The Use Of Fog Precipitation By Plants In Coastal Redwood Forests

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[26]

Abstract: Fog inundates the coastal regions of northern California and southern Oregon for a significant proportion of each summer. Hydrological studies have shown that a significant fraction of the annual water input to these regions can come from fog. Past literature has often claimed that fog may serve as a potential source of water for plants, yet no investigation has explicitly quantified if this is true and to what extent fog water is used by the vegetation. Therefore, stable hydrogen isotopic analysis of water from fog, rain, soils, ground water, and within the dominant plant species were quantified monthly over a three-year period to characterize which water sources the vegetation used. During the summer months when fog was most frequent, the isotopic data indicated that between 8-34% of the water used by the coast redwood, Sequoia sempervirens, and between 6-100% of the water used by the understory vegetation came from fog precipitation after it had dripped from the tree foliage into the soil. Direct uptake of fog by plant foliage was not quantified. Fog-collector and foliar interception data showed that between 22-46% of the moisture input to the ecosystem was due to the presence of the Redwood trees themselves (interception input); when trees were absent, interception input declined by 19-40% These data show that not only are plants of coastal redwood forests using a high proportion of fog precipitation but that the presence of the trees has a real influence on the magnitude of water input from fog precipitation. These results have important implications for ecologists, forest managers, and hydrologists interested in fog inundated ecosystems.

Introduction

During the growing season (June - November) the coastal redwood (Sequoia sempervirens,) forests of northern California and southern Oregon are inundated by fog nearly every day due to the development of a summer subsidence inversion caused by the Central Pacific high pressure cell which interacts with cold water up welling and vertical mixing of moist air eddies off of the Pacific Ocean (Harris 1987). As fog moves inland it baths the plants which inhabit the coastal plains and hills in this region. Fog is the heaviest from midnight until early- to mid-morning (0700-1100 hours) and is at its minimum in the mid-afternoon (1500 hours; Harris 1987 and unpublished data). Hydrologic studies have shown that moisture input to the Redwood forests from fog can constitute between 30-75% of the annual water budget, and claims were made that fog may serve as a potential source of water for plants (Byers 1953, Oberlander 1956, Parsons 1960, Freeman 1971, Azevedo and Morgan 1974; Harris

1987). Several investigations have shown that soil moisture was higher around trees or in forests stands where the plant canopies "stripped" fog from the air mass (Oberlander 1956, Parsons 1960, Azevedo and Morgan 1974). Freeman (1971) showed that fog drip from redwood tree foliage could be equivalent 50 mm, or more, of precipitation per tree per day. Several authors have gone on to suggest that moisture input from fog would in turn reduce plant moisture stress (Monteith 1963, Kerfoot 1968) and even enhance growth (Becking 1968) or the nutrient cycling in the soil which may all influence the development and composition of the vegetation community (Stone 1957, Azevedo and Morgan 1974, Harris 1987). Despite all of these claims, to date, no investigation has explicitly quantified if plants use fog precipitation and if so, to what extent. Therefore, an investigation was initiated in 1992 to quantify the patterns of water use by plants inhabiting a coastal redwood forests of northern California.

Methods

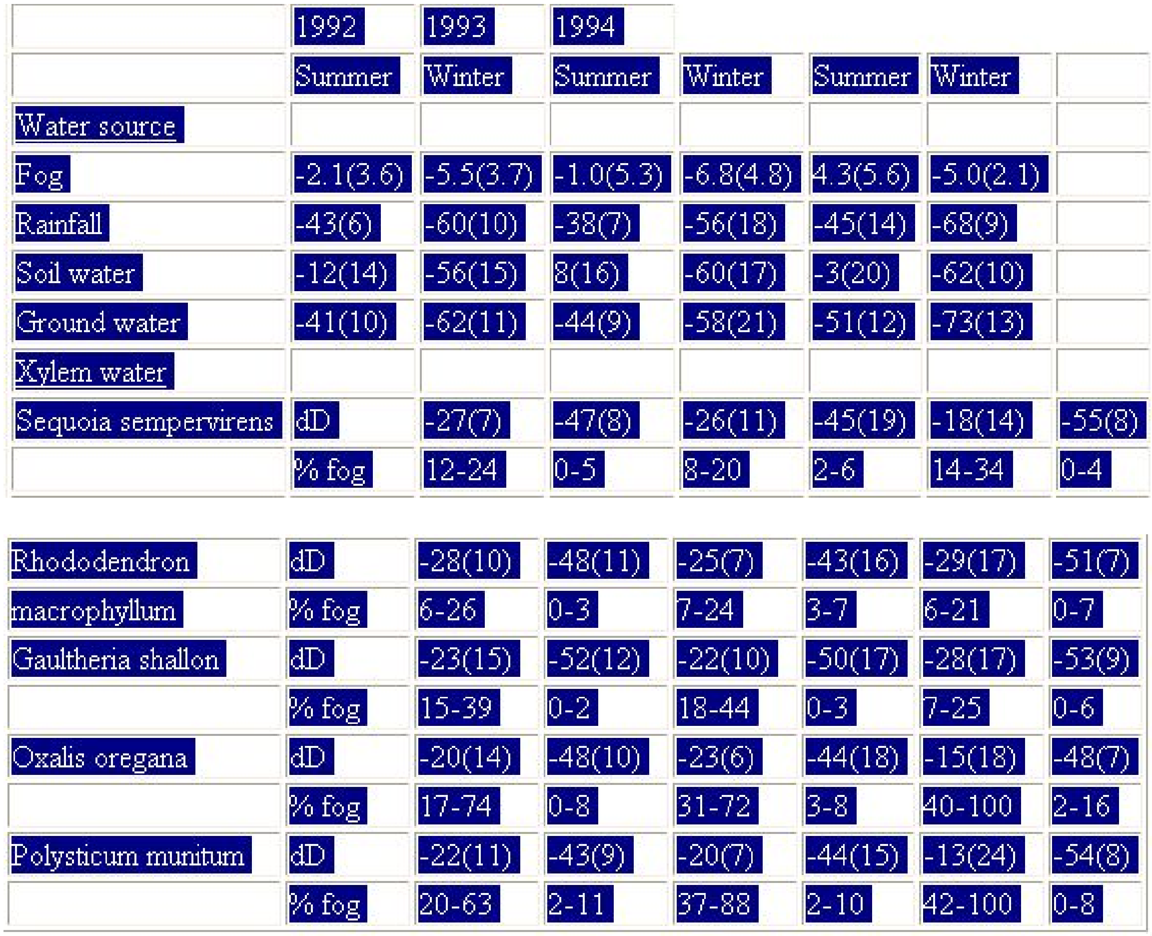
The study sites were 26 km north of Arcata and 14 km south of Crescent City, California. Both sites were less than 1 km from the coast at between 47-191 m above sea level. I used stable hydrogen isotopic analysis of water from fog, rainfall, soil samples, ground water, and within the dominant plant species to characterize which water sources the vegetation used. Samples were collected each month from January 1992 until December 1994. Soil water was obtained from soil cores extracted beneath redwood trees to a depth of 20 cm (n = 12). Ground water was obtained from a well drilled to a depth of 12 m approximate 150 m from the site. Fog water was collected by placing collectors directly beneath trees (n=7) and with cylindrical fog-collectors (n=10) placed in a 115 x 85 m open area adjacent to the site. Rain water was collect with a rain gauge in the same open area. Plant samples (n=15/species) were collected following the methods outlined by Dawson (1993a, b). Water was extracted from soil and plant samples by cryogenic vacuum distillation. The stable hydrogen isotopic composition was determined from hydrogen gas introduced into an isotope ratio mass spectrometer (after Dawson 1993a). Moisture input to the site was determined with fog-collectors and drip from tree foliage into a circular collector placed at the drip line around the entire circumference of 7 redwood trees for which the leaf-area (interception area) had been estimated (unpublished).

Results

Rainfall and "fog-day" information was obtained from records taken at the Arcata, California, airport (35 years) and near Crescent City, California (17 years). A fog-day is defined as a day where visibility was 0.8 km (1/2 mile) or less for 6-12 hours. During the growing season ("summer"; June-November), rainfall (dD) was at its lowest for the year and fog-days were at their highest (precip. = 55.46 +/- 65.24 mm; fog-days/month = 10 +/- 3.3). In contrast, during the "winter" (December-May), rainfall was highest and the number of fog-days at their lowest for the year (precip. = 154.9 +/- 75.17 mm; fog-days/month = 3.8 +/- 1.1).

Table 1. The stable hydrogen isotope ratio (dD) of fog, rainfall, soil water (0-20 cm depth), ground water, and water extracted from the xylem of plant stems as well as the

percentage of the water in the plants which is derived from fog (% fog) during the "summer" (June-November) and "winter" (December-May) seasons in 1992-1994. Samples were collected each month (see Methods section) and fog, rainfall, soil water and ground water values are means (+/- s.d.). Because the time periods over which the plant samples were collected spanned several months, and because there was a great deal of plant-to-plant and month-to-month variation, the % fog information are ranges, rather than means (+/- s.d.), for the entire "summer" or "winter" time periods.



	1992	1993	1994				
	Summer	Winter	Summer	Winter	Summer	Winter	
Water source							
Fog	-2.1(3.6)	-5.5(3.7)	-1.0(5.3)	-6.8(4.8)	4.3(5.6)	-5.0(2.1)	
Rainfall	-43(6)	-60(10)	-38(7)	-56(18)	-45(14)	-68(9)	
Soil water	-12(14)	-56(15)	8(16)	-60(17)	-3(20)	-62(10)	
Ground water	-41(10)	-62(11)	-44(9)	-58(21)	-51(12)	-73(13)	
Xylem water							
Sequoia sempervirens	dD	-27(7)	-47(8)	-26(11)	-45(19)	-18(14)	-55(8)
	% fog	12-24	0-5	8-20	2-6	14-34	0-4
Rhododendron	dD	-28(10)	-48(11)	-25(7)	-43(16)	-29(17)	-51(7)
macrophyllum	% fog	6-26	0-3	7-24	3-7	6-21	0-7
Gaultheria shallon	dD	-23(15)	-52(12)	-22(10)	-50(17)	-28(17)	-53(9)
	% fog	15-39	0-2	18-44	0-3	7-25	0-6
Oxalis oregana	dD	-20(14)	-48(10)	-23(6)	-44(18)	-15(18)	-48(7)
	% fog	17-74	0-8	31-72	3-8	40-100	2-16
Polysticum munitum	dD	-22(11)	-43(9)	-20(7)	-44(15)	-13(24)	-54(8)
	% fog	20-63	2-11	37-88	2-10	42-100	0-8

Table 1 shows the hydrogen isotope values for fog, rainfall, soil water, ground water, the redwood tree itself, and 6 of the most common understory plants. A mixing model was applied to the data (after Dawson, 1993a) to determine the percent-fog water used by each plant species (Table 1). When fog was most frequent, the isotopic data indicated that between 8-34% of the water used by S. sempervirens and between 6-100% of the water used by the understory vegetation came from fog precipitation after is had dripped from the tree foliage into the soil. Direct uptake of fog by plant foliage, which can occur, was not quantified.

Data obtained from fog-collectors showed an interception input of 36-73 mm/m2 for a 12 hour fog-day while interception input from tree foliage itself ranged between 59-132 mm/m2 for the same period. On average, fog water interception off of trees was 19-40% higher that input from fog-collectors. This difference may be due to the fact that tree foliage is more effective at "stripping" moisture out of an air mass because of the way it is formed (e.g., much like a layered comb rather than the hair-like structure of the fog-collector) or because in the "open" area where the fog-collectors were placed the radiation balance and thus evaporative conditions were modified in such a way that fog dissipation increased and thus less was collected. The annual hydrologic input from fog was estimated from these and the rainfall data and showed that between 22-46% of the total moisture input to the site was due to the presence of the redwood trees themselves.

Discussion

The isotopic data show that plants inhabiting the fog inundated coastal redwood forests of Northern California take up a considerable amount of this water source. The canopy tree species, S. sempervirens, which is largely responsible for "stripping" the fog-water vapor from the air mass, took up the smallest proportion of fog water. This species appeared to largely depend on deeper soil or ground water provided by rainfall during winter rainfall recharge events. During the summer, however, when fog was more frequent and fog-drip an almost daily occurrence, up to 34% of the trees' water was derived from fog. Even though redwoods seemed the least dependent upon fog-water, there may be other benefits of living in the fog-laden coastal zone which would have an impact on the growth and survival of this species. For example, Harris (1987) summarized previous work on this topic and discussed how higher CO2 concentrations "trapped" within the fog inversion as well as higher relative humidities, lower evapotranspiration, and higher diffuse radiation which may enhanced canopy photosynthesis could all be beneficial to trees (and perhaps other plants) inhabiting this fog-inundated ecosystem.

By contrast, some understory plant species took up a very high proportion of fog water and during the summer fog periods and at times appeared to be completely dependent upon it (e.g., sword fern). For the most part, fog composed a high fraction of the water used by understory plants during the summer. Differences among the understory plant species in the proportion of fog-water in their xylem sap is likely to reflect (a) their unique rooting patterns and rooting depth, and/or (b) their demands for water and hence the opportunistic nature by which they are able to proliferate roots to take advantage of the fog drip. Water in the shallow roots of all the plants studied was either identical to the soil water/fog water dD beneath redwood trees or a mixture of shallow (fog) and deep (rainfall) water. Water extracted from the xylem of aboveground stems was nearly always identical to root water dD, indicating that water uptake by roots rather than direct uptake of fog through plant foliage was how plants obtained the bulk of their water. Other benefits which may results from the presence of fog, such as enhanced nutrient inputs, and/or decreased stress within the understory plants have not yet been studied.

The hydrologic input of fog water to the redwood forests ecosystem is extremely high. When the fog collector data was compared to the data obtained from fog-drip collectors beneath trees it was clear that the trees were a full 19-40% more effective at `stripping' fog water out of the air mass. Moreover, between 20-50% of all the moisture input to the study site was due to the redwood trees themselves. These results suggest two things. First, that the hydrology and therefrom the ecology of redwood forests is intimately linked to the presence of the tree canopies themselves and the role they play in stripping fog, ameliorating the forest microclimate, and increasing the total annual income of water. Secondly, and, perhaps most importantly, from a management perspective, is the fact that loss of redwood trees due to natural disasters (e.g., fire, windthrow, or floods) or from logging or other land use practices which convert the forests to open habitats will dramatically alter the hydrological and ecological balance of these forests (see Bruijnzeel 1991). Loss of the canopy tree, S. sempervirens, therefore, would mean not only the loss of the biomass, nutrients within the biomass, and the soils (by post-disturbance erosion), by also a fundamental conversion of a once moist, cool, forested ecosystem into a more drought prone, and warmer ecosystem. Plants which depend upon the moisture input from fog drip, as well as the other microclimatic benefits of living in the forest, would certainly experience more frequent water stress because of lower water input and higher heat and evaporative conditions. It is also possible that both redwood seedlings and understory plants species which require forest conditions to regenerate including fog drip and cooler temperatures could disappear if the integrity of the redwood forests is disrupted.

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