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Stemflow variation in Mexico's northeastern forest communities: Its contribution to soil moisture content and aquifer recharge

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SUMMARY

Stemflow hydro-ecological importance was measured in trees and assessed in Mexico's northeast forest stands by answering three basic questions: (a) what are the intra and inter-specific stemflow variations; (b) is the stemflow coefficient constant from tree level to stand scales? and (c) what is the stemflow area and wetted soil volume in individual trees and the stemflow volume discharged at the stand scale in two plant communities of northeastern Mexico? Gross rainfall and stemflow flux measurements were conducted on 78 trees of semi-arid, sub-tropical (31 *Diospyros texana*; 14 *Acacia rigidula*; four *Bumelia celastrina*; five *Condalia hookeri*; three *Cordia bioissieri*; three *Pithecellobium pallens*) and temperate forest communities (six *Pinus pseudostrobus* Lindl. and 12 *Quercus* spp.). Stemflow was extrapolated from individual trees to the stand scale using 98 inventory plots (1600 m^2 ha^{-1} each) placed in oak–pine forests and 37 quadrats (5 m × 5 m each) distributed across the Tamaulipan thornscrub forest range. Stemflow infiltration flux and infiltration area measurements assessed the wetted soil volume. Daily measurements were conducted from May of 1997 to November of 1998. Results showed that stemflow coefficients varied between plant communities since they averaged (confidence intervals, $\alpha = 0.05$) 2.49% (0.57), 0.30% (0.09), and 0.77% (0.27) of the bulk precipitation for Tamaulipan thornscrub, pine, and oak forests, respectively. Intra-specific stemflow variations could not be identified in Tamaulipan although in temperate tree species. Basal diameter explained intra-specific stemflow variation in both plant communities. Stemflow increased threefold since it accounted for by 6.38% and 2.19% of the total bulk rainfall for Tamaulipan thornscrub quadrats and temperate oak–pine inventory plots, respectively. Small shrubs growing underneath large trees, in combination with the presence of small-diameter trees that recorded the largest stemflow coefficients appear to explain the increase of the stemflow coefficient from trees to stands. Stemflow replenishes soil moisture on the average 4.5 (1.4) times larger than does incident rainfall in open soils and appear to contribute to aquifer recharge in temperate forests due to a combination of shallow soils, high infiltration fluxes and the stemflow volume generated during rainfalls with depths >15 mm. Tracing studies should be conducted to test the hypothesis of the stemflow contribution to aquifer recharge in temperate forests of northeastern Mexico.

1. Introduction

Plant cover plays a key role affecting eco-hydrological and hydro-pedological processes at the local and catchment scales because of the control that plant cover exerts on rainfall and chemical redistribution, preferential rainfall channeling inside the soil, soil moisture content and aquifer recharge. The integrated interdisciplinary research of hydrology (stemflow), pedology (soil moisture), and how different vegetation types (ecology) interact would enhance our understanding in the critical soil zone (Lin et al., 2005; Newman et al., 2006).

Tree communities partition rainfall into interception loss, throughfall and stemflow. Interception loss is the rainfall retained on the canopy that evaporates back to the atmosphere. Throughfall is the rainfall portion that reaches the ground by passing directly through or dripping from tree canopies. Stemflow is the rainfall portion that flows to the ground via trunks or stems (Crockford and Richardson, 2000; Dunkerley, 2000). Throughfall redistribution variations have been found and explained by canopy drip points that vary within and between rains as well as increased throughfall from the stem to the canopy periphery. Stemflow is a localized point source input of precipitation and solutes at the plant stem base, creating islands of soil moisture and fertility (Navar and Bryan, 1990; Whitford et al., 1997; Johnson and Lehmann, 2006; Návar et al., 2009). In general, stemflow accounts for less than 5% of the total rainfall (Levia and Frost, 2003),

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although individual studies reported that it could be 6% in beech trees (Chang and Matzner, 2000), *Diospyros texana* trees (Navar and Bryan, 1990), 16% in *Larrea tridentata* shrubs (Whitford et al., 1997) up to 40% in Californian chaparral trees and Australian *A. aneura* shrubs (Slatyer, 1965; Pressland, 1973; Li et al., 2009). Levia and Frost (2003) reported maximum mean values of 3.5%, 11.3% and 19% for tropical, temperate, and semi-arid plant communities, respectively.

The stemflow hydrological importance was originally informed by Navar and Bryan (1990) by computing the stemflow infiltration area and calculating that it receives more than three times the annual rainfall in Mexico's northeast semi-arid shrubs. Latter research conducted by Whitford et al. (1997), Johnson and Lehmann (2006) and Li et al. (2009) found this rainfall flux infiltrates deep into the soil following roots and root channels, remaining available for transpiration processes. Taniguchi et al. (1996) and Tanaka et al. (1996) modeled stemflow fluxes into soils and observed that it could be impossible to disregard the importance of this rainfall component in groundwater recharge. Herwitz (1986) calculated the beech tree stemflow contribution to streamflow. Stemflow also contributes to soil moisture variation (Durocher, 1990; Navar and Bryan, 1990), soil chemistry (Chang and Matzner, 2000; Johnson and Lehmann, 2006), soil erosion (Herwitz, 1988) and the understory vegetation distribution (Falkengren-Grerup, 1989).

Stemflow is an important source of soil moisture in dry lands (Tromble, 1987; Navar and Bryan, 1990; Martinez-Meza and Whitford et al., 1997; Bhark and Small, 2003). Mauchamp and Janeau (1993) and Whitford et al. (1997) found *F. cernua* and *L. tridentata* are species capable of funneling approximately 50% and 20%, respectively of the incident gross precipitation to the plant stem base. Other arid and semiarid shrubs like *Ceanothus cuneathus*, *Arctostaphyllos mariposa*, *Banksia ornata*, *Xantohorrea australis*, *Haloxylon aphyllum*, *Acacia rigidula*, *Acacia aneura*, *Diospyrus texana*, *Acacia farnesiana*, *Tamarix ramosissima*, *Caragana korshinskii* and *Reaumuria soongorica* divert significant stemflow volumes to the stem base where it subsequently infiltrates deep into the soil and remains available for plant uptake (Hamilton and Rowe, 1949; Pressland, 1976; Nulsen et al., 1986; Navar and Bryan, 1990; Martinez-Meza and Whitford, 1997; Llorens and Domingo, 2007; Li et al., 2009). Deep stemflow infiltration could be a potential source of water for desert plants to cope with drought spells.

Stemflow is also important for several temperate tree species. The species *Fagus* spp., *Quercus* spp., and *Populus* spp., channel important rainfall quantities to the stem base via stemflow (Mulchanov, 1963; Bellot and Escarré, 1988; Chang and Matzner, 2000; Levia and Frost, 2003). In mesic plant communities, stemflow has a significant influence on other hydrologic variables such as runoff generation, soil erosion, groundwater recharge, and streamflow generation (Crabtree and Trudgill, 1985; Herwitz, 1988; Levia and Frost, 2003; Carlyle-Moses and Price, 2006; Li et al., 2009).

Regardless of this wealth of information, several important issues must be solved before we understand better the role of tree cover on the rainfall redistribution close to the stem base. Levia and Frost (2003), in an important stemflow review research paper, stressed that several questions must be answered before we predict other hydro-pedology and hydro-ecology issues. Hence, this paper addresses several raised questions: (a) what are the intra and inter-specific stemflow variation in two Mexico's northeastern tree communities? (b) Is the stemflow coefficient constant from trees to stand scales in both plant communities? (c) What is the stemflow contribution area and wetted soil volume for individual trees and for stand scales? The working hypothesis was that there are no stemflow intra or inter-specific variations and that its magnitude is too small at the tree and stand scales to account for by triggering other hydrological processes such as increased soil moisture and its contribution to groundwater recharge.

2. Materials and methods

2.1. The study area

The study was conducted in two Mexico's northeastern plant communities: the Eastern Sierra Madre mountain range dry, temperate mixed forests and the Northern Gulf of Mexico's Plains covered by Tamaulipan semi-arid, sub-tropical thornscrub forests.

The Tamaulipan thornscrub forest are distributed in southern US and Mexico's northeast Plains, covering a total area of close to 200,000 km^2. In Mexico, it covers an area of 32,188 km^2 according to the year 2000 forest inventory (Palacio-Prieto et al., 2000). This ecosystem is limited to the northwest by the Chihuahuan Desert, to the west by the Sierra Madre Oriental mountain range, and to the south by the Sierra Azul tropical rainforest. Native thornscrub forests are the main land cover in these plains. Plant communities are dense and diverse and contain at least four endemic genera of woody plants. Spiny shrubs and low trees dominate the plant community, but grasses, forbs, and succulents are also prominent. Manzano and Návar (2000) recorded 22 shrub species in 0.1 ha plots and more than 5000 shrubs per ha in 0.025 ha plots. Medium and small shrubs (less than 10 m in height) are common life forms, and they are disappearing because of selective harvesting for fuel wood, timber harvesting of selected valuable tree species, gas mining, and shifting cultivation (Treviño et al., 1996; Návar-Cháidez, 2008).

Moist, subtropical climate typical of southeastern Nuevo Leon and southwestern Tamaulipas features the southern portion of this ecosystem, while the northern bordering region is characterized by a semi-arid climate. Average annual precipitation ranges from 400 to 500 mm in the northern region; 700–800 mm in the south central area, to 1000 mm for the piedmont of the Sierra Madre Oriental mountain range and the southern distribution range. Pan evaporation is less variable than annual precipitation, with approximately 2200 mm yr^{-1} for the plains of the northern Gulf of Mexico (Návar et al., 1994).

The soils correspond, according to the FAO nomenclature, to Fluvisols, located along floodplains. The valleys are characterized by Castanozems originated by sedimentary and alluvial process. Leptosols are typical in high slope terrain with marked soil erosion. Regosols distributed throughout the mesas and plateaus. Deep Vertisols (>1.0 m) dominate the landscapes of the piedmont and lower plains, which are underlined by limestones of Cretacic origin (Woerner, 1991).

Temperate forests cover an area of approximately 3486 km^2 in the state of Nuevo Leon, Mexico (SARH, 1994; Palacio-Prieto et al., 2000), of which 36%, 39%, and 26% are characterized by pine, mixed pine–oak and oak forests, respectively. They play a key role in the hydrologic cycle since most rivers spring out from the upland Sierra Madre Oriental mountain range temperate forested watersheds (Návar et al., 1994). Oak–pine stands were selected to measure rainfall and stemflow daily fluxes. These are located in the Facultad de Ciencias Forestales forestry School property of the Universidad Autonoma de Nuevo Leon. The forestry school is located 40 km to the southwest of the city of Linares in the municipality of Iturbide of the State of Nuevo Leon, Mexico (24°43'N 99°52'W) between 1200 and 1900 m above sea level.

Summer rains and cold winters characterize the climate of this portion of the Sierra Madre Oriental mountain range, with average annual temperature and precipitation of 18 °C and 640 mm, respectively (1950–2004). A bimodal precipitation distribution characterizes regional climate with the first peak in late spring