Investigating the contribution of stemflow to the hydrology of a forest catchment

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Abstract

Ten stemflow collectors were installed at the Alice Holt 'Level II' plot. The plot forms part of a European wide network established under European Union legislation to monitor forest condition. During the study period seasonal changes in stemflow and interception were observed with stemflow at a maximum of 2% of gross precipitation during the winter months and almost zero during the summer. Average stemflow over the whole of 2003 was 1%. Interception was at a maximum of 37% after new leaves had fully developed at the end of May and at a minimum of almost zero after leaf abscission. Significant correlations for both basal area and dominance were found, with larger more dominant trees producing the greatest stemflow. Overall stemflow is not a significant contributor to the hydrology, in terms of quantity to a red oak (*Quercus robur*) woodland, but maybe important as a soil nutrient input.

Introduction

Precipitation reaches a forest floor through the canopy via two main pathways: (1) as throughfall (*TH*) – part of the rain drips from the foliage or branches of the canopy, falling to the ground in a more or less regular pattern; (2) as stemflow (*ST*) – when water flows along the wet branches and trunks into the soil around the tree trunks (Hanchi Rapp, 1997). Interception is calculated by the difference between total rainfall and the amount of water that reaches the ground (i.e., throughfall and stemflow):

Interception = rainfall – (throughfall + stemflow)

At a slightly more detailed level, interception can be divided into canopy surface water storage (*C*) and evaporation (*E*), throughfall can also be divided into free throughfall (*Th*) and canopy drip (*D*).

$$C + E = P_g - (Th + D + ST)$$

The equation above is taken from Xiao et al (2000) based on findings by Rutter et al (1971), he recognises the fact that the terminology used in canopy interception studies has not yet become consistent or standardised. In this study the definitions of the following terms shall be used.

Gross precipitation (P_g) is the precipitation measured above the canopy or in the open area where the fetch is sufficient to avoid the forest edge or topographic effects.

Net precipitation (P_n) is the quantity of rain water that actually reaches the ground. It is the sum of throughfall and stemflow.

Free throughfall (*Th*) is the rain drops that reaches the ground surface through the gaps in the canopy leaves and branches without hitting the canopy surfaces (Rutter *et al*., 1971).

Canopy drip (*D*) is the water drip from the canopy surfaces that occurs when the canopy surface rain-water exceeds its storage capacity. It can also occur when the equilibrium status of the tree surface water storage decreases as a result of the impact ejection from drip or mechanically, from wind blowing the tree.

Throughall (*TH*) is the portion of the precipitation that reaches the ground directly through the gaps in the canopy and drips from leaves, twigs and stems. It is the sum of free throughfall (*Th*) and canopy drip (*D*).

Stemflow (*ST*) is the portion of precipitation intercepted by the canopy and reaches the ground by flowing down the stems.

Canopy storage (*C*) is the precipitation that falls on the canopy and is temporally stored on these surfaces. Intercepted water can either be evaporated (*E*) directly to the atmosphere, absorbed by the canopy surfaces or transmitted to the ground surface.

Interception (*I*) is the same as canopy storage.

Interception loss (*IL*) is the portion of precipitation that is retained by canopy surface storage and later is either evaporated or absorbed by the plant.

In this study we shall not be concerning ourselves with canopy drip (*D*) and free throughfall (*Th*), these shall be combined to throughfall (*TH*).

The proportion of rain which reaches the ground as throughfall depends upon the amount of rain (Ovington, 1954; Rutter, 1963), density of the tree crowns, and the presence or absence of foliage (Reynolds and Henderson, 1967). The amount of stemflow is strongly dependent on the following factors:

- Canopy structure and stand density
- Presence or absence of epiphyte mats
- Species composition
- Variation in bark texture and water storage capacity
- Precipitation event:-
    - Frequency
    - Duration
    - Magnitude
    - Intensity

The amount of water returned within the canopy depends on crown density and form, and is dependent on the patterns of precipitation, rainfall intensity and meteorological factors controlling evaporation (solar radiation, relative humidity and wind speed).

Ford and Deans (1978) investigated the effects of rainfall intensity on stemflow. They argued that medium density precipitation events provided the optimal conditions for stemflow generation. Low intensity rainfall events evaporate off the canopy. When there is high intensity rainfall, the canopy reaches a point where conducting channels to the stem become saturated. If no additional water can flow it must drip or evaporate when it is received. Therefore during intense precipitation, throughfall percentage tends in increase whereas stemflow remains constant. This finding applies to rough barked trees but not to smooth. A beech tree for example where the bark is smooth, stemflow will increase with rainfall intensity once the canopy storage capacity is reached.

Studies such as Ford and Deans (1978) assume that rainfall is falling in straight lines and the trees are perfectly straight. During precipitation events when there is angled rain and only one side of a tree trunk is wetted, stemflow can be produced when the rest of the trees branches and trunk have not reached their storage capacity (Crockford *et al* 1996b).

Stemflow volumes have been confirmed to be influenced by wind speed (Kittredge *et al*., 1941; Tang, 1996; Xiao *et al*., 2000) and direction (Kittredge *et al*., 1941; Herwitz and Slye, 1995). Xiao *et al* (2000) found that for isolated trees on there own in an urban environment wind speed increased stemflow volume. Kuraji *et al* (2001) also found this at the stand level. The amount that the tree stem is wetted has an effect on stemflow yields (Tang, 1996) but it is unknown whether wind will cause more or less to be wetted. As already stated the angle of precipitation and direction will affect stemflow yields and this is determined by wind direction and speed. It follows that strong winds are likely to disperse rain drops resulting in reduced drop size and a more random dispersal of drops. This will intern wet more of the tree surface area increasing the number of channels that stemflow can flow down. Wind direction is likely to cause the saturation of the windward side of the tree trunk at the beginning of the rainfall event. Trees tend to have a varying amount of epiphyte mats round the trunk which would affect stemflow generation. The mats will absorb water and increase the amount of precipitation required before stemflow begins.

Although unlikely to effect the site in this study because the percentage of precipitation falling as snow will be very low, it is important to consider stemflow generation in icy and snow precipitation conditions. There are only two studies that focus on stemflow generation in these conditions. The paper by Herwitz and Levia (1997) investigated stemflow from *Populus grandidentata*, inputs ranged from 2.0 to 25.0% of gross precipitation. The latitude of the study site means that incidence of snow will be rare and so unlikely to effect results significantly.

Kittredge *et al* (1941) realised and Herwitz and Slye (1995) confirmed that rainfall hitting the canopy at an angle is going to create a rain shadow, which would determine the area of the crown intercepting rainfall. The actual crown area of a tree intercepting gross precipitation is defined as the effective crown area (Herwitz and Slye, 1995). Herwitz and Slye (1995) found that the tree's effective crown area and therefore its potential to intercept precipitation changed as a function of wind direction. Levia and Frost (2003) state therefore that stemflow yield may be spatially and temporally variable within a forest because of its dependence on wind direction and canopy position of individual tree crowns and their stems (e.g. adjacent to rides).

Neal *et al* (1991) carried out a study in beech plantation to determine if interception was any different at the forest edge compared to within. They set up small plots of $100m^2$ containing four trees at varying distances from the forest edge. The plots were at 20, 50, 100, 200 and 350m from the edge. In each plot, eight throughfall and four stemflow collectors were installed. The study found that there was no significant difference between rows for throughfall at the 80% confidence level; however a small decrease in throughfall was seen. Stemflow did show a significant difference at the 99% significance level. Within 20m of the forest edge there was an increase in stemflow volume. Neal also found that stemflow increased as a proportion of net rainfall from 2% in leafed periods to 6% during unleafed periods. The second part of the Neal (1991) study, Neal *et al* (1993) concludes that if an edge effect does exist it is small and is only going to be significant in smaller plantations. The study only investigated precipitation, stemflow and throughfall. Neal recognised that there could be an edge effect in relation to transpiration from the canopy. The 1993 study also investigated the effect of storm damage on interception. It was anticipated that losing trees would have a big effect on interception values, but this was not as significant as expected. Loss of trees due to storm damage could be equated with what might be found in thinned woodland. Neal *et al* (1993) explained this by suggesting the loss of canopy is compensated by an increased roughness that increases turbulence that in turn increases interception losses.

Ovington (1954) found that within a uniform plantation the amount of water conducted down the stems is highly variable and is largely dependent on structure of the tree canopy rather than tree size. The branches of young oaks, because they rise at a steep angle from the main stem conduct more water to the stem than older shallower angled branches. Clark (1985) also noted this effect and named branching as either excurrent or decurrent. In an excurrent branching pattern, branches slope towards the stem. This increases the likely hood of water being directed to the stem. In a decurrent branching pattern, upper branches may slope towards the stem but lower branches slope away. This would generate stemflow in the upper canopy but as the water came down the stem to the lower branches could cause water to be directed away. A decurrent branching system is common to conifers, while an excurrent system is common to deciduous or broadleaf trees.

Most studies investigating the effect of canopy structure on stemflow production have concentrated on branch inclination angle (Hertitz, 1987). Herwitz carried out a laboratory based experiment using a rainfall simulator and branches from a tropical tree species. He found a linear relationship between branch flow yield and branch inclination angle when the branches were dry. The relationship for wet branches was found to be logarithmic. With branch angles in excess of 60° above the horizontal, branchflow yields were more than 80% of simulated rainfall. Branch inclination angle may increase stemflow yields however there is likely to be a critical threshold where the steeper branch angle will decrease crown area and stemflow yields begin to decline.

Other studies looked at have seen positive correlations between stemflow production and tree basal area (Crockford and Richardson, 2000) and height (Martinez-Meza and Whitford, 1996). Taller larger trees will be capable of producing larger stemflow yields because they will have greater projected surface area (Ford and Deans, 1978). Stemflow yield has been shown to decrease as trees age and the bark roughness and interception storage capacity increases (Johnson, 1990), despite greater crown size. Branch number, presence of canopy gaps and flow path obstructions has been looked into in relation to stemflow yield. Navar (1993) investigated stemflow yields in shrubs and found the greatest yields came from dominant branches at the top of the canopy.

Ford and Deans (1978) looked at the effect of canopy gaps on stemflow yield. No correlation was found because of the significant over lap between crowns. The study was in a young dense *Picea sitchensis* (sitka spruce) plantation. Ford and Deans hypothesised that as the plantation thins with age, crown overlap will decrease and increase stemflow yield in canopy gaps. Stemflow yield in canopy gaps is likely to increase by exposing a greater surface area to incident precipitation (Crockford and Richardson, 2000). Stemflow drainage occurs on the underside of branches and any obstructions in these areas such as breaking bark will decrease stemflow yield. Where these obstructions occur drip points will form, turning stemflow into throughfall.

Hutchinson and Roberts (1981) investigated the vertical variation of stemflow generation in *Pseudotsuga menziesi* (Douglas fir). The tree was split into four sections using major whorls, and stemflow measured below these sections. Vertical rainfall was simulated and it was found that 98% of stemflow was generated by the upper half of the canopy volume. The results suggested that the lower sheltered, depressed branches of the lower canopy contribute little to stemflow generation, although they have 31% of the branch interception area. Hutchinson and Roberts were able to explain these results in terms of differences in branch inclination angle over the entire branch length between upper and lower branches. Although these lower branches did not make a significant contribution in vertical rainfall events, they are important during wind-driven angled rainfall. It was also noted that although stemflow may begin higher up the trunk during a rainfall event; the time stemflow is seen at the bottom depends on the water holding capacity of the bark.

Canopy storage capacity (*C*) is very important in determining the quantity of precipitation intercepted and stemflow generated. Herwitz (1985 and 1987) investigated this and found bark had a greater water holding capacity than foliar surfaces. He also found that the water holding capacity of tropical species change depending on bark texture. Interception storage capacity of bark ranged from 0.51 to 0.97ml cm^{-3}. Flaky barked species such *Quercus robur*, were found to have much higher water storage capacities than smooth barked species. Also important to stemflow production and the degree of chemical enrichment that takes place is the presence or absence of epiphyte mats. A tree with large amounts of epiphytes growing on its bark will produce less stemflow as some of the water is going to be absorbed as it flows down the trunk. As the water does this, it is likely to pick up organic material.

Horton (1919) and Voigt (1960) both decided that stemflow generation could be explained by the biophysical characteristics of tree species. Voigt (1960) found that smooth barked *Fagus grandifolia* (American beech) produced twice as much stemflow as the rougher barked *Tsuga canadensis* (eastern hemlock). The smooth barked *Fagus grandifolia* provided less resistance to stemflow drainage than the bark of *Tsuga canadensis*. Voigt and Zwolinski (1964) reported that rougher bark disrupted the continous film of water over the bark surface resulting in reduced stemflow volume.

For upland sites interspecific differences in stemflow volume have been attributed to differential vegetative surface areas (Cape *et al*., 1991). Four different species were selected *Picea abies* (Norway spruce), *Pinus sylvestris* (Scots pine), *Quercus patraea* (sessile oak) and *Alnus glutinosa* (black alder). Of these, the Norway spruce produced the greatest amount of stemflow as a percentage of gross precipitation (13-14%). The reason given for this difference between species was that *P. abies* is capable of collecting deposition from hill clouds because of its greater above ground vegetative surface area.

At the present time stemflow is being estimated within the 'Level II' plots when calculating interception loss within the forest. In order to complete the picture and obtain an accurate water budget for the forest stemflow needs to be measured no matter how insignificant in terms of volume it may be. Horton (1919) was the first to publish a paper on rainfall interception by forests and subsequent studies have shown interception loss to be a major component in the water balance of a forested area (Rutter, 1963; Helvey and Patric, 1965).

Cape *et al* (1991) reinforce the importance of stemflow; their study was an interspecies comparison of throughfall and stemflow. It was found that up to 15% of the total unintercepted rainwater reached the forest floor by stemflow. The study also found that solutes in stemflow waters are more concentrated than in throughfall, and so stemflow assumes even more importance in terms of nutrient and pollutant transfer. Akhtar *et al* found that the concentrations of nutrients in precipitation were in the order K > Ca > Mg > N > P. For throughfall and stemflow the order was K > Ca > Mg ≤ N > P. The study was carried out in an oak-hickory forest, the total water associated nutrients reaching the forest floor was 115.5 kg/ha/year; of which 38% was contributed by precipitation, 35% by throughfall and 27% by stemflow.

Gersper and Holowaychuk (1975) reviewed previous literature and carried out their own study into the chemical differences between stemflow, throughfall and gross precipitation. Bulasubramaniam and Jayaraman (1952) reported that drips from trees contained about six times more P_2O_5 and K_2O, three times more NH_4, Cl, and CaO, and the same amount of NO_3 compared to rainwater. The precise values vary according to tree species, location, the nutrient content of soils, differences in species composition and canopy structure, the presence or absence of adventitious roots, the availability of nutrients from atmospheric and rock weathering sources, and exposure to acid precipitation. But it has been found stemflow is more enriched than throughfall.

There have been relatively few studies that have dealt with how different meteorological conditions may impact on stemflow leachate chemistry. Crockford et al. (1996a) found that for eucalypt species the leached nutrients in stemflow was greatly influenced by the intensity of the rainfall event. Stemflow concentrations for high intensity, short duration rainfall events were relatively low (Crockford et al., 1996) compared with events of longer duration and lower intensity due to shorter contact times with the bark surface. The total stemflow nutrient input at the base of a tree is however likely to be greater during precipitation events with higher rainfall intensities because the shorter contact time will increase the concentration and diffusion gradient from the bark causing a kinetic solubility gradient (Levia, 2000; Levia and Herwitz, 2000). The angle of incident precipitation has also been shown to affect stemflow chemistry as well as volume (Crockford et al., 1996a). The meteorological conditions that exist will affect the physical properties of the precipitation itself and these will have effect on the chemistry of the leachate. For example the viscosity and surface tension of water retained on the tree crown varies directly as a function of the air temperature. Levia and Herwitz (2000) found during low intensity, mixed (rain-snow) precipiation events that the stemflow was significantly enriched compared to warmer rain events. They explained the enrichment by suggesting it was caused by an increased residence time of the precipiation on the bark due to increased kinematic viscosity and surface tension caused by colder air temperatures.

The aim in the future will be to carry out chemical analysis on stemflow samples and to feed this data into the level II programme looking at critical loads. The 'critical load' is the amount of atmospheric pollutant below which no significant harmful effects on the forest ecosystem are expected in the long term (ICP Forests, 2002). The difference between the critical load and the actual deposition is termed the critical load exceedance. This has been at the centre of pollution emission reductions since the 1980s.

The importance of gaining a full understanding of the hydrological cycle within broadleaf woodland has increased since the late eighties and early nineties when it became government policy to promote the planting of broadleaf woodlands, especially in southern England. It was recognised that in the UK and Europe there was an overproduction of cereal crops, because the UK only produced about 10% of its timber requirement some of this land could usefully be turned into plantations to meet more of this demand. Schemes introduced in 1988 to promote the establishment of broadleaf woodlands on agricultural land included the Farm Woodland Schemes and Woodland Grant Schemes. This promotion of afforestation continues today in the England Forest Strategy – A New Focus for England's Woodlands.

There has already been massive afforestation in the uplands of the UK where rainfall is high. These mainly coniferous plantations have shown greater evaporation of water than adjacent grassland areas, resulting in reduced streamflow. If a similar increase in evaporation was found in southern England where rainfall is much lower, this could have serious hydrological consequences. Groundwater is the main source of water for public supply in southern England. There is also a significant change in streamflow when deciduous hardwood stands are converted to conifers. Swank and Douglas (1974) reported a decrease in streamflow of 20%. Current policy is to convert conifer plantations back to deciduous broadleaf but this was not the case 30 years ago when the pine and conifer timber market was thriving.

In the UK, there is very large spatial variation in rainfall (from 500 to 4000 mm a^{-1}), but the average rainfall rate and potential evaporation during rainfall are uniform. You would therefore expect the interception loss to be a fixed proportion of the rainfall total. In the coniferous forests, this is the case with typical values between 30 and 40%. There have been comparatively few studies carried in broadleaf woodland, especially oak; from the studies that have been done interception loss has been generally smaller than in coniferous woodland but much more variable. Typical values are between 10 and 36% (Hall and Roberts, 1990). The variability of these studies can be accounted for because they were carried out on a diverse range of tree species and structures in very different geographical locations.

The hydrological difference between grassland and coniferous forest was illustrated by Cooper (1980). He compared the drainage to the chalk aquifer beneath the Breckland in Norfolk under both coniferous forest and grassland. Over three years the study showed that drainage under the coniferous forest was 46% less than under the grassland. This is however an extreme example; the grassland was on sandy soils and often showed signs of severe water stress, considerably reducing its overall water use, the deeper rooted forest showed a small reduction in water use due to water stress.

The contribution that stemflow makes to water input into forest and agricultural soils is highly variable between and within types of vegetation cover found within tropical, temperate, and semi-arid and arid ecoregions. Table 1 gives a summary of stemflow as a percentage contribution of incident rainfall in these regions.

Table 1: Stemflow values in different vegetation types and regions (Levia, 2003)

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

Creosotebushes	5.9-26.9	Whitford et al (1997)
Thornscrub community	3.0	Navar et al (1999)
Laurel forest	1.2-13.6	Aboal et al (1999)
Mediterranean holm oak forest	2.6-12.1	Bellot et al (1999)

Using the studies in table 2 the mean stemflow contribution as a percentage of rainfall were 3.5, 11.3 and 19% for tropical, temperate, and semi-arid and arid ecoregions. Table 2 illustrates how variable stemflow is between forest types. This is down to differences in climatic patterns, meteorological conditions, and species composition.

From the results of the literature search it is envisaged that stemflow will not be a large contributor to the overall water budget of oak woodland. Answering the question as to whether stemflow is a major contributor is important, but equally so was devising a workable method which could be rolled out to all the Level II sites across four different species.

The aims of the project were to:-

- Design a method to measure stemflow in oak trees but could be adapted to other species.
- Compare the stemflow in different stands in terms of their diameter, position in relation to one another (dominant and submissive) and branching.
- Look at past papers and research into stemflow of oak trees and other species.
- Use data to complete accurate water budget for ‘Level II’ plot at Alice Holt.

Description of the Study Area

Geography and Topography

The stemflow study was undertaken at the Forestry Commission owned Level II plot within the Straits inclosure of Alice Holt forest. The plot is 2.75 miles from the Alice Holt Research Station located in Farnham, Surrey and 0.2916 hectares in size. The plot makes up a mainly oak forest which was planted in 1935. The plot area is flat and lies 80 metres above sea level. A map of the study site outlining the positioning of trees, throughfall and stemflow collectors can be found in appendix F.

Geology and Soils

The parent material in the study plot is cretaceous clay (gault). The soil type is non-calcareous pelo-stagno gley (surface water gley). The Soil Association characterisation of the soil is Dentchworth 7.12. There are no rocky outcrops and drainage is very poor. The poor quality of the soil and regularly water logged soil has resulted in thin small diameter trees of poor quality.

Vegetation

Alice Holt forest is probably the most heavily monitored forest in the whole of the UK, for this reason it is a mix of both coniferous and deciduous trees. In the plot itself the majority of trees are oak (*Quercus robur*) but there are ash mixed in. Adjacent to the plot there are some very large beech trees. The forest is commercially managed for timber so the understorey has been cleared; this was last done four years ago. The ground vegetation consists of grasses, mosses, brambles and hazel.

Climate

Average annual rainfall in the area of the plot is 780 mm. Average temperatures between 1995 and 2002 have been 17.1 °C in July and 5.3 °C in December. The climate is typical of the region with rainfall being quite variable between years but there is very little rain during July and August. The year of study was however an exceptional year with record breaking high temperatures and a period of 6 weeks in the summer without rain. Table 2 summarises the characteristics of the plot.

Table 2: Characteristics of the Straits Level II Plot

Characteristic	
Species	Oak (Quercus robur)
Planting date	1935
Altitude (m)	80
Aspect	Flat Ground
Slope	0
Average Rainfall (mm)	780
Area of plot (ha)	0.2916
Total Trees	227
Top Height (m)	19.3
DBH (cm)	25.9
Basal Area (m^2 ha^{-1})	22
National Grid Reference	SU795402

Methods

Rainfall and Throughall

The collector shown below was developed at Alice Holt Research Station in 1995 to measure open rainfall and throughfall in the ten level II plots. Work conducted by Neff (1977) and Rodda and Smith (1986) showed that the accuracy of rainfall measurements depended mainly on the collector height above the ground, diameter and shape. The design below is a combination of previous findings.

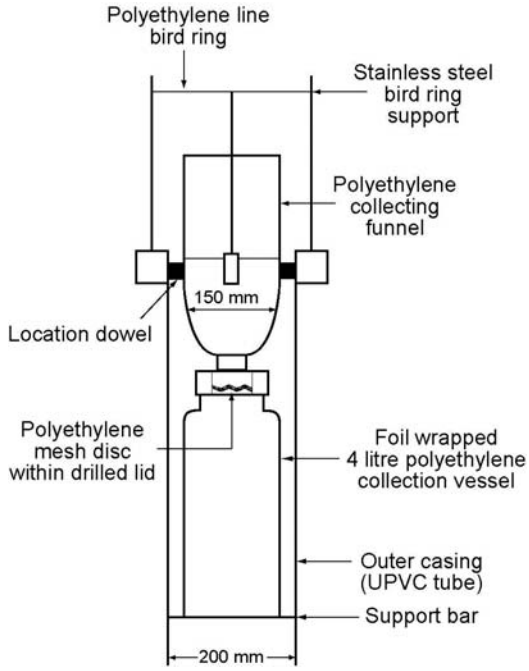

Figure 1: Level II Rainfall and Throughfall Collector

The paper by Houston *et al* (2002) investigated the variability of results obtained from these throughfall collectors. Over a period of four years twenty additional throughfall collectors were installed, on top of the ten already there, to ensure that the positioning of the collectors was representative of the whole plot. It has been recognised that throughfall chemistry and volume is highly variable both spatially and temporally in a forest stand, and that the number of collectors required to estimate the mean within a certain confidence interval is normally uneconomically large.

Ten throughfall collectors are located within the Level II plot itself using the data from Houston *et al* (2002) to make sure these were in representative positions. Two rainfall (open) collectors are located at Alice Holt Research Station a distance of 3.5 miles from the main plot. The rainfall and throughfall data are expressed in millimetres derived from the volume collected and the area of the collecting funnels. It is important to note that the plot is adjacent to a forest ride/track; two throughfall collectors are located near to this track so maybe exposed to edge effects.

When results every two periods (weeks) were required, data for throughfall and open rainfall from the rainfall collector in figure 1 were used for calculations. These collectors are only emptied every two weeks so this was the maximum sensitivity possible. The stemflow collectors however were emptied after every single event so a higher rainfall resolution measurement was required. For this the rainfall measured by an automatic weather station situated less than half a mile from the site was used. The mechanism measured rainfall hourly using a tipping bucket rain gauge to an accuracy of 0.2mm.

Stemflow

Stemflow was collected from ten trees from within the plot. All trees within the plot were grouped according to their diameter. The number of collectors in each class was proportional to the number of trees of that class size. This was an attempt to ensure that the trees chosen were representative of the plot. Trees used for foliar analysis were avoided as well as all trees within the mensuration sub plot. Trees close to throughfall collectors were also preferentially selected over others. It was also important not only to attach gauges to different size trees but also to ones in different locations. Collectors were well spaced around the plot so not all trees in a particular area were selected. At this tree selection stage, the possibility of edge effects caused by the adjacent ride was not thought of; three trees therefore were selected along this edge. Before installation commenced, a general description of the trees intended for stemflow measurement was done. The information noted included if the tree was sub-dominant, co-dominant or dominant. What the branching pattern was like, were there many low branches and how big were they. Was the bark deeply grooved or relatively smooth, was it covered thickly with moss and finally was the trunk straight or tilted at an angle.

Table 3: Tree selection according to DBH class

Diameter (cm)	Frequency (n)	No. of Collectors
12-16	7	1
17-20	36	2
21-24	40	3
25-28	17	2
29-32	10	1
33-36	2	1

Loustau *et al* (1992) investigated the variability of throughfall and stemflow in a pine stand. It was found that the variation between trees decreased asymptotically with increasing gross rainfall. There was huge variability between trees and it was concluded that these differences were down to individual tree effects. However, no significant relationship could be found between the stemflow collected and any size characteristics. The conclusions of the Loustau study were that the number of stemflow collectors required to get the confidence interval of mean stemflow below 10% would be in excess of 40 stems. As with the throughfall collectors this number is unworkable so a compromise of 10 collectors well selected and sampled was decided upon.

The design of the stemflow collector was researched thoroughly by looking at previous studies; the final design is a combination of all these ideas. There are papers that report interception and stemflow values for oak stands but these did not explain how the method of how the stemflow was collected. Most of the recent studies involve wrapping a split piece of tubing round the trunk of the tree and adhering it using a silicon based adhesive. The materials used for the tubing and adhesive vary, as does the collection method. For this study the water collected from the trunks was directed into 25 litre fermenting barrels. The most important part of the design was to ensure a good seal between the tubing and the tree bark. The reason that little work has been done on oak trees is probably because it is so difficult to obtain this without damaging the bark. It is very important that as part of the ICP Forest protocol that the trees are not damaged. The method that was devised is outlined in appendix A and this was tested first on a tree of similar age and size near to the study plot. Important lessons were learnt at the trial stage. Not touching the tree bark proved impossible as it was often covered in moss which would not allow the silicon sealant to stick. The moss was removed using a wire brush initially just in a strip where the tubing was going but later all the moss was removed in between the rings of tubing as well. Leaving the moss there encouraged slugs and snails into the tubing which would cause a blockage. It was decided that the tubing should run from just below the 1.3m DBH measurement line and go twice round the trunk. The positioning of the tubing was limited by the height of the collecting barrels i.e. there needed to be sufficient gradient from the end of the tubing into the barrel to enable water to flow. The tubing could not be stuck to the tree through the DBH measurement line as the trees would need to be measured here in subsequent years. The tubing could go above 1.3m but this would have caused installation difficulties, having to carry a step ladder out to the site for example.

Collection of stemflow volumes took place after and during every day that rainfall occurred. At each collection the water was measured in a 4 litre graduated container but if smaller volumes were collected a measuring cylinder was used. There were occasions when rainfall was unusually high or collection was not possible, at these times some collection barrels overflowed. On these occasions in order to maintain a constant record a linear regression for individual trees of gross rainfall against stemflow from all known storms was drawn. The volume we would have expected to collect was then predicted from this.

After July 2003 five of the stemflow collectors were converted to automated collection using tipping bucket rain gauges. These were installed as part of another project which was interested in looking at the timing of stemflow generation at the start of a precipitation event. These rain gauges like the AWS had a resolution of 30 minutes and measured to an accuracy of 0.2mm, this could then be converted to volumes. These five gauges were fed back to a data logger which could be downloaded to a laptop in the field. The remaining five gauges remained on manual, but collection was reduced from after every precipitation event to once a week.

From the end of February to the beginning of June canopy photographs of the plot were taken every 2 weeks. The purpose of these was to know the time when leaves reappeared on the trees and see if this coincided with a change in stemflow production. These photographs are shown in appendix E.

Calculations

The problem that we face with calculating interception and stemflow in particular is how to get all the values in the same units (mm). The approach taken here is to treat the plot as one and work all the throughfall and stemflow values up as if they were falling on an area this size. With stemflow the volumes on the ten trees being measured had to be related to a known characteristic of all the trees in the plot. A relationship between this characteristic and the volume of stemflow being measured could then be developed which would allow us to then estimate the volume of rainfall from each tree within the plot.

A scatter graph was plotted for each tree of stemflow volume against rainfall. The rainfall data for each precipitation event was taken from the automatic weather station (AWS) that had a resolution of one hour. The instances where the collection barrel overflowed were omitted. The linear regression of the remaining points allowed us to predict what volume should have been collected had the barrel been larger. The predicted volumes for these high precipitation events were used in subsequent working.

The volumes and rainfall were totalled every four weeks and compared to each trees basal area. A linear regression line was drawn and the relationship used to predict the stemflow from the other trees in the plot. The stemflow was totalled and converted into millimetres by dividing by the plot area. This was divided by the rainfall in that four week period and a percentage stemflow of gross precipitation calculated. The percentage stemflow for each four week period was plotted and any trends identified. The stemflow calculated can then be used with data of open rainfall and throughfall to calculate a value for interception, the amount of water the canopy stores plus the evaporation.

To determine the importance of tree dominance on stemflow generation the observations about trees before installation were used to characterise trees as sub-dominant (1), co-dominant (2) or dominant (3). The stemflow generated by the trees and there dominance was then plotted against each other. Other characteristics noted such as the degree of branching, moss coverage and trunk angle have an impact on stemflow generation but were not so easily quantifiable so could not be looked at.

To test if the correlations between stemflow volume and different variables were significant regression analysis was carried out. For these tests a p-value was calculated from the correlation coefficient (r) and tested at the 5% level, a p-value greater than 0.05 indicated a non-significant result and therefore no significant correlation. A p-value less than 0.05 indicated a significant result.

Results

Measurements were started in September of 2002 but it was not until January 2003 that all ten stemflow collectors were installed. The period of study therefore runs from January 2003 to December 2003. This whole year record will allow us to look for seasonal differences in stemflow generation. Figure 2 summarises the amount of stemflow generated in the whole plot from all trees in each period and expresses this as a percentage of total gross precipitation.

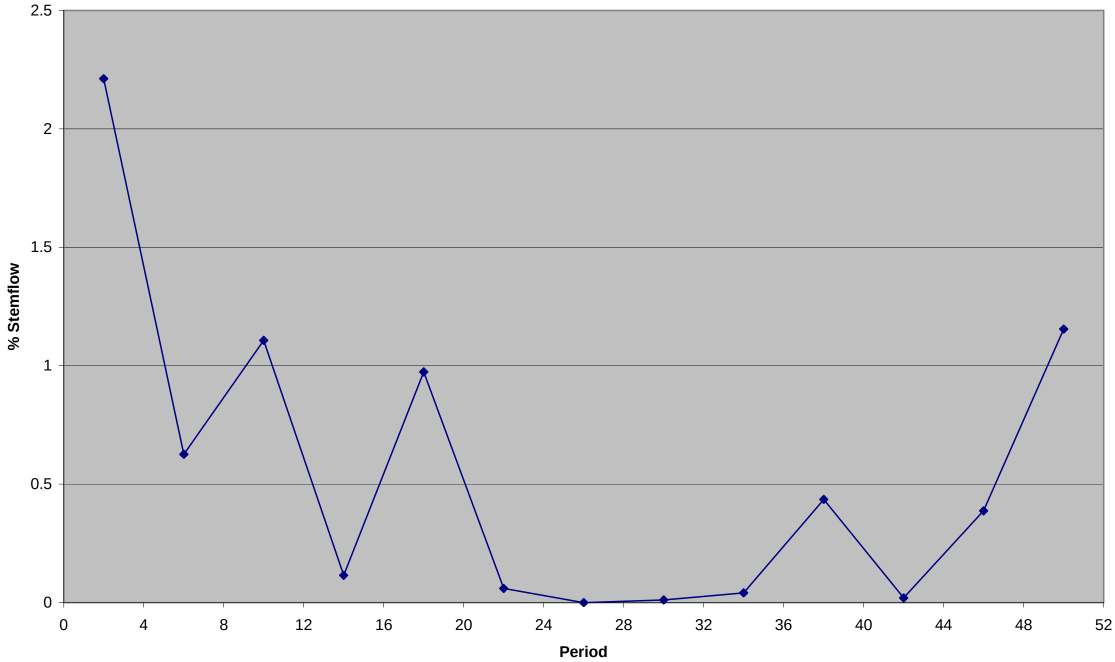

Figure 2: Stemflow generation as a percentage of gross precipitation (auto)

In order for the data in figure 2 to be produced a known characteristic of all the trees needed to be found which we could use to estimate stemflow generation for the whole plot. The plot is monitored extensively so the options available were diameter, basal area or height. The best estimator was basal area (Crockford and Richardson, 2000); figure 3 shows the relationship between basal area and stemflow. On analysis of figure 3 we notice that there is one significant outlier (T152), if this tree is removed then the correlation coefficient is significantly improved. Regression analysis of figure 3 gives a P-value of 0.1376 which shows there is no significant correlation between basal area and stemflow, removal of T152 makes this a strong and significant correlation (P-value of 0.003852). For the purposes of predicting stemflow from other trees in the

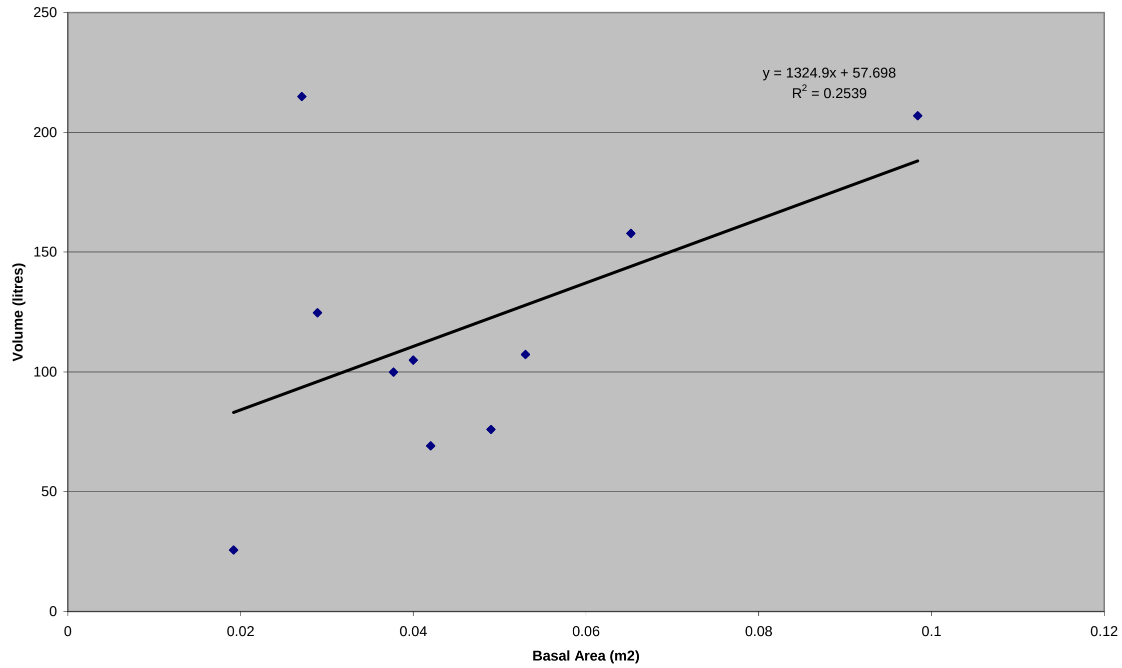

Figure 3: Relationship between stemflow and basal area

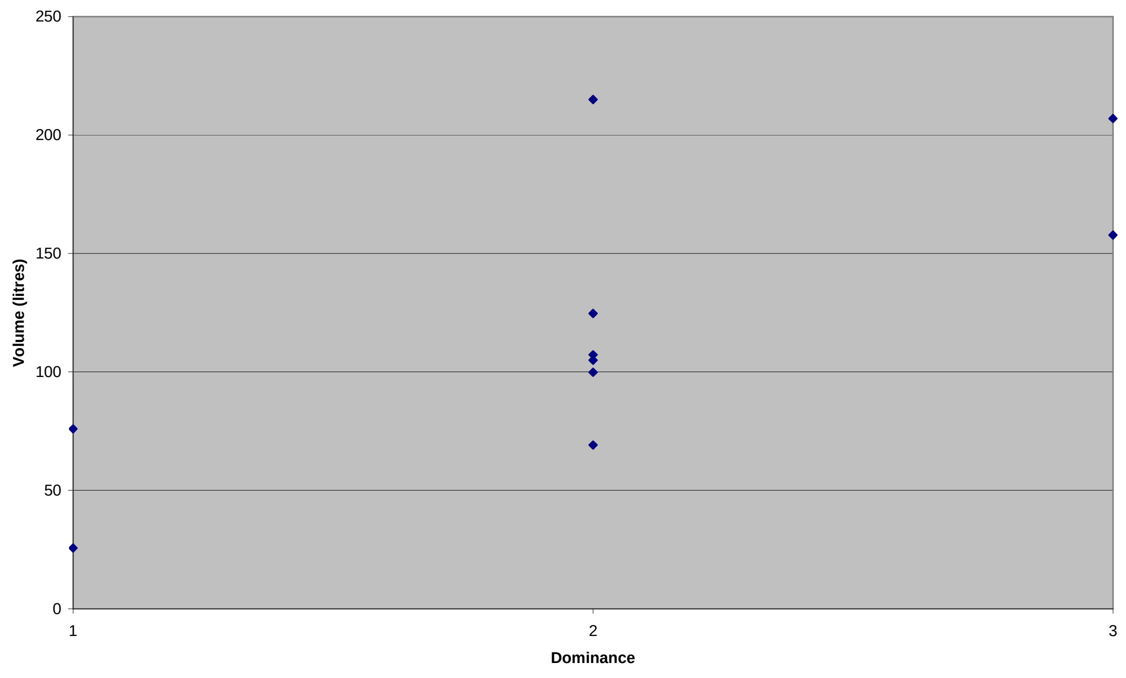

Figure 4: Comparison of stemflow volume and dominance

plot using this correlation where T152 was seen as an obvious outlier it was not used in determining a best fit line. This same graph was produced for each period of 4 weeks to predict stemflow giving the graph in figure 2.

A comparison of stemflow between trees in terms of their dominance yielded the results shown in figure 4. Trees were labelled according to their dominance, sub-dominant (1), co-dominant (2) and dominant (3) and compared with stemflow volumes up to day 153 in 2003. There is a trend of more dominant trees producing more stemflow with regression analysis this relationship is significant with a P-value of 0.01594. The majority of trees in the investigation were co-dominant and there is huge variation in this group with stemflow ranging from 69 to 214 litres.

Figure 5 shows the mean stemflow volume from all ten trees for each precipitation event measured. The error bars are one standard deviation above and below the mean and highlight the massive variability between trees. The standard error for each event from tree to tree was huge, as high as 100% and never lower than 20%. It also shows the high number of small precipitation events measured compared to large, these larger events influence strongly the degree of correlation. From figure 5 we can estimate the amount of rain required before stemflow begins. The point where the best fit line crosses the x-axis is 2.0 mm.

The final part of the investigation was to use the stemflow to calculate an accurate value for interception in oak woodland and complete the water budget. Figure 6 shows how interception has changed through the year. Cape *et al* (1991) reported seeing no seasonal pattern in interception loss for deciduous species however figure 6 does seem to show some pattern. Interception slowly increases with time from a minimum in the winter months to a maximum in May. There is then a slight decrease and interception remains constant during the summer and then there is a sudden decrease when autumn begins.

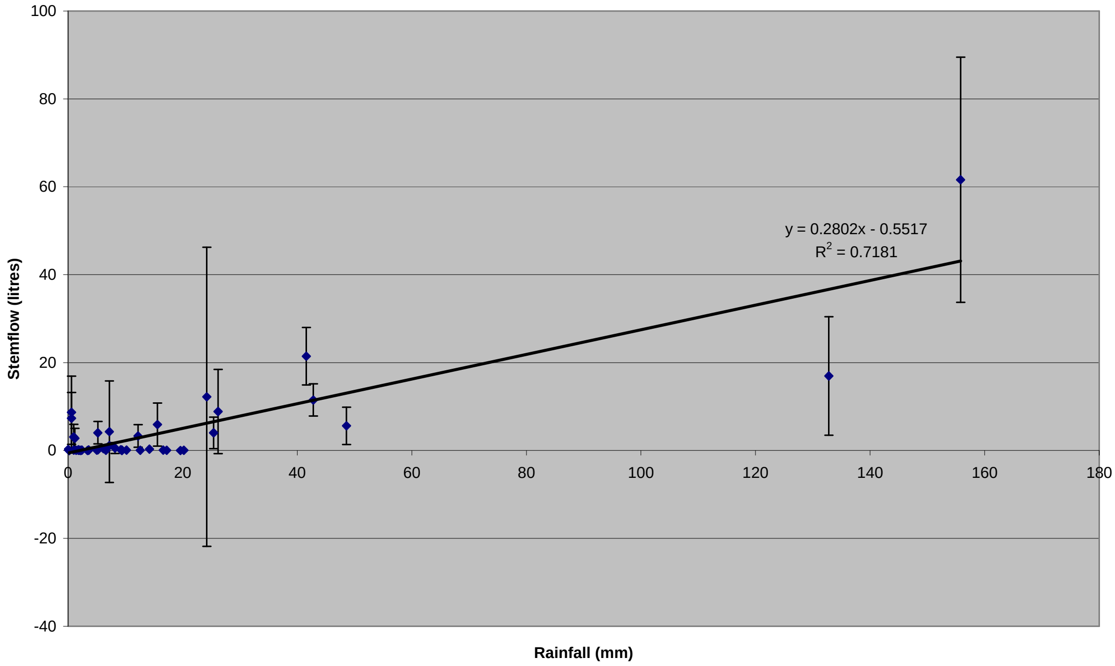

Figure 5: Mean stemflow volume across all trees against gross rainfall (error bars one S.D)

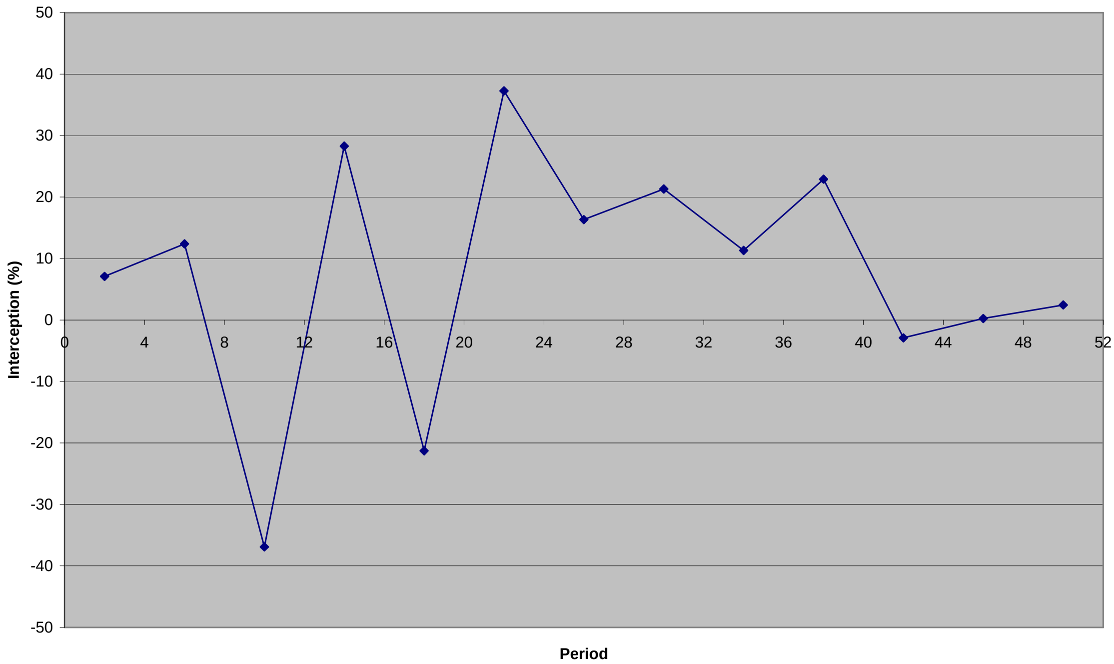

Figure 6: Changes in interception as a percentage of gross precipitation

Discussion

Many problems were encountered during the design and operation of the stemflow collectors. The design for the stemflow gauges was altered half way through the sampling period to incorporate automatic rain gauges. This was so that another project could look at the timing of stemflow generation after the beginning of a precipitation event. Installation of these automatic measuring devices should have ensured more accurate measurement and also removed the need for regular emptying of buckets. They do however have their own maintenance requirements and problems. The compatibility of these two different ways of measuring stemflow was unknown, it was unfortunately assumed.

Where the PVC tubing originally went into the fermentation bucket it was redirected into the tipping bucket rain gauge, these were sealed using an up turned plant pot tray with a hole drilled. The plumbing fitting then was screwed into this hole instead of the lid of the fermentation bucket. Sealing the system prevented leaf litter entering and blocking the system. The cables from the gauges had to run right round the plot as there was only data logger. To overcome rabbits and deer chewing on the cables they were suspended above head height but some parts had to be run on the ground so this would still be a problem.

At the half way period two of the gauges which were to remain as manual collections had to be removed. The bark beneath the tubing had become soft and the water tight seal between the PVC tubing and the bark had been lost. It was not known whether this damage was caused by the stemflow collectors themselves or would have occurred anyway. There were other trees in the plot showing similar symptoms which had not been touched but installation of stemflow collectors may have been a contributing factor. A sample of bark was sent to pathology at Forest Research to see if anything could be identified to cause such damage.

At the present time the method described has not been used on other species other than oak. Oak is the most difficult to work with because of the rough and grooved bark. The Level II program has been expanded to include beech plots, stemflow measurement is mandatory under the European protocol for these plots. The described method would be very suitable for these plots as beech bark is very smooth and requires little pre-treatment. Voigt (1960) found that *Fagus grandfolia* (American Beech) trees produced twice the volume of stemflow than *Tsuga Canadensis* (Eastern Hemlock) because the smoother bark had a lower total surface area and water storage capacity. For use on beech therefore an automated tipping bucket measuring system or large capacity storage system (100 litres) would be essential.

A look at the possible relationships between stemflow generation, basal area and tree dominance revealed that both basal area and tree dominance were important factors. It follows that a tree with a large basal is likely to have a large canopy capable of intercepting rainfall. Having a large canopy does not automatically mean large stemflow volumes if branches are not orientated to direct water to the trunk. A general positive correlation for basal area and tree dominance was found. The correlation was insignificant for basal area but significant for dominance.

Stemflow generation as percentage of gross precipitation (fig. 2) ranged from just over 2% in winter months to almost zero during the summer; the average over the whole sampling period was 1%. Compared with values in table 1 of northern red oak and holm oak forest this is low. The changes in stemflow as percentage of gross rainfall change depending on if it is a foliated or defoliated period. Canopy photographs were taken from January to June to determine the time when leafs appeared (see appendix). The first appearance of leaves was on the 30th April (period 20) and the canopy had fully developed by 3rd June (period 24). This coincides with a decrease in stemflow. The point of minimum stemflow is also the point of maximum interception. The foliation increases the surface area for interception of rainfall but directs intercepted rainfall more towards canopy drip than stemflow. Canopy drip forms part of throughfall in this study.

Cape *et al* (1991) found no seasonal variation in interception loss but Neal *et al* (1991 and 1993) did observe some differences with lower values during defoliated periods. This is broadly what can be seen from figure 5. Interception rises to a maximum at period 22 which is when the new leaves have fully developed. Newer fresher leaves have a larger leaf area index (LAI) then older ones so are able to intercept more rain. Interception then settles at a constant value for the summer and then when the trees lose their leaves interception falls to zero. There are two large anomalies with periods 10 and 18 giving large negative interception values. This maybe because of water inputs from other sources other than normal precipitation such as mist, fog, dew and ice which has been caught by the canopy. Or caused by snowfall which is being over estimated by throughfall or underestimated in the open.

The location of the site is particularly susceptible to edge effects. One end borders a forest ride which is approximately 5 metres wide. The study by Neal *et al* (1991) showed that there was a significant increase in stemflow up to 20 metres in from the forest edge. Further in no significant effect was seen. The study also found no significant effect on throughfall as a result of proximity to the forest edge. Within the Straits plot four of the stemflow collectors were within 20 metres of the forest edge. In figure 3 three of these collectors (T112, T120 and T127) form a perfect straight line when their basal area is compared with stemflow. It was thought that possibly we could split the plot into two halves, one area within 20 metres of the ride and then the rest, in an attempt to get a more accurate estimation of stemflow. It was decided this was not a viable option as more collectors would need to be installed in each half to get a representative sample. These trees produce more stemflow because they are more susceptible to wind blown rain and rain angled in towards this edge. These trees also larger with big canopies as there is less competition at the forest edge.

There are many different factors that effect the partitioning of rainfall into throughfall, stemflow and interception. The aim is ultimately to produce a model to predict each part from a known rainfall. This either has to be done a period basis how stemflow has been measured here or on an event by event basis. Methods also range from using just one or two trees (Xiao *et al*, 2000) up to using a representative plot such as here. The required data is available to carry out this analysis and would be a good continuation of this project.

Further work could also include:-

- Calculation of canopy water storage using evaporation calculated from eddy correlation tower.

- A chemical analysis to investigate the amount of nutrient enrichment of stemflow for calculation of more accurate critical loads.

In conclusion we have successfully designed a stemflow collector which would be suitable for use on all trees within the level II network. We have identified some seasonal changes in stemflow generation and been able to attribute these to foliation and defoliation periods. Tentative correlations between basal area, dominance and stemflow have been established. But it is recognised that stemflow yields are dependant on other complex interactions including meteorological conditions and canopy structure. An investigation into the degree of chemical enrichment of precipitation through the process of stemflow generation would further the study to see if stemflow is a significant contributor to soil chemistry in an oak woodland.

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Appendices

Appendix A: Procedure for installing stemflow collectors in the level II plot within the Straits inclosure.

1. Screw in black M3 clamp from RS Components (cat. 666-723) below diameter breast height (1.3m).
2. Using a black cable tie from RS Components (cat. 233-430) attach 25mm bore PVC tubing (VWR Apparatus, Instruments and Equipment cat. 275/1267/18) to clamp and wrap around tree a minimum of one and a half times.
3. Ensure that all the way round a sufficient angle is maintained so water is able to flow down the tube. When you have an idea of path the PVC tube is likely to take, remove the tubing, and using a wire brush remove any moss in a five centimetre strip where the tubing is likely to go. If the bark is extremely rough try to smooth it as much as possible but do not try to cut or plane it smooth
4. Reattach tubing top clamp and screw in second M3 clamp to secure the other end of PVC tubing with a cable tie, but do not pull tight.
5. Using a permanent black marker pen, mark the PVC tubing with a line running from the top clamp down to a distance of five centimetres from the bottom clamp. The line should be as close to the bark as possible but you need to ensure you have a good surface to attach the tubing to the bark. Then draw a second line on the tube on the outside of the ring so you have a strip on the tubing that is about 3cm wide.
6. Undo cable ties and remove tubing. Using a Stanley knife remove the strip marked out on the tube and reattach to tree. Do not pull tubing too tight.
7. At this stage, check to ensure the tubing has not closed in on itself too much. With large trees this shouldn't be too much of a problem but smaller trees (DBH less than 20cm) may require some further trimming.
8. Using Dow Corning 732 RTV clear multipurpose silicon adhesive (VWR Chemicals, Reagents, Media etc cat. 63426 4U) secure tubing to trunk. This must be done when the bark is dry.
9. Once sealant has set, carefully trim the tube to obtain a smooth finish. Attach 25 litre fermenting barrel (Home Brew Shop, Farnborough) covered in foil tape to

avoid sunlight entering. Connect tubing onto barrel using pluming connections, and fit small filter.

Appendix B: Photographs of Apparatus

Plate 1: Trial Stemflow Collector (September 2002)

Plate 2: Final Stemflow Collector Design (December 2002)

Plate 3: Automated Stemflow Collector (July 2003)

Appendix C: Stemflow and Interception Data during 2003

Appendix D: Regression Analyses

Appendix E: Canopy Photographs (25^{th} February to 10^{th} June 2003)

Appendix F: Map of the study site