently route it to the ground surface as stemflow, than trees not possessing these attributes.

CHAPTER II

DESCRIPTION OF THE STUDY AREA

Geography

The stemflow study was undertaken in the Caspar Creek Experimental Watershed, located within the Coast Range geomorphic province of northern California. Located approximately 240 kilometers north of San Francisco, the watershed lies largely within Jackson Demonstration State Forest (JDSF) (Figure 1). The 2,167 ha watershed is orientated east-west, and can be reached from State Highway One by heading east on Road 500 via Fern Creek Road. A one-hectare rainfall interception study plot is located in the North Fork of the Caspar Creek watershed near the ridge-top within the Iverson sub-watershed. The plot has a south-facing slope, steep topography, and a 100-year-old second-growth redwood forest. The plot lies within a zero-order swale (i.e. no surface channels are present) approximately 10 kilometers east of the Pacific Ocean.

Topography

The topography is characterized by marine terraces that have been deeply incised by coastal streams. Concave hillslopes are common with steep slopes near the stream and gentle slopes on the ridgetops. Slopes as steep as 35 to 75 percent are common in the region. Elevations in the Caspar Creek Watershed range from 0 to 320 meters above mean sea level. The elevation of the study plot is approximately 220 meters above mean sea level.

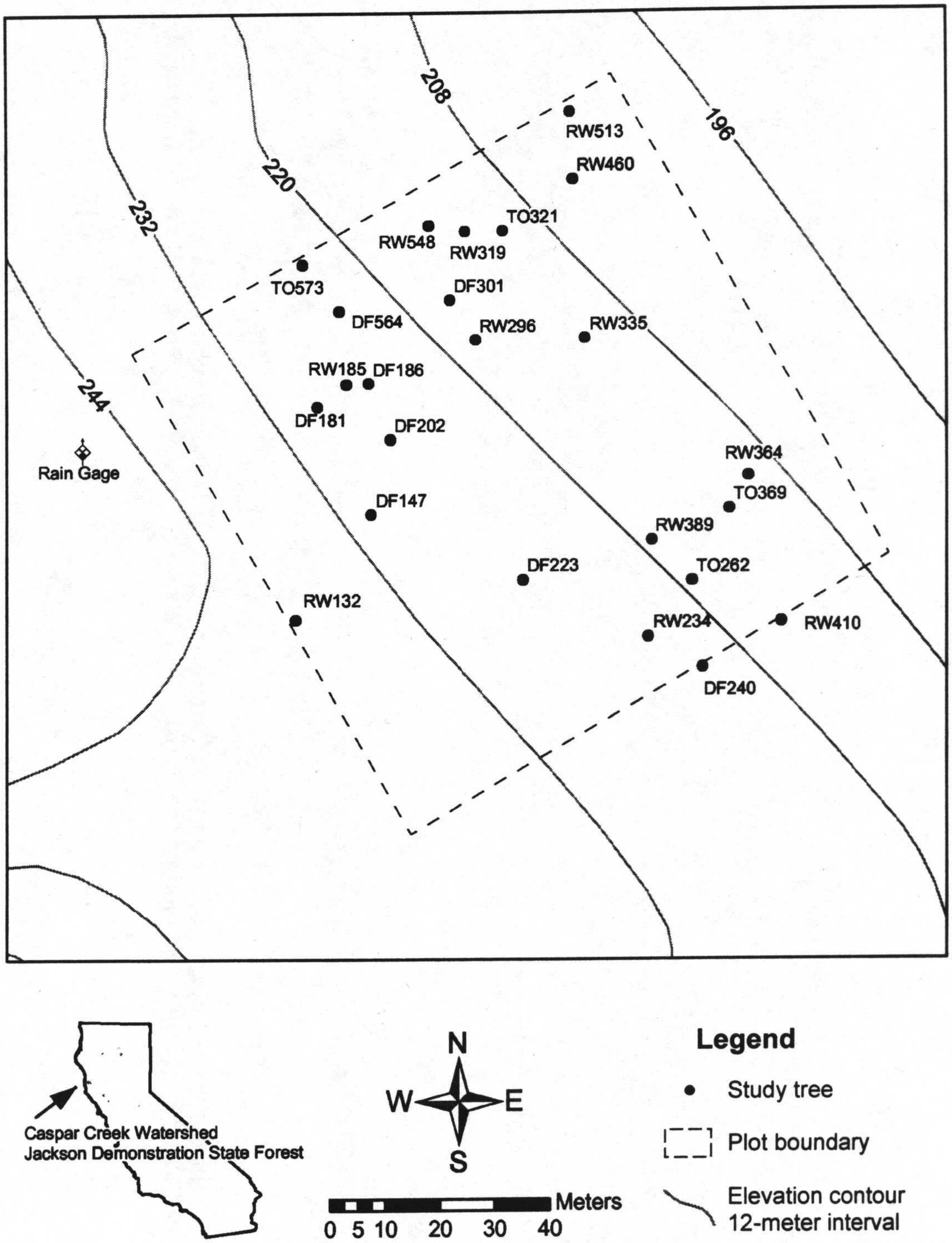

Figure 1. Stemflow site and location map of Caspar Creek in California and distribution of study trees in the one-hectare plot

Geology

Geologic research conducted in the coastal belt of the coast range mountains reveals that rapid uplift of the region is occurring (Norris and Webb, 1990). Basement rocks in the coastal belt of the coast range mountains have been described as the Cretaceous-aged Franciscan Assemblage (Norris and Webb, 1990). Greenish-gray graywacke sandstones are the predominant rock types of the coastal belt Franciscan. Formation of the graywacke sandstone was thought to have occurred by the process of eroding volcanic highlands and depositing the detritus in marine basins (Norris and Webb, 1990). Outcrops observed in the field generally indicate a fractured and/or folded rock that has undergone some degree of metamorphism.

Soils

Soils found in the region include the Mendocino, Hugo, and Caspar series. All three are characterized as being well-drained soils ranging from sandy clay to gravelly loam. Soils within the study plot have been identified as Hugo series. This soil series is pedologically the youngest of the three, and is one of the most common mountain soils in the redwood region. Thickness varies from one to two meters depending on location (Wosika, 1981).

Vegetation

The vegetation within the one-hectare study plot is a dense second-growth forest. Coast redwood (*Sequoia sempervirens* (D. Don) Endl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and tanoak (*Lithocarpus densiflorus* (Hook. and Arn.) Rohn) are the dominant species in the plot, while grand fir (*Abies grandis* (Dougl. ex D. Don)

Lindl.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) commonly occur in other areas of the forest. Common understory vegetation, regionally and locally, includes evergreen huckleberry (*Vaccinium ovatum* Pursh) and Pacific rhododendron (*Rhododendron macrophyllum* D. Don) (Henry, 1998).

Climate

The climate of the region is typical of most of north coastal California with cool, wet winters and warm, dry summers. Average annual rainfall in Caspar Creek from 1962 to 1997 was 1190 mm, with a majority of the precipitation occurring in the winter months. Fog drip in the area is usually confined to summer months and isolated to the tops of ridges, so it does not contribute a significant quantity of water to the overall water budget. Snow is rare in the region and does not make a significant contribution to the hydrologic budget. Average monthly air temperatures between 1990 and 1995 in December were 6.7°C, with an average minimum of 4.7°C. Average July temperatures were 15.6°C, with an average maximum of 22.3°C (Ziemer, 1996).

Land Use

JDSF is managed for the production of wood products by the California Department of Forestry and Fire Protection (CDF). The Caspar Creek Watershed Project is a cooperative research effort between CDF and the United States Forest Service, Redwood Sciences Laboratory (USFS). Previous to CDF ownership, land use on the site included extensive clearcut logging from 1860-1890. Slash burning was commonly used to remove obstructions before yarding old-growth logs. Oxen teams moved logs into the stream channels to be taken by winter storm flows to the mill at the mouth of the creek.

The site lies within the Iverson sub-watershed, which has not been harvested since the initial clearcutting of 1860-1890. A raingage adjacent to the site lies within the Gibbs sub-watershed, which was clearcut and burned in 1991 as part of the North Fork watershed study (Henry, 1998).

CHAPTER III

DATA COLLECTION AND DESCRIPTION

Several sets of data were collected to meet the objectives of this thesis. A random sample of trees was selected for stemflow measurement (Lewis, 2002). Rainfall and stemflow data were collected from January 2000 to April 2001. In addition to event and annual stemflow volume, the timing of stemflow was measured on a subsample of trees. Several tree morphology parameters were also measured to explain the variability in stemflow volume. The influence of bark texture on stemflow was investigated in detail with an in situ field experiment modified from Voigt (1960).

Sampling Design

Stemflow was monitored on a one-hectare plot previously selected as a representative location in the Caspar Creek Experimental Watershed. The plot center and perimeter were located and flagged using a standard tape, compass, and clinometer survey. Once boundaries were established, a 100% timber survey (or cruise) was conducted to define a population of trees for sampling. All trees over 15 cm in diameter at breast height (approximately 1.4 m above ground surface) on the uphill side were given a unique identification number and the diameter was measured to the nearest 0.25 cm with a diameter-tape. All trees less than 15 cm in diameter at breast height (DBH) were tallied by species. Standing dead trees (snags) were not included in the study because of the small percentage (<5%) they represent in the entire stand.

The stemflow sampling design (Lewis, 2002) incorporates a proposal by Hanchi and Rapp (1997) to employ power functions relating stemflow and diameter into a sample design known as model-based stratified sampling (Wright, 1983). In this design, stratum boundaries are optimized to yield a representative sample of diameters for each study species: coast redwood, Douglas-fir, and tanoak. Identification numbers and diameters of the 24 selected trees can be found in "Tree Morphology Characterization" in this chapter.

Rainfall Collection

A tipping bucket raingage recorded gross precipitation in the clearcut adjacent to the 1-ha plot. The tipping bucket raingage electronically recorded events every 0.25 mm of precipitation. The measured volume was funneled into a bucket for subsequent manual measurement and confirmation of accuracy. The datalogger summed the number of events over the 5-minute interval and recorded that total to a data file. This resulted in a continuous rainfall record with a 5-minute resolution. Rainfall collected during the study period measured 542 mm in water year 2000 and 751 mm in water year 2001.

Stemflow Collection

Collection collars (Figure 2) to capture stemflow volume were installed on 24 randomly selected trees within the plot (Lewis, 2002). Installation involved first stripping off the bark in a 5 cm band around the circumference of the tree to allow for a tight seal between the collar and the tree. A tree sealant was used to seal the exposed notch on the tree after bark removal. Subsequent installation of the collar was performed by first wrapping a minimum of two layers of foam weather-stripping around the circumference of the tree just above the notch to provide a suitable amount of space around the tree for water running down the furrows of the tree bark.

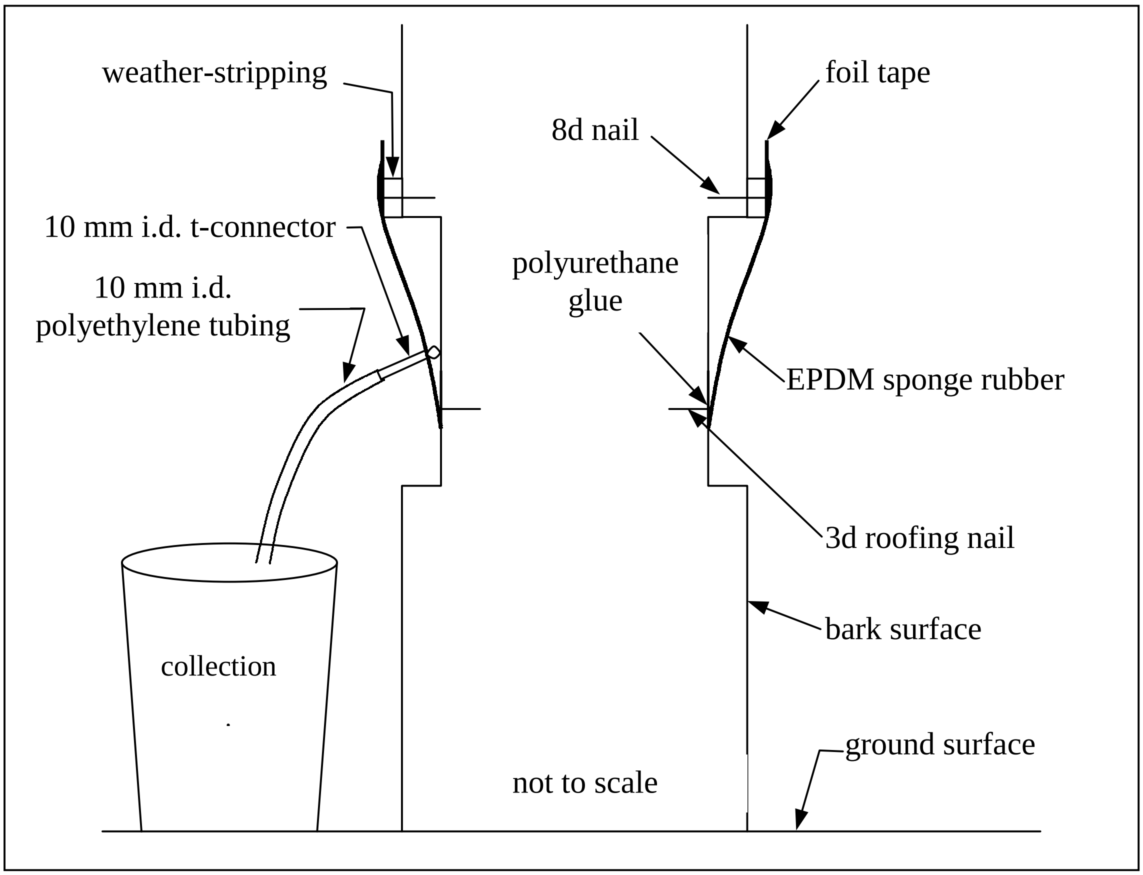

Figure 2. Vertical cross section of typical stemflow collector

Over the weather-stripping, a heavy gauge foil tape was installed to provide the collar a firm lip around its entire circumference. After application of an expanding polyurethane glue on the surface of the notch, a precut strip of sponge rubber was stretched around the tree and nailed-off through the foam weather-stripping with 8d nails at approximately 15-20 cm intervals. This affixed the top edge of the collar to the tree. The low point in the collar was then located and punched with a hole punch and fixed with a 10 mm inside diameter t-connector to pass the volume of the stemflow from the collar to the collector container. The lower edge of the collar was fixed to the tree by use of 5 cm nails inserted at approximately 8 cm intervals around the entire circumference of the tree. The collars were tested for leaks by applying water via a squirt bottle. Leaks were sealed with expanding polyurethane glue. The volumes of stemflow were conveyed to the collection barrels by use of 10 mm inside diameter, 13 mm outside diameter, ployethylene tubing.

Six of the collars were equipped with tipping bucket raingages to provide timing of stemflow events. Raingages were installed on a level support lag-bolted into the bole of the tree. Dataloggers equipped to record instantaneous stemflow data were wired to the raingage switches. The study site was usually visited after every storm from December 1999 to May 2001 to measure and empty the collection barrels, offload the electronic data, and check the collars for obstructions or leaks. Generally, stemflow volume (Table 1) was measured with a calibrated dipstick, although small volumes (less than two liters) were often measured with a graduated cylinder.

Over the two-year study period, stemflow volumes were lost on occasion due to failure of the measurement system. Clogging of the t-connector outlet and polyethylene tubing occurred infrequently due to debris being flushed from the tree into the measurement collar. In order to obtain stemflow volumes from every tree for every storm event, volumes that were lost were estimated by a linear function that employed diameter as the predictor of stemflow volume. The model was based on the accurate

Table 1. Stemflow volume during study period

Tree i.d. #	Stemflow volume (liters) Water year 2000	Water year 2001	Total
RW319	42	56	98
RW389	9	5	14
RW460	58	57	115
RW185	165	185	350
RW410	55	38	93
RW335	141	74	215
RW548	117	101	218
RW364	107	84	191
RW513	155	81	236
RW296	166	91	257
RW132	152	96	248
RW234	351	174	525
DF181	68	81	149
DF564	798	962	1760
DF223	684	743	1427
DF186	306	219	525
DF147	999	1459	2458
DF202	827	987	1814
DF240	1380	1414	2794
DF301	826	995	1821
TO573	267	170	437
TO262	350	412	762
TO369	523	606	1129
TO321	1718	2225	3943

volumes captured from all other trees of like species during the same period of measure. The data presented in Table 1 suggest a great deal of variability in annual stemflow volume not only between species, but also between trees within species. Stemflow volume collected from redwood trees during the study period ranged from 14 to 525 liters, with an average catch of 213 liters. Stemflow volume collected from Douglas-fir trees during the study period ranged from 149 to 2794 liters, with an average catch of

1593 liters. Stemflow volume collected from tanoak trees during the study period ranged from 437 to 3943 liters, with an average catch of 1568 liters.

Tree Morphology Characterization

Several tree morphology parameters were measured to determine which explain the most variability in stemflow volume. The 24 sampled trees were measured for diameter, height, bark thickness, crown projection area, branching habit, and stem surface area. All measured morphological variables, including units of measurement, are defined in Table 2.

Table 2. Definition of tree morphology variables

Variable	Description
DBH	Diameter of tree at breast height, centimeters
HT	Height of tree, meters
BRKTHK	Thickness of bark at breast height, centimeters
CPA	Crown projection area, square meters
POSBRCH	Percent positive branches, percentage of all live branches
SA	Stem surface area, square meters

Diameter and Height

Diameter (DBH) was measured with a diameter-tape as described under “Sampling Design” in this chapter. Tree height (HT) was measured from the ground with a survey tape and clinometer and calculated using basic trigonometric relationships.

Bark Thickness

Bark thickness (BRKTHK) was measured via tape measure in the notch made to fit the stemflow collar. An average of four measurements per tree was made to determine average bark thickness.

Crown Projection Area

Crown projection area (CPA) was measured with a clinometer and survey tape. The standard method of measuring CPA is to project the edges of the crown to a horizontal surface using the clinometer. The crown diameter is then determined based on an average of two measurements: one at the maximum crown diameter, and one perpendicular to the first measurement. Very small individual branches and minor crown irregularities were generally ignored. The CPA was then calculated based on the formula for the area of a circle.

Branching Habit

Branching habit was quantified by counting the total number of branches with live crown, the number of positive branches, the number of negative branches, and the total number of unmeasurable branches. Positive branches were those raised above a horizontal line from the branching point on the stem. Negative branches were classified as those hanging below a horizontal line from the intersection of branch and stem. Steep slopes in the study area allowed for up-slope determination of the branch habit from the ground using a clinometer to verify the line of sight to the branch intersection as being horizontal. Branches at the tops of the tallest trees and on the down-slope side of the stem were generally unmeasurable. Branching habit data were analyzed as a ratio of positive branches to total number of measureable branches (POSBRCH).

Stem Surface Area

Stem surface area (SA) was quantified to yield a value relating to the bark texture of a given study tree. This was quantified by pressing a light-gauge wire over the irregular bark surface in the same location as a circumference measure was made. The result of the wire measure is a percentage circumference increase (CI). Consideration was given to the differences in bark texture between the bottom of the tree, which is more textured, and the top of the tree, which is less textured. As such, measurements were made at various diameters and heights, both on the study trees and on wind-thrown trees in the vicinity of the study area. In most instances a partial measurement of the bark circumference was deemed representative of the entire circumference. This conclusion was based on multiple partial circumference measurements on one tree of each species. Agreement between partial measurements were all within 5%; therefore the partial measurements were accepted as representative of the entire circumference.

Results from wind-thrown trees in the vicinity of the site revealed a linear relationship between diameter and CI (Appendix A: Figures A1, A2, and A3). A linear regression was used to determine the average diameter at which CI was equal to zero for each species: 9.9 cm for redwood, 24.1 cm for Douglas-fir, and 12.4 cm for tanoak (Appendix A: Figures A1, A2, and A3).

For each study tree the circumference measurements were then incorporated into a linear regression model to determine the CI for every diameter on the stem. Two data points were used in the model: a measured diameter and corresponding CI at 1.4 meters height, and a measured diameter and corresponding CI at 4.9 meters height. The regression line was forced to cross the x-axis at the average x-intercept for windthrown trees of the same species. The equation from the linear model was used to determine the CI at any diameter on the stem of the study tree (Appendix A, Table A1).

A taper model for use in the redwood region of north coastal California was utilized for the purpose of estimating the diameter of the study tree at various heights on the stem (Wensel and Krumland, 1983). Input variables for the taper model included DBH and height. The study trees were discretized into segments and the taper model was utilized to determine the diameters at the top and bottom of the segments. The first segment was from 1.4 meters to 6.1 meters height. Subsequent segments were 3.05 meters long, and the leftover height at the top was included as a fraction of a segment.

The linear model relating CI to diameter was then used to determine the true circumference at the bottom and top of the discrete segments. The surface area for each segment was calculated by multiplying the length of the segment by the average of the top and bottom true circumferences (the circumferences adjusted by the CI coefficient). Summing all segments resulted in an estimate of the total stem surface area.

The tree morphology data (Table 3) indicate that the three study species have very different form characteristics. A summary table of descriptive statistics (Table 4) highlights specific differences in morphology. Among the study species, Douglas-fir has the greatest average diameter and height, while tanoak has the smallest. Additionally, Douglas-fir has the largest average crown projection area, while redwood has the smallest. Differences in branching habit are revealed as tanoak has the largest average percent of positively inclined branches, while redwood has the smallest. Bark thickness data indicates a relatively significant difference in the average thickness of the bark on the study species. Redwood, a conifer, has a very rough textured and fibrous bark, while Douglas-fir, also a conifer, has a medium bark texture. Tanoak, a local broadleaf evergreen hardwood, has a smooth hard bark that exhibits little texture. Among the study trees, redwood has the greatest average bark thickness, while tanoak has the smallest.

Table 3. Tree morphology data

Tree i.d.	DBH (cm)	HT (m)	BRKTHK (cm)	CPA (m^2)	POSBRCH (%)	SA (m^2)
RW319	15.0	9.90	0.4	7.30	18	2.15
RW389	16.8	7.42	0.4	4.67	0	1.72
RW460	30.0	17.13	2.0	14.30	5	8.15
RW185	36.8	28.80	2.0	42.03	21	17.42
RW410	41.9	28.54	5.8	12.33	25	22.45
RW335	46.0	23.64	3.8	35.32	22	18.48
RW548	52.8	32.44	5.9	23.64	18	30.07
RW364	60.7	43.40	6.5	26.34	25	50.17
RW513	72.6	34.15	8.3	42.03	35	44.17
RW296	75.9	42.93	5.3	74.72	13	61.59
RW132	89.9	46.58	7.3	74.72	11	76.44
RW234	105.7	45.80	9.0	94.56	13	84.82
DF181	16.0	17.26	0.4	1.17	44	4.65
DF564	43.9	41.00	2.0	26.34	100	31.61
DF223	61.2	46.56	1.6	45.60	66	48.27
DF186	66.8	50.77	3.5	29.19	33	56.92
DF147	68.6	41.43	3.5	116.75	65	46.48
DF202	73.2	44.02	5.0	105.36	52	52.39
DF240	98.8	48.92	3.3	189.78	53	74.05
DF301	99.6	63.71	3.8	182.41	50	101.62
TO573	14.7	16.68	0.1	3.58	33	4.08
TO262	18.0	18.74	0.1	18.68	93	5.61
TO369	35.1	29.21	1.3	32.18	73	16.91
TO321	51.1	30.74	2.6	128.71	91	25.65

Bark Texture Experiment

Bark texture as a stemflow controlling variable was further investigated by modifying and implementing a field experiment presented by Voigt (1960). The experiment was conducted by applying water to the stem 3.05 meters above the measurement collar. One similar-sized tree of each species was selected from the collared study trees: Redwood 548, Douglas-fir 564, and Tanoak 369. Water was added in one-liter increments and allowed to flow for fifteen minutes before the recovered volume at the collection collar was measured. Subsequent to measurement of the

Table 4. Tree morphology descriptive statistics

		Redwood	Douglas-fir	Tanoak
DBH (cm)	Minimum	15.0	16.0	14.7
	Median	49.4	67.7	26.6
	Mean	53.7	66.0	29.7
	Maximum	105.7	99.6	51.1
HT (m)	Minimum	7.42	17.26	16.68
	Median	30.62	45.29	23.98
	Mean	30.06	44.21	23.84
	Maximum	46.58	63.71	30.74
BRKTHK (cm)	Minimum	0.4	0.4	0.1
	Median	5.6	3.4	0.7
	Mean	4.7	2.9	1.0
	Maximum	9.0	3.8	2.6
CPA (m^2)	Minimum	4.67	1.17	3.58
	Median	30.83	75.48	25.43
	Mean	37.66	87.08	45.79
	Maximum	94.56	189.78	128.71
POSBRCH (%)	Minimum	0	33	33
	Median	18	53	82
	Mean	17	58	73
	Maximum	35	100	93
SA (m^2)	Minimum	1.72	4.65	4.08
	Median	26.26	50.33	11.26
	Mean	34.80	52.00	13.06
	Maximum	84.82	101.62	25.65

recovered volume, the next liter was applied. Modification of the experiment involved developing a method of application that would work well for all three study species. This proved to be challenging as all three bark types are very different. A manual pump garden sprayer with an adjustable spray nozzle was modified for this purpose. The container was calibrated to 0.25 liters accuracy. The spray nozzle was modified to allow for easy application of the water to the entire circumference of the stem from one location (on an extension ladder leaning against the tree). A systematic approach to application of the water was employed to provide even distribution of water on the stem. The circumference of the stem 3.05 meters above the collar was divided into four even quadrants. Each quadrant received a quarter of the liter applied. The pressure in the tank and the adjustment of the spray nozzle regulated the rate of application. After several trials, a steady even spray proved to be the most effective in preventing loss from the impact of the water on the bark surface.

A total of twenty liters were applied to the tanoak and Douglas-fir before determining that a relatively static condition had been reached (Table 5). Essentially, the amount of water being recovered was not fluctuating enough to justify continuation of the experiment. Although a static condition was not reached when conducting the experiment on the redwood, twenty-five liters were applied to the tree before cessation of the experiment. These data indicate that the redwood tree was the least efficient at delivering the applied water to the measurement collar. Douglas-fir was slightly more efficient, while tanoak was quite efficient at routing the water to the measurement collar (Table 5).

Table 5. Bark texture experiment data

Water applied (liters)	Water recovered (liters), 15 minutes after application		
	Redwood	Douglas-fir	Tanoak
1	0.006	0.003	0.013
2	0.007	0.022	0.120
3	0.011	0.080	0.230
4	0.016	0.250	0.480
5	0.025	0.390	0.730
6	0.035	0.450	0.850
7	0.090	0.500	0.880
8	0.160	0.540	0.870
9	0.210	0.590	0.890
10	0.270	0.530	0.920
11	0.280	0.500	0.910
12	0.320	0.630	0.910
13	0.340	0.700	0.920
14	0.390	0.670	0.940
15	0.400	0.730	0.920
16	0.390	0.690	0.920
17	0.400	0.680	0.940
18	0.430	0.670	0.930
19	0.480	0.680	0.940
20	0.500	0.680	0.920
21	0.490	-	-
22	0.550	-	-
23	0.560	-	-
24	0.550	-	-
25	0.570	-	-

CHAPTER IV

ANALYSIS AND DISCUSSION

Four separate analyses were conducted on the data to meet the objectives of the study. First, annual stemflow volumes were used to calculate funneling ratios (Herwitz, 1986) as a means of offering comparison between crown funneling effects of these redwood forest species and species from other studies. Second, multiple regression analysis of the morphology data was used to determine which morphologic characteristics of the trees could be used to explain the variability in total stemflow volume. Third, results from the bark texture experiment were incorporated into a simple linear regression model in order to test the effectiveness of the stem surface area measurements as a means for characterizing the effect of bark texture on stemflow volume. Fourth, five discrete precipitation events were analyzed to determine the differences in rainfall prior to stemflow inception between the three species.

Funneling Ratios

A meaningful yardstick for comparing stemflow volumes between trees, and between species, is the funneling ratio (Herwitz 1986):

$$F.R. = \frac{V}{(B*G)} \qquad (1)$$

where *V* is the stemflow volume for the given tree (*ml*), *B* is the basal area of the tree (cm^2), and *G* is the rainfall depth (*cm*). The funneling ratio is a means for determining if there is a contribution from the branches in generating stemflow. A ratio of 1.0 indicates the measured stemflow volume would be equal to the measured volume from a hypothetical raingage with a collecting area the size of the basal area of the tree. Therefore, a ratio greater than 1.0 indicates a contribution from the branches in funneling water to the stem and increasing the total volume of water captured from the tree. The means and ranges of annual funneling ratios from 2000 and 2001 indicate tanoak is very efficient at routing water from the branches to the stem (Table 6).

Table 6. Annual means and ranges of funneling ratios

	Tanoak	Douglas-fir	Redwood
2000 Mean	20.0	4.5	1.3
2000 Range	10 – 29	1.6 - 9.7	0.4 - 4.3
2001 Mean	14.4	3.8	0.9
2001 Range	8.4 – 21.5	0.8 - 8.4	0.2 - 4.2

The annual funneling ratios observed from Douglas-fir are smaller, but they suggest a relatively significant contribution from the canopy in generating stemflow. The ratios computed for coast redwood suggest a minimal contribution, if any, by the canopy in generating stemflow. This seems reasonable as only one redwood study tree (RW513) had greater than 25% positively inclined branches. The annual funneling ratios observed for tanoak are similar to those reported for several other similarly structured species (Crockford and Richardson, 1990; Aboal *et al*., 1999). Other funneling ratios reported include a *Pinus radiata* plantation with positively inclined branching (32.6), and different *Eucalyptus* species (4.7-21.7) (Crockford and Richardson, 1990; Aboal *et al*., 1999).

Multiple Regression Analysis

Tree morphology characteristics and annual stemflow volumes were incorporated into a multiple linear regression model to determine which characteristic, or combination of characteristics, best predicted the annual stemflow volume. The statistics presented here are found throughout many statistical publications. This material was compiled from texts by Devore and Peck (1993) and Cook and Weisberg (1994). The linear model relates a criterion, or dependent, variable to two or more predictor, or independent, variables:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_p x_p + e \qquad (2)$$

in which y is the criterion variable, x_1, x_2, …, x_p are predictor variables, β_0, β_1, …, β_p are parameters to be estimated, and *e* is a normally distributed random error with mean equal to zero. The principle of least squares is used to regress *y* on the x_i values of Equation 2.

The coefficient of multiple determination (R^2) is interpreted as the proportion of variation in the observed *y* values (stemflow volumes) that is explained by the fitted model. Mathematically, R^2 is defined as:

$$R^2 = 1 - \frac{SSres}{SStot} = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \qquad (3)$$

in which $\hat{y}$ is the predicted value of y, and $\bar{y}$ is the mean value of y. The corrected

Akaike Information Criterion (*AICc*), described by Burnham and Anderson (1998), was used to determine which model was best supported by the observed data. Among two or more reasonable models, the model with the smallest *AICc* is considered best. In least squares regression *AIC* (uncorrected) can be expressed as:

$$AIC = n\log\left(\hat{\sigma}^2\right) + 2K \tag{4}$$

in which n is the number of observations, p is the number of predictors, $K = p + 2$, and $\hat{\sigma}^2$, the maximum likelihood estimator of residual variance, is defined as:

$$\hat{\sigma}^2 = \frac{1}{n}\sum \hat{e}_i^{\,2} \tag{5}$$

in which $\hat{e}_i = y_i - \hat{y}_i$, where $\hat{y}_i$ is the i^{th} predicted value of the criterion variable, y_i is the i^{th} measured value of *y*, and $\hat{e}_i$ is the i^{th} residual. The 2*K* term effectively penalizes the addition of new predictors to the model. The corrected version of AIC is used for small sample sets and is defined as:

$$AICc = AIC + \frac{2K(K+1)}{n - K - 1} \tag{6}$$

Stemflow volume during the study period was modeled using multiple linear regression on morphology variables. Regression models were also developed between stemflow volume and individual predictors, and between each predictor and remaining predictors, to determine if variable transformations were needed (Cook and Weisberg, 1994) or if collinearity would be a potential problem. Four candidate regression models were considered for selection. Model 2 was accepted using the predictors CPA, POSBRCH, and SA (previously defined in Table 3) to predict stemflow volume (Table 7).

Table 7. Candidate regression models

Model #	Variables Included	Intercept Included	R^2	S_e	AIC
1	POSBRCH, CPA, SA	Yes	0.89	362.4	294.2
2	POSBRCH, CPA, SA	No	0.88	375.3	293.5
3	POSBRCH, CPA	No	0.77	513.2	306.5
4	POSBRCH, CPA	Yes	0.85	422.4	299.2

Model 2 was selected over model 1 for two reasons. Firstly, model 2 excluded the intercept coefficient. Physical reasoning suggests that as the measured morphology variables become zero, stemflow also becomes zero. Secondly, the AICc value returned from the model with no intercept coefficient was less than the AICc value returned from the model with an intercept coefficient. Model 2 explained 88 % of the variation ($R^2 = 0.88$) in the stemflow volumes captured during the study period (Table 3). The form of the model is:

$$Stemflow(l) = 17.55CPA + 14.41POSBRCH - 16.21SA \quad (7)$$

The relationship between model residuals and fitted stemflow volume is depicted in Figure 3, which shows no systematic relation between the residuals or their variance and the fitted values. The plot, however, reveals two residuals significantly different from the others. The large negative residual represents TO262, while the large positive residual is from TO321. This suggests that the model was not as accurate at predicting stemflow volume from tanoak as from redwood and Douglas-fir.

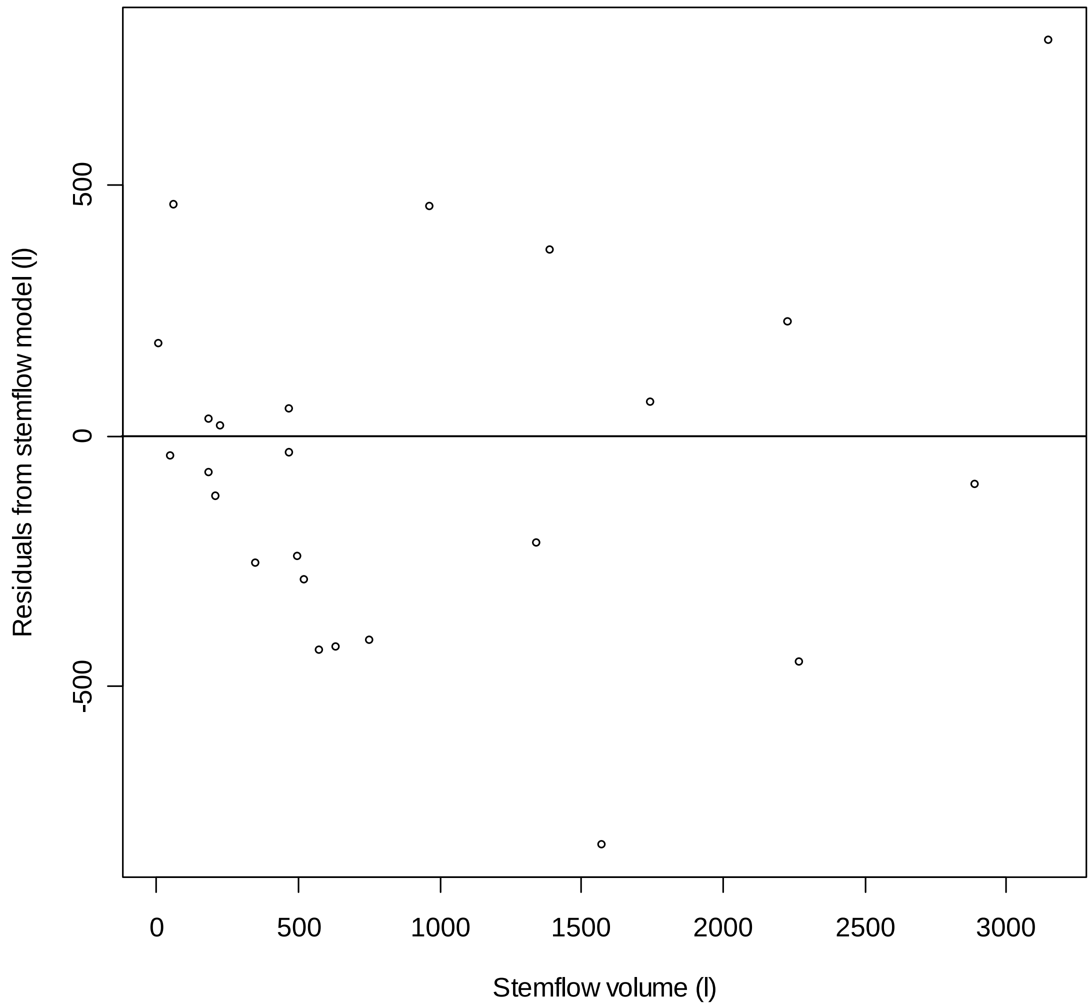

Figure 3. Relation between model residuals and fitted stemflow volume. Residuals are from least squares fit to the model $Stemflow(l) = 17.55CPA + 14.41POSBRCH - 16.21SA$.

The model suggests that the trees with the greatest percentage of positively inclined branches, with the largest projected crown area, but with the smallest stem surface area, produced the most stemflow during the study period. Intuitively, this is reasonable, as a large projected crown area will intercept large amounts of rainfall, the high percentage of positively inclined branches will effectively route the intercepted rainwater to the stem, and the small stem surface area will reduce the amount of loss from the stem in the form of stem-drip and absorption/evaporation. These findings are consistent with results of other stemflow studies presented in the literature. Navar (1993), Ford and Deans (1978), Johnson (1990), Cape *et al*. (1991), Kellman and Roulet (1990), and Herwitz (1993) all found that branching habit was a controlling factor in the generation of stemflow. Additionally, Ford and Deans (1978), Sood *et al*. (1993), Aboal *et al*. (1999), and Lawson (1967) noted the importance of crown projection areas as a predictor of stemflow. No findings in the literature indicate that any previous researchers have studied stem surface area as a stemflow controlling factor, although the relationship between stemflow and bark texture has been presented by Navar (1993) and Aboal *et al*. (1999).

Bark Texture Experiment Analysis

Analysis of the water recovery volumes as cumulative water recovered per 20 liters applied reveals that bark texture at least partly explains the differences in recovery volumes between the three species. For this analysis 20 liters was used as the amount applied because it was the minimum amount applied on all three trees. Results of this analysis are presented in Table 8 and depicted in Figure 4.

Table 8. Cumulative water recovery from the bark texture experiment

Cum. water rec.	Tanoak	Douglas-fir	Redwood
(20 liters applied)	15.233	9.985	4.760
% total recovered	76	50	24

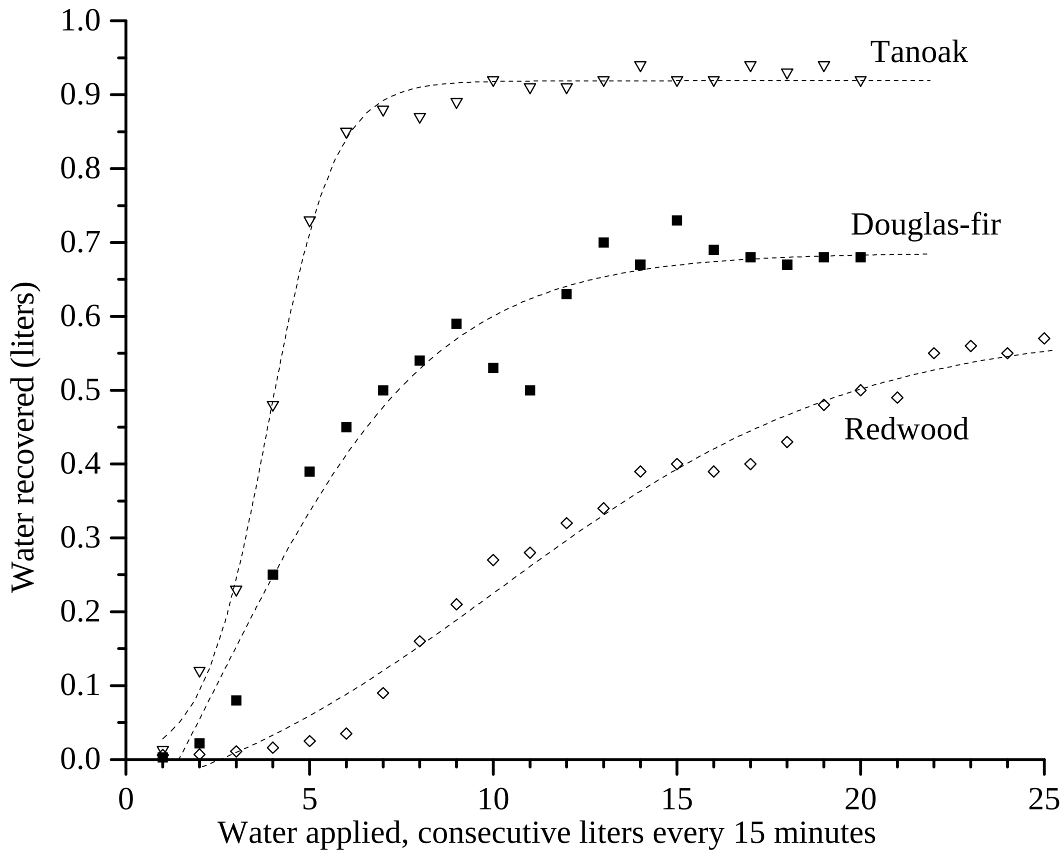

Figure 4. Water recovery from 3.05 meter segment of stem.

Results of the experiment reveal that tanoak allowed for the most complete recovery of water. Approximately 90% of the volume applied was recovered after the addition of the sixth liter. At this point the stem of the tree was almost completely saturated, with only a small dry patch on the downslope side of the stem. Water loss in the form of stem drip was observed from a fixed drip point on the downslope side of the stem, although the volume lost seemed negligible. With Douglas-fir, the slope of the line does not approach horizontal until the eleventh liter of water was applied, at which point the tree was recovering approximately 70% of the volume of water applied. At this point, several dry patches of bark still existed, and loss in the form of stem drip was more substantial than that of the tanoak. The curve for redwood indicates a much less efficient recovery of water during the experiment. Equilibrium (a horizontal line) was never truly reached, as less than 50% of the water was being recovered after 20 liters were applied. This is likely due to the thicker and more textured redwood bark. Redwood bark seems capable of storing greater quantities of water than either tanoak or Douglas-fir. Additionally, stem drip was occurring from drip points on the redwood during the entire length of the experiment. This may indicate that stemflow from redwood trees may fall in a somewhat scattered pattern around the stem of the tree instead of flowing down the bark surface. Voigt (1960) found similar results from red pine (*Pinus resinosa* Ait.), which also exhibits a textured bark.

The surface area of the segment of stem for the three trees used in the bark experiment was determined by methods described in Chapter III (textured SA). Additionally, the surface area of the segment was computed from diameter only (smooth SA). The wire-measurement adjustment increased the surface area of the segment by 33%, 15%, and 2% (SA increase) for redwood, Douglas-fir, and tanoak, respectively. The cumulative volume of water recovered during the experiment was regressed on each of the above variables: textured SA, smooth SA, and SA increase (Table 9).

Table 9. Regression statistics from the bark texture experiment

Predictor	R^2	S_e
Textured SA	0.999	0.231
Smooth SA	0.986	0.891
SA increase	0.994	0.559

These simple linear regressions revealed that textured bark surface area (textured SA) of the isolated segment of stem accounted for 99.9% (R^2 =0.999) of the variation in the volume recovered during the experiment, and was the most efficient at minimizing the standard error (Figure 5).

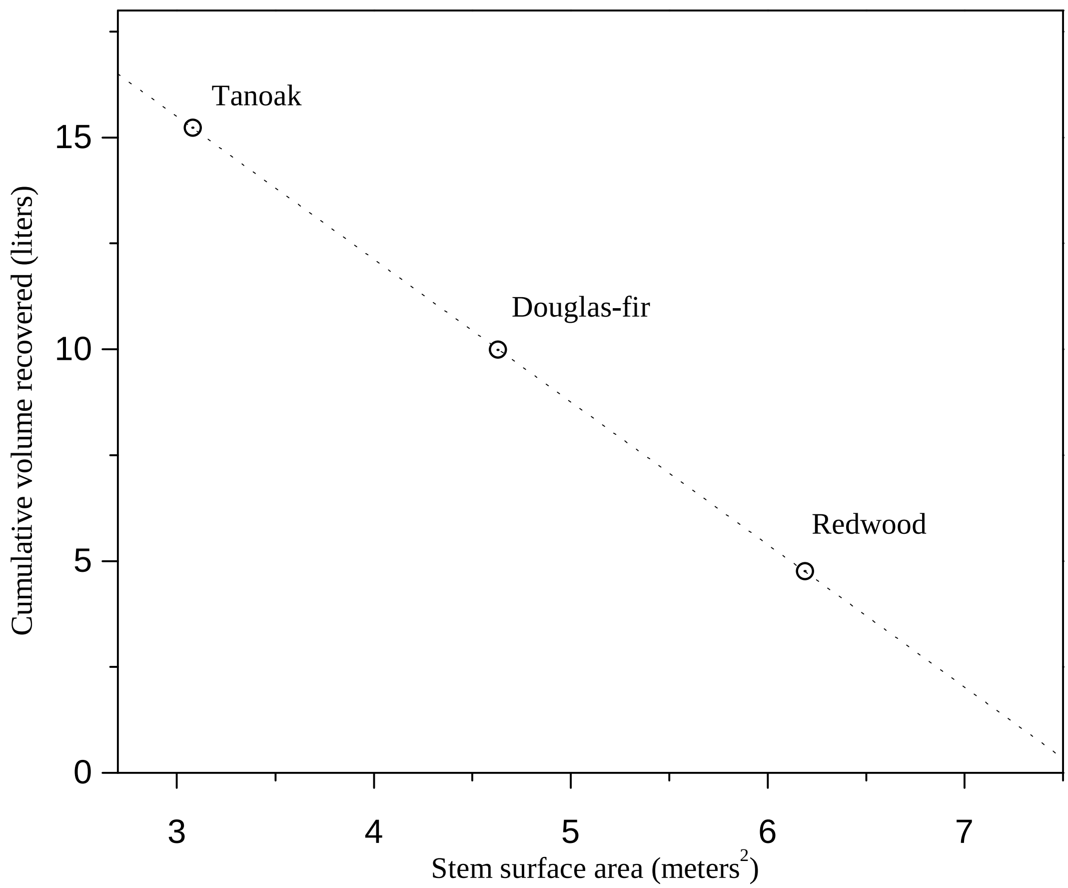

Figure 5. Relationship between stem surface area and cumulative volume recovered

Although this high correlation was based solely on three observations (one tree of each species), the result suggests support for the method developed herein for characterizing stem surface area as a stemflow regulating factor. Additional data would be needed to increase the value of this analysis. However, conducting the experiment on many trees of each species, over a range of diameters, was beyond the scope of this thesis.

Stemflow Timing Analysis

Five rainfall events of varying intensities were plotted and analyzed in detail to determine the differences between species in rainfall amount received prior to stemflow inception (Table 10).

Table 10. Rainfall prior to stemflow inception on 3 selected trees for events 1-5

	Tanoak	Douglas-fir	Redwood	Maximum rainfall intensity
Event 1 (mm)	5.8	10.9	12.2	38mm / 6 hour
Event 2 (mm)	8.9	15.2	16.5	21mm / 6 hour
Event 3 (mm)	2.3	5.6	8.6	18mm / 6 hour
Event 4 (mm)	3.6	8.4	9.1	16mm / 6 hour
Event 5 (mm)	4.8	13.0	22.9	25mm / 6 hour
Mean (mm)	5	11	14	24mm / 6 hour

Individual rainfall events were demarcated by intervening dry periods of at least 4 hours (Hamilton and Rowe, 1949). Figures 6-10 depict the rainfall events, with stemflow volume from one tree of each species plotted below the precipitation during each rainfall event. Of the six trees equipped with recording raingages, the three of relatively similar DBH were used in this analysis: DF564, TO369, and RW548.

Event 1: February 22, 2000

Rainfall in this event (Figure 6) began with a light-intensity rain (1.8 mm/hour) falling between 0200 and 0300 hours, followed by a cessation in rainfall until nearly 0600. Light-intensity rain continued falling for the next four hours, at which point

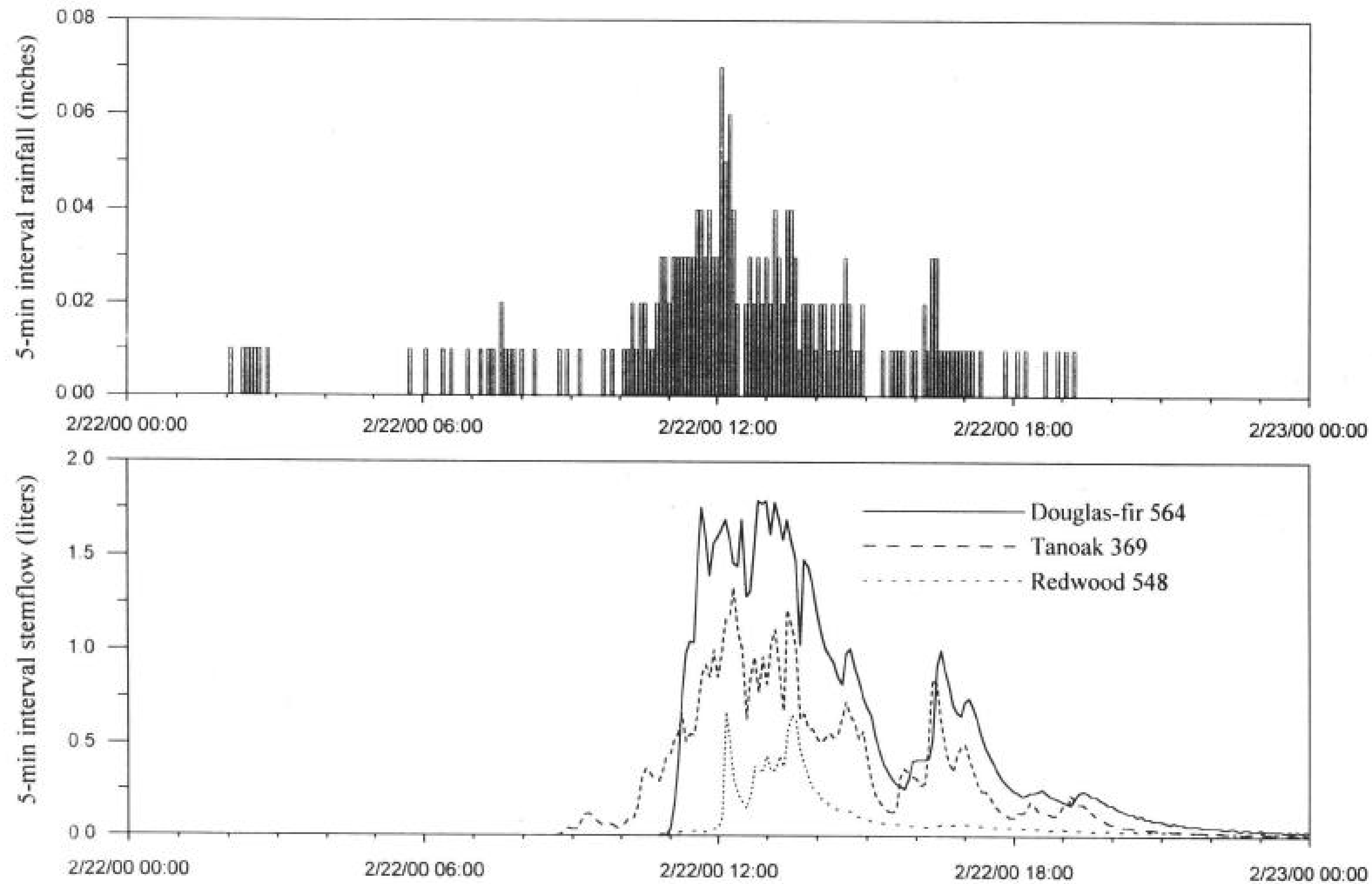

Figure 6. Stemflow response to a February 22, 2000 rainfall event

stemflow began to be produced by the tanoak after 5.8 mm of rainfall. The intensity of rainfall increased to 10.4 mm/hour by 1200 hours, and stemflow was being produced by the Douglas-fir and coast redwood after 10.9 mm and 12.2 mm of rain, respectively. However, the magnitude of stemflow was quite different between the Douglas-fir and the redwood. In the first hour of stemflow production, the Douglas-fir had produced at least 9.27 liters, while the redwood had produced only 0.27 liters. The volume produced by the Douglas-fir is approximate, however, as the tipping bucket appeared to become overwhelmed by rates of stemflow exceeding approximately 1.5 liters per five-minute interval. This is evident on the plot where the Douglas-fir stemflow trace appears unstable during the period of most intense rainfall (just after 1200 hours on 02/22/00). Although the electronic volume measurements were generally an underestimate of the manually measured stemflow volume, the timing of stemflow inception was not affected.

Event 2: January 7-8, 2001

This event (Figure 7) is characterized by rainfall with an intensity of 3.6 mm/hour from 2000 to 2300 hours, at which point stemflow began to be produced by the tanoak tree after a total of 8.9 mm of rain. Rainfall intensity increased slightly to 4.3 mm/hour over the next hour and the Douglas-fir began producing stemflow after a total of 15.2 mm of rain, while the redwood began after 16.5 mm of rain. Although the timing of stemflow inception was relatively similar between the Douglas-fir and the redwood, the magnitude was quite different. In the first hour of stemflow production, the Douglas-fir had produced 1.33 liters, while the redwood had produced only 0.09 liters.

Event 3: January 9, 2001

Rainfall during this event (Figure 8) began just over 24 hours after the

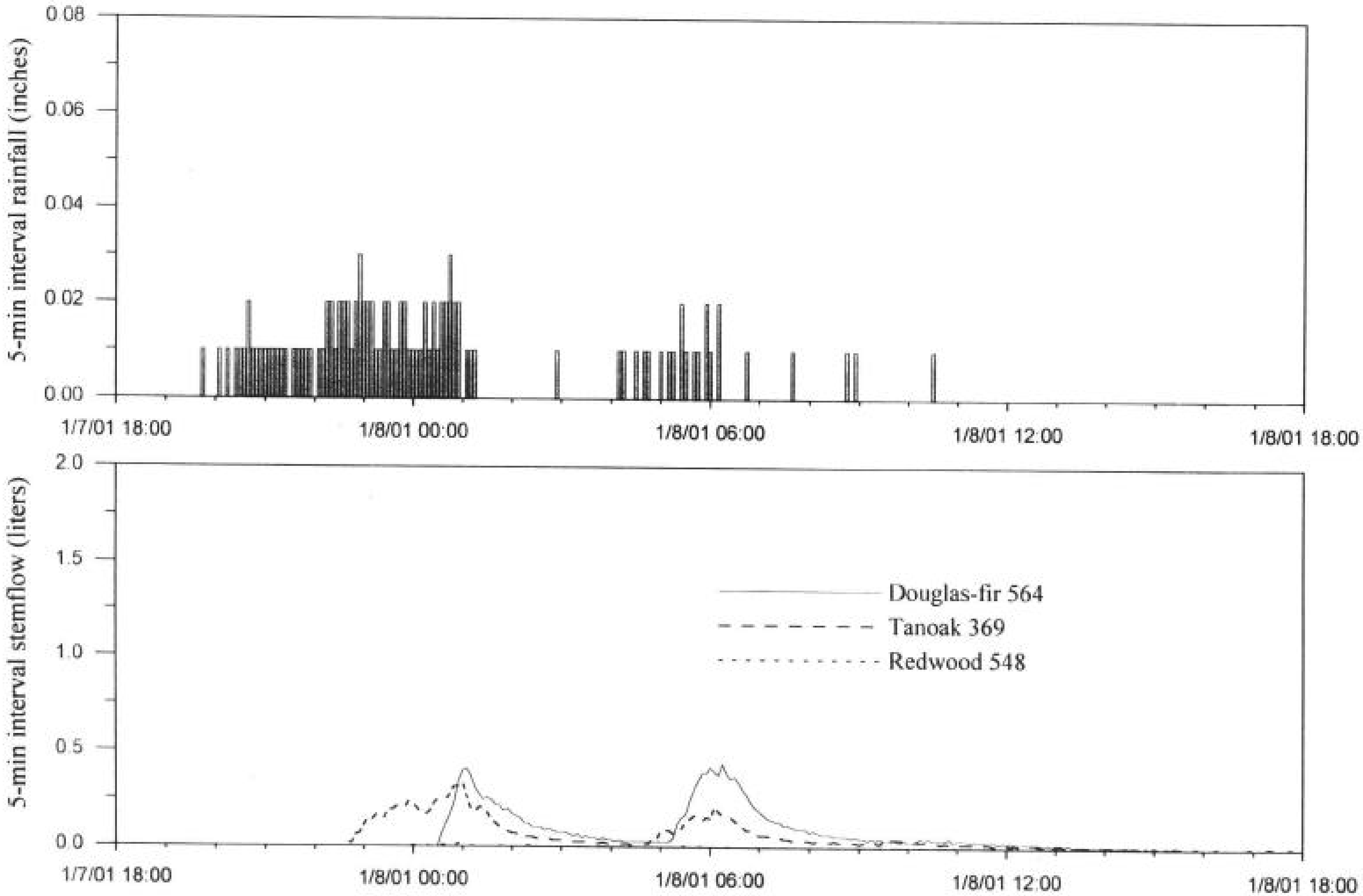

Figure 7. Stemflow response to a January 7, 2001 rainfall event

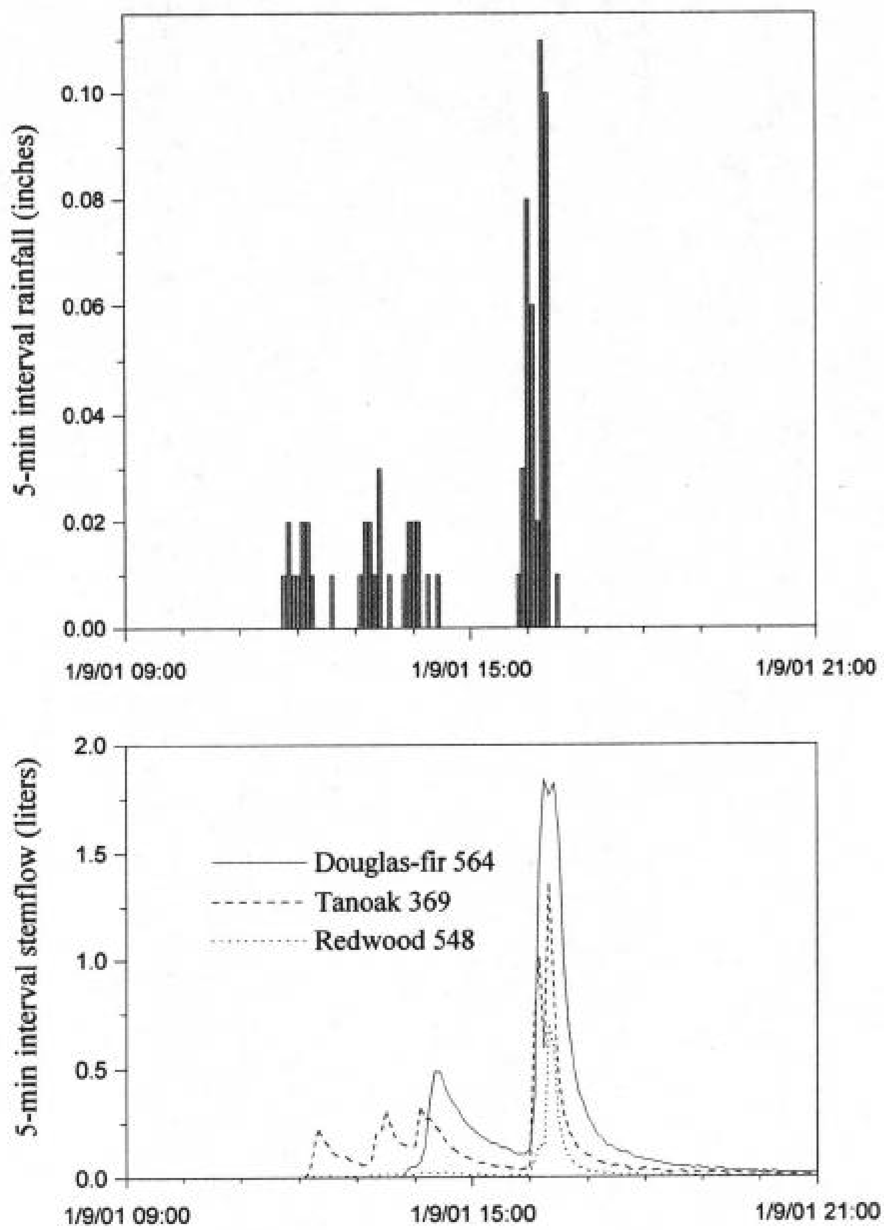

Figure 8. Stemflow response to a January 9, 2001 rainfall event

previous event (event 2). Stemflow inception occurred after less rainfall, suggesting the canopy may have stored water from the previous event. Rainfall intensity of 2.8 mm/hour produced stemflow from the tanoak after merely 2.3 mm of rain. The Douglas-fir began to produce stemflow after 5.6 mm of rain. The redwood had a very slight response after 2.5 mm of rain, although the majority of stemflow produced during this event began after 8.6 mm of rain. The small early response of the redwood suggests that stem drip, or wind-driven canopy drip, may have been occurring. These processes could quickly route water to the collection collar without entirely flowing down the bark surface. Findings from this event are consistent with results from previous studies in which the temporal pattern of stemflow was found to vary strongly with crown wetness at the time rainfall was initiated (Xiao *et al*., 2000).

Event 4: January 10, 2001

Rainfall during this event (Figure 9) began just 15 hours after the previous event (event 3). Rainfall intensity of 3.8 mm/hour induced stemflow on the tanoak after 3.6 mm of rain. After nearly an hour hiatus in the rainfall record, rainfall began again at an intensity of 4.3 mm/hour. Stemflow was initiated from the Douglas-fir and redwood after 8.4 mm and 9.1 mm of rainfall, respectively.

Event 5: March 3-4, 2001

This event (Figure 10) is characterized by light-intensity long-duration rainfall. Rainfall in the initial twelve hours was relatively steady, with an average intensity of 1.3 mm/hour. Stemflow was produced from the tanoak after 4.8 mm and from the Douglas-fir after 13 mm. Rainfall intensity increased over the next three hours to an average of 2.3 mm/hour prior to the inception of stemflow from the redwood after a total of 22.9 mm. Although Douglas-fir and tanoak appear to respond to pulses in the rainfall record at approximately the same rate, close examination reveals there may be a slight phase shift in the stemflow response. The Douglas-fir response lags behind the tanoak response slightly. Additionally, the redwood seems relatively unresponsive to

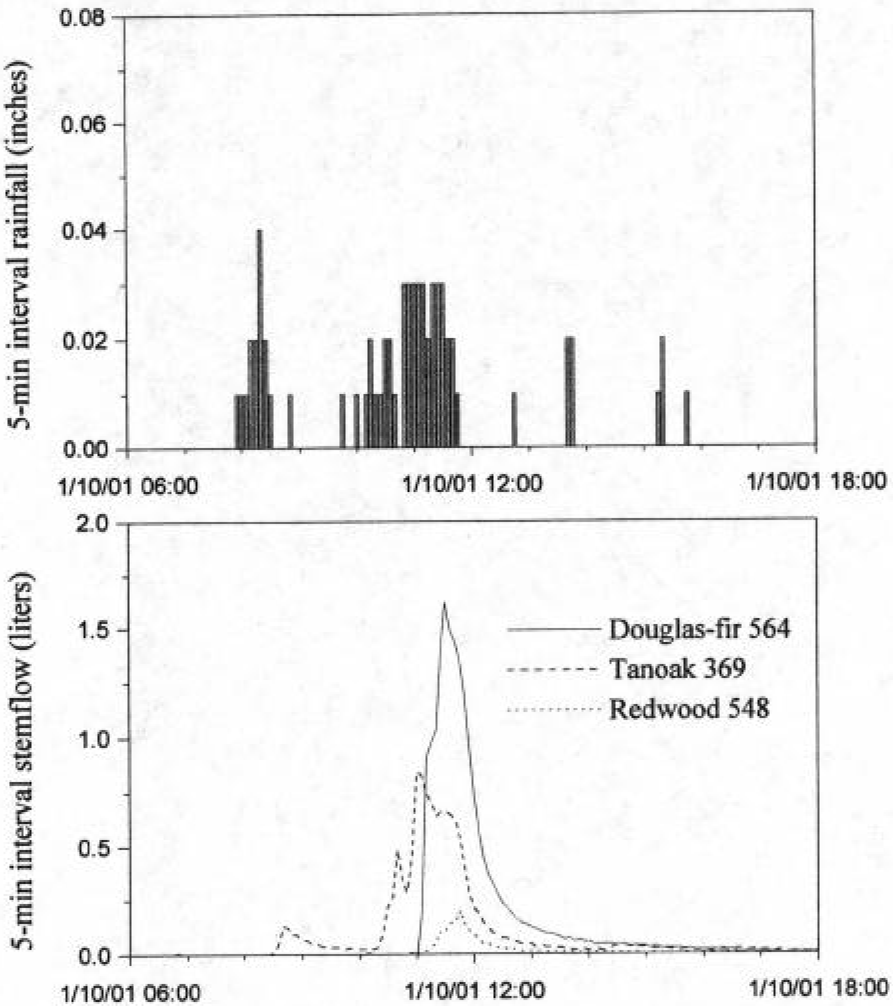

Figure 9. Stemflow response to a January 10, 2001 rainfall event

changes in rainfall intensity. The stemflow trace for redwood is quite flat over the last five hours of the event, while the Douglas-fir and tanoak traces rise and fall with changes in rainfall intensity. The smooth redwood stemflow trace suggests that the thick-textured and fibrous bark of the redwood may act as a storage reservoir buffering the delivery of stemflow.

The timing data are consistent with the idea that the same morphologic characteristics that control the magnitude of stemflow (CPA, POSBRCH, and SA) also

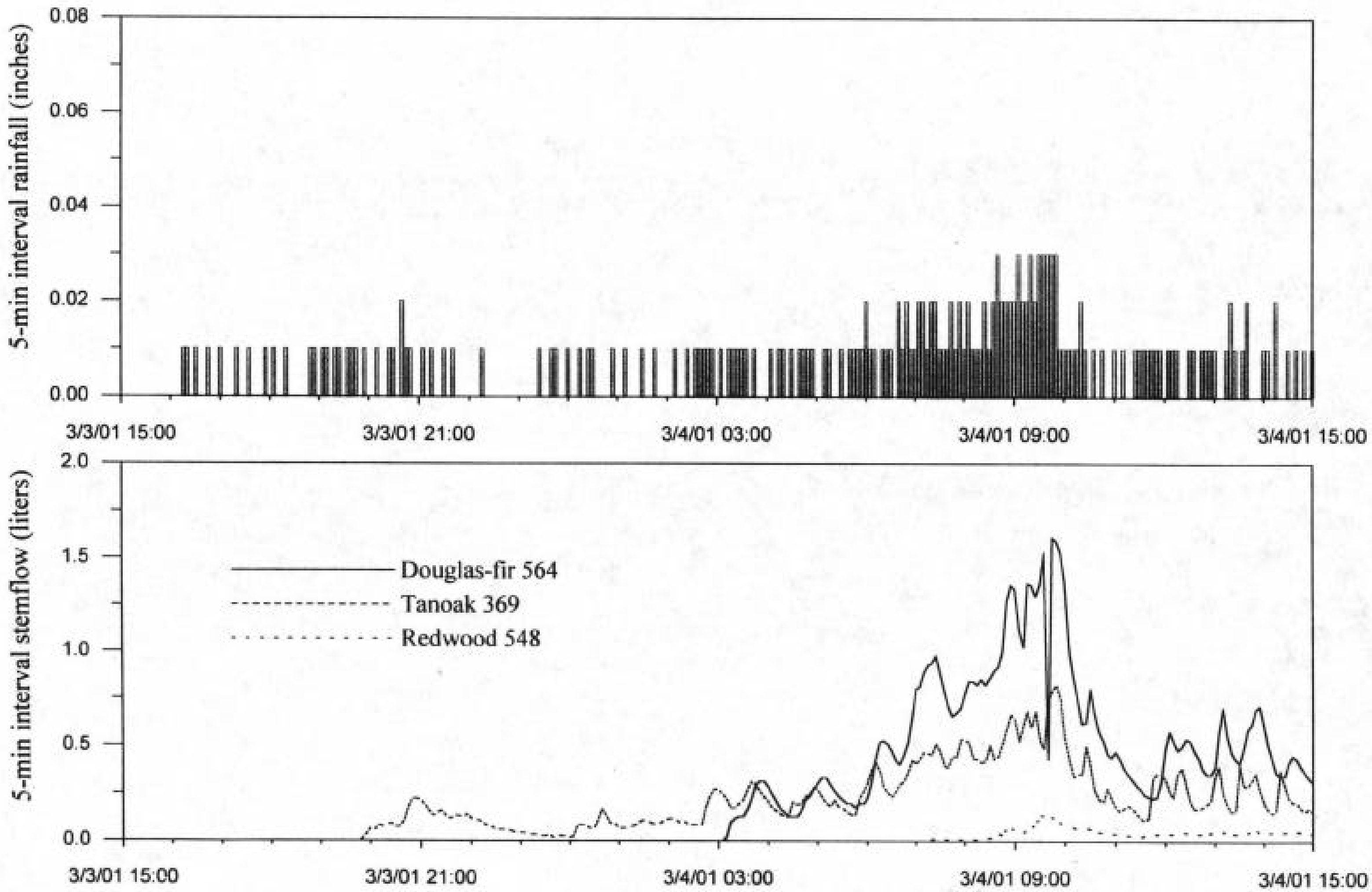

Figure 10. Stemflow response to a March 3, 2001 rainfall event

control the timing of its inception. A large crown of positively inclined branches will likely deliver more water to the stem at a faster rate than a smaller crown of predominately negatively inclined branches. Additionally, rough-textured bark (with a greater SA) may act as a sponge, absorbing and later releasing or evaporating large quantities of water. This would delay the time it takes for water to flow down the stem. On the other hand, stem drip could accelerate stemflow on rough-textured bark if water drips to lower portions of the stem or directly into the measurement collector from various drip points on the stem. However, stem drip is more likely to bypass the measurement collar entirely. Wind may also play a role in the timing of stemflow during rainfall. Under the influence of wind, water falling to the ground as drip from the canopy can be deflected and deposited directly on the stem (Xiao *et al*., 2000). This process is likely to be more of a factor in a sparsely vegetated forest (urban forest) where wind is less buffered by the dense surrounding forest canopy.

CHAPTER V

CONCLUSIONS

Stemflow volumes were collected and analyzed from coast redwood, Douglas-fir, and tanoak trees in a second-growth redwood forest from January 2000 to April 2001. Several morphologic characteristics of these species partly explain the variability in stemflow.

The magnitude of stemflow volumes collected from the three study species indicates a great deal of variability not only between species, but also between trees within species. Stemflow volume collected from redwood trees ranged from 14 to 525 liters, with an average catch of 213 liters. Volume collected from Douglas-fir trees ranged from 149 to 2794 liters, with an average catch of 1593 liters. Volume collected from tanoak trees ranged from 437 to 3943 liters, with an average catch of 1568 liters. Funneling ratios computed for redwood trees ranged from 0.2 to 4.3, with an average of 1.1. Douglas-fir funneling ratios ranged from 0.8 to 9.7, with an average of 4.2. Ratios computed for tanoak ranged from 8.4 to 29, with an average of 17.2. The funneling ratios indicate tanoak receives the greatest contribution of intercepted rainwater from the crown. Variability in stemflow volume was best explained by a three-variable linear model incorporating the crown projection area, the percentage of positively inclined branches, and the stem surface area. This model explained 88% of the variability in stemflow volume over the study period.

An in situ bark experiment to isolate the stem from the crown suggests that the stem surface area, as determined from the measurement method outlined in Chapter III, has a negative linear relationship with the volume of water recovered from the stem. Generally, a textured stem has a greater surface area that stores more water before producing stemflow. Additionally, drip points observed on Douglas-fir and redwood suggest that stem drip may explain why stems with a greater surface area continued to produce less water throughout the entire experiment. Based on data collected from the bark experiment, a simple linear model was developed which used stem surface area to predict water recovery (stemflow). The model supports the stem surface area methodology as a useful characterization that accounts for the influence of bark texture on stemflow.

Five-minute interval rainfall and stemflow data collected during precipitation events indicates that the timing of stemflow differs considerably among the three species. The data are consistent with the idea that the same morphologic characteristics that control the magnitude of stemflow may also control the timing of its release.

Future research on this topic should examine the possible linkage between stemflow and subsurface pipeflow. Tanoak and Douglas-fir trees are capable of funneling relatively large quantities of water into a concentrated area. In the redwood region where subsurface storm flow is likely the main run-off generating mechanism, stemflow may contribute to the development of subsurface channels (macropores), potentially increasing soil permeability and piping (Voigt, 1960; Herwitz and Levia Jr., 1997). Subsurface pipeflow has been reported as a locally important process for routing water and sediment from steep upland watersheds (Ziemer and Albright, 1987).

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APPENDIX A

Table A1. Stem diameter, circumference, and percent of increased circumference for each standing study tree

Tree	Measure at 1.4 m height [a]			Measure at 4.9 m height			Regression equation [b]	
i.d. #	D (cm)	C (cm)	CI (%)	D (cm)	C (cm)	CI (%)	Slope	y-Intercept
RW319	15.0	47.1	11.33	10.7	33.5	4.00	2.30	-22.74
RW389	16.8	52.7	7.65	11.4	35.9	6.00	1.25	-12.36
RW460	30.0	94.2	26.00	22.4	70.2	13.50	1.24	-12.24
RW185	36.8	115.7	17.67	28.7	90.2	13.00	0.67	-6.63
RW410	41.9	131.7	50.00	31.5	98.9	41.00	1.67	-16.54
RW335	46.0	144.4	35.33	36.6	114.9	34.67	1.09	-10.84
RW548	52.8	166.0	39.63	43.4	136.5	20.67	0.81	-8.00
RW364	60.7	190.7	47.33	49.3	154.8	26.00	0.83	-8.23
RW513	72.6	228.2	50.33	61.2	192.3	35.67	0.76	-7.53
RW296	75.9	238.6	50.25	65.8	206.7	48.00	0.80	-7.96
RW132	89.9	282.5	47.00	82.6	259.3	46.25	0.61	-6.05
RW234	105.7	332.0	47.50	95.5	300.0	46.33	0.52	-5.11
DF181	16.0	50.3	6.04	13.0	40.7	4.29	N/A [c]	
DF564	43.9	138.0	17.00	39.4	123.7	11.50	0.82	-19.76
DF223	61.2	192.3	17.33	53.8	169.2	10.00	0.42	-10.07
DF186	66.8	209.9	14.00	57.4	180.3	13.00	0.35	-8.46
DF147	68.6	215.5	18.00	54.6	171.6	11.00	0.39	-9.41
DF202	73.2	229.8	17.50	60.2	189.1	12.50	0.35	-8.55
DF240	98.8	310.4	16.25	85.6	268.9	14.50	0.22	-5.42
DF301	99.6	312.8	17.50	82.8	260.1	17.00	0.25	-6.08
TO573	14.7	46.3	0.65	12.2	38.3	0.00	0.00	0.00
TO262	18.0	56.7	0.00	14.0	43.9	0.00	0.00	0.00
TO369	35.1	110.1	3.67	26.7	83.8	0.00	0.00	0.00
TO321	51.1	160.4	10.48	43.4	136.5	6.50	0.25	-3.09

[a] D = Diameter, C = circumference, CI = percent of increased circumference.

[b] Regression equation to estimate CI at any diameter. The x-intercept of each of the regression equations is forced through the average x-intercept from windthrown trees of the same species (figures A1, A2, A3).

[c] Not applicable. Both diameters on the stem of DF181 were less than the average x-intercept from the windthrown Douglas-fir trees (24.1cm), so the surface area was calculated directly from the field measurements. The CI above the measurement at 4.9 m height was assumed to be zero, therefore no linear estimator of CI was needed to determine the surface area.

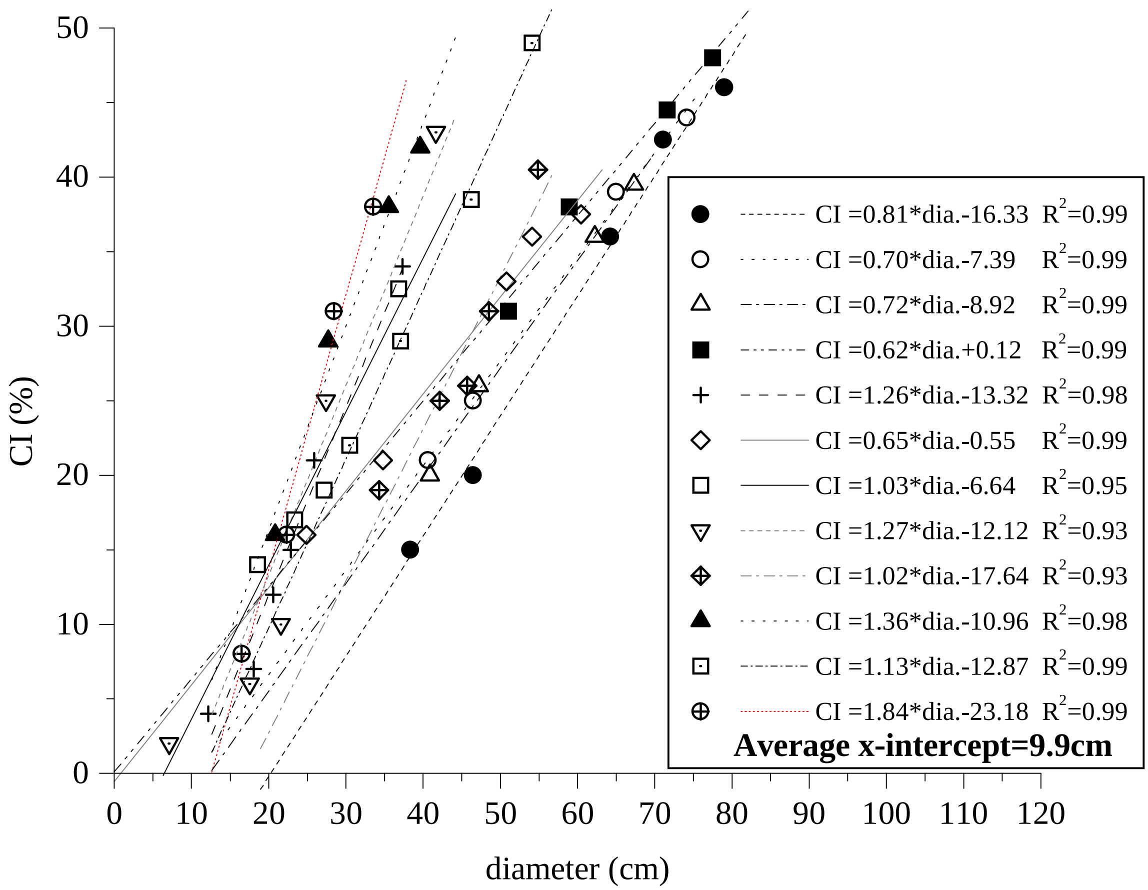

Figure A1. Relations between stem diameter (cm) and percent of increased circumference (CI) for individual windthrown redwood trees. Linear regressions were developed for each windthrown tree to determine an average x-intercept. The average x-intercept (9.9 cm) was used to determine the linear equation for predicting CI at any diameter on the redwood study trees (Table A1).

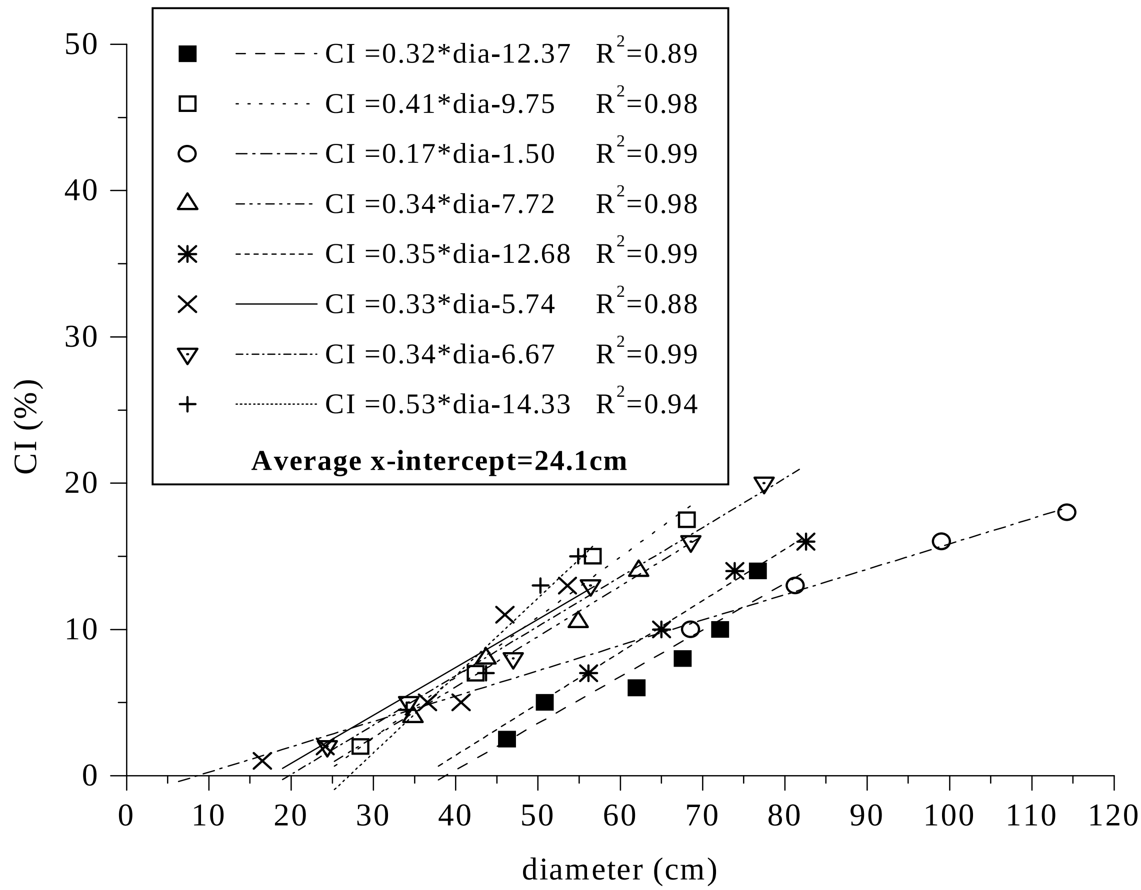

Figure A2. Relations between stem diameter (cm) and percent of increased circumference (CI) for individual windthrown Douglas-fir trees. Linear regressions were utilized on each windthrown tree to determine an average x-intercept. The average x-intercept (24.1 cm) was used to determine the linear equation for predicting CI at any diameter on the Douglas-fir study trees (Table A1).

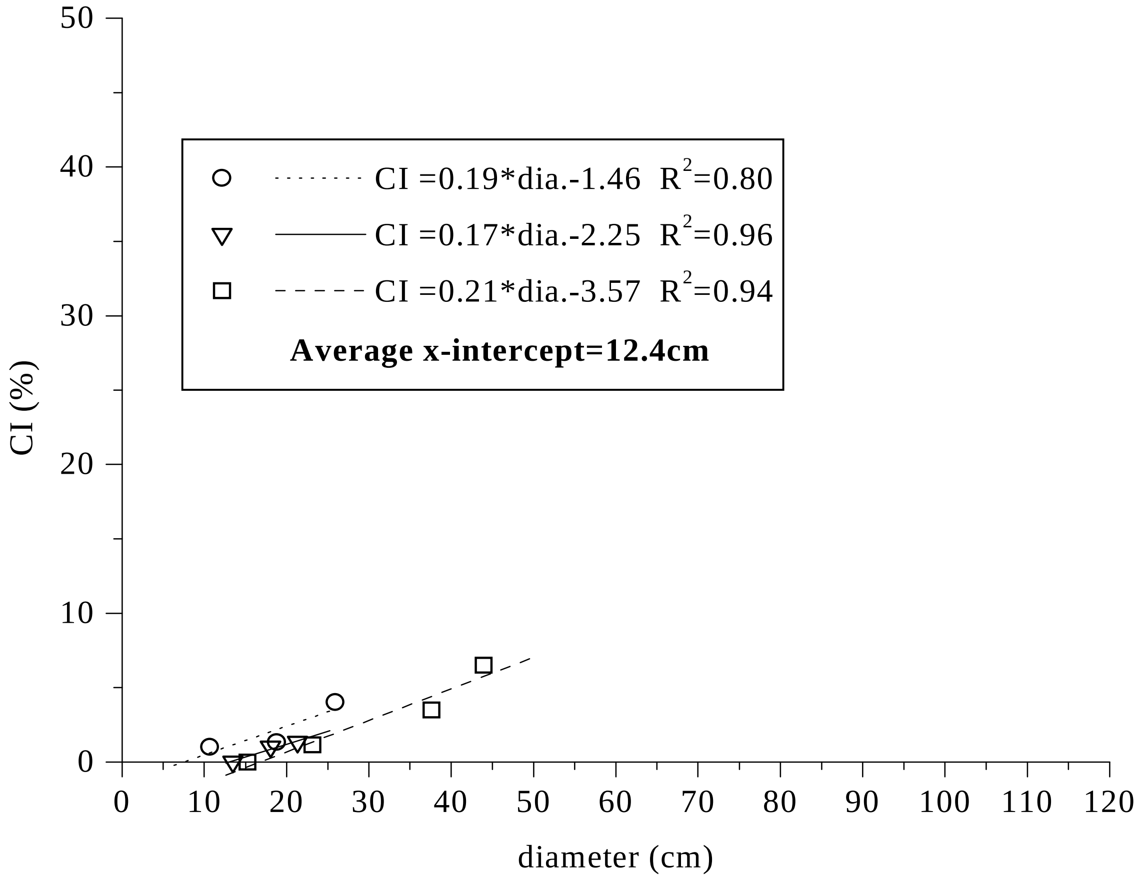

Figure A3. Relations between stem diameter (cm) and percent of increased circumference (CI) for individual windthrown tanoak trees. Linear regressions were developed for each windthrown tree to determine an average x-intercept. The average x-intercept (12.4 cm) was used to determine the linear equation for predicting CI at any diameter on the tanoak study trees (Table A1).