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Microtopographic Ecohydrology of a Forested Wetland in Louisiana

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MICROTOPOGRAPHIC ECOHYDROLOGY OF A FORESTED WETLAND IN LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The School of Renewable Natural Resources

by

Yu-Hsin Hsueh

B.S. National Taiwan University, 2002

M.S. National Taiwan University, 2004

May 2015

To my parents who love me relentlessly

To my brothers and sisters in law

To my dear friends near and far

To the people of Louisiana who fight for environmental threats

To wetlands

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ABSTRACT

Coastal wetland forest ecosystems rely on the intimate interactions of hydrology, salinity, and coastal forest vegetation. The boundary between marsh and forest is often where hummock-swale terrain exists. It remains unknown as to the degree to which trees may experience varied salinity level within hummocks provided with freshwater flux. This study examined the hydrological regime of the hummock-swale terrain that resulted in salinity variation and whether freshwater source exists for baldcypress. Natural tracers of stable isotopes of water and salinity were applied to understand the sources of water. To better examine the tracers used, we conducted several experiments to gain a clearer understanding of the variability in isotopic compositions in throughfall and by extracting water from wood and soil. The studies indicated that baldcypress are able to avoid saline flooding from hummocks. We found that the throughfall process does correspond with the canopy structure enough to strongly influence throughfall amount but only weakly influence isotopic composition. Also at microtopographic scale, salinity of the groundwater in hummocks remained chronically high and vertical solute exchange was little. The shallow subsurface of hummocks was a zone characterized by slow dilution and episodic salinization rather than slow salinization and episodic flushing. Rainfall and frequent inundation by generally low-salinity water flushed salts and maintained lower salinity in upper layers. Thus the baldcypress forest overall occupies a nonsaline site, but the episodic influxes followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season. In addition, the systematic errors were little considering the isotopic fractionation during water extraction from wood.

CHAPTER 1. INTRODUCTION

1.1 Challenges for coastal swamps

Coastal wetland forest ecosystems rely on the intimate interactions of hydrology, salinity, and coastal forest vegetation. Understanding how these factors interact is often hampered by the complexity of the interactions and the paucity of specific data (National Research Council, 1995). In the state of Louisiana, coastal forested wetlands are deteriorating due to sea level rise, subsidence, channel building for hydrocarbon exploitation, increasing saltwater intrusion, faulting, and impact of tropical storms. In addition, the reduction of freshwater and sediment input from rivers and streams has made these wetlands prone to such coastal influences.

Along the southeast coast of the United States, baldcypress (*Taxodium distichum* (L.) Rich) is considered one of the most flood tolerant species when it comes to long-term flooding. In Louisiana, baldcypress and water tupelo (*Nyssa aquatica* L.) are the primary swamp tree species in coastal forests (Chambers et al., 2005) and facing threats from salinity (Pezeshki et al., 1988; Allen et al., 1997; Krauss et al., 2000). Baldcypress has slightly higher tolerance to salinity than water tupelo (Conner, 1994; Krauss et al., 2000; Effler and Goyer, 2006). Baldcypress remains a dominant species in back swamps of riverine floodplain (Keim et al., 2006) and in a remnant forest in the delta of the Mississippi River where flooding persists, and sometimes is subjected to saltwater intrusion (Conner and Toliver, 1990; Nelson et al., 2002; Day et al., 2012).

1.2 The importance of hummock-swale terrain (HST)

Tidal freshwater swamps of the southeastern coastal of the U.S. are at the interface with freshwater and brackish water marshes. The boundary between marsh and forest is often where hummock-swale terrain exists (Zoltai and Johnson, 1985; Rheinhardt and Hershner, 1992; Sklar and van der Valk, 2002; Day et al., 2007; Duberstein and Conner, 2009). The term “hummock”

generally refers to high ground on a microtopographic scale, and it is used in conjunction with “swale (hollow)”, a low depressional area (Odum et al., 1984). Hummock-Swale-Terrain (HST) predominantly exists in tidal freshwater swamps (Casey and Ewel, 2006), saltwater marshes (Keough et al., 1999; Stribling et al., 2007), and peat swamps (Shimamura et al., 2006) where flooding, anaerobic conditions, and sometimes salinity vary (Cowardin et al., 1979; Mitsch and Gosselink, 2007; Larsen and Harvey, 2010). Hummock-swale terrain exists in multiple wetland ecosystems, and it plays a crucial role in structuring plant communities and defining the structure of ecosystems.

More trees are established on hummocks than in swales in coastal swamps of the Mississippi River Delta (Huenneke and Sharitz, 1990). Species distribution also differs on hummocks versus in swales in southeastern coastal of the U.S. (Duberstein and Conner, 2009). Raised mounds are strengthened by intertwined root systems and dense muck soil (Huenneke and Sharitz, 1990).

Hydrological forces help shape zonation of plant species in tidal swamps where heterogeneity in biogeochemistry increases in biodiversity and productivity (Day et al., 2007; Light et al., 2007; Duberstein and Conner, 2009; Saha et al., 2010). Hummocks are not all developed or maintained by a single set of mechanisms. Instead, the presence of HST mostly signifies a dynamic balance of factors from hydrologic processes (Larsen et al., 2012), nutrient (Eppinga et al., 2008, 2009), soil properties (Bliss and Gold, 1994; Bledsoe and Shear, 2000), root of plants (Keough et al., 1999; Stribling et al., 2007), and activities of animals (Burke et al., 1999; Lindquist et al., 2009). It remains unknown as to the degree to which trees may experience varied salinity level within hummocks provided with freshwater flux because spatial heterogeneity of salinity is greatly influenced by water budget, and hydrological fluctuations. In

addition, changes in subsurface salinity of a backswamp may not be homogenous as water level increases.

1.3 Water sources used by trees

Trees root systems exploit needed resources depending upon availability of advantageous conditions (e.g. White et al., 1985). Stable isotopes of water serve as a potential method for identifying source water for plants (Roden et al., 2000; Stratton et al., 2000; Dawson et al., 2002; Sekiya and Yano, 2002; Schoonmaker et al., 2007) because the xylem most often passively transports water unchanged in stable isotopes from the soil matrix downward along the water potential gradient to the leaves. Hence, except in the leaves, xylem water is relatively consistent along the path and reflects the water sources from roots (Washburn and Smith, 1934; Dawson and Ehleringer, 1991, 1993; Walker and Richardson, 1991; Ehleringer and Dawson, 1992; Thorburn et al., 1993). By measuring the isotopic composition of water in the xylem, and multiple potential sources of water, the tree water use can be identified.

1.4 Use of isotope tracers in tracing water sources in natural ecosystems

There are multiple complications involved in using isotopic composition of natural waters as tracers of hydrologic and ecologic processes. First, forest canopies modify isotopic composition of precipitation by fractionation, mixing, and exchange within the canopy (Saxena, 1986; Ikawa et al., 2011; Kato et al., 2013) and spatially and temporally varying transmission of water through the canopy (a.k.a. “selection”; Dewalle and Swistock, 1994). Second, extraction of water from plants and soils and analysis for isotopic composition is a complex process with multiple opportunities for errors. In particular, this analysis is susceptible to errors resulting from

cryogenic vacuum distillation (West et al., 2006) and contamination of laser absorption spectroscopy by organic compounds (West et al., 2010).

1.5 Knowledge gap and research needed

Salinity gradients, microtopographical conditions, and differences in tolerance of baldcypress may account for the differences in the stability in the HST ecosystem, and decide the transition of a swamp to marsh. In other words, knowledge gap exists in how microtopography and changes in salinity affect baldcypress and other species in this coastal wetland forest. The overall objective of this study is to close this knowledge gap between interactions of water sources, water use, salinity, and the existence of baldcypress in HST.

Thus, specific objectives are:

- Objective 1: Understand whether the canopy structure relates to throughfall amount and isotopic variation by quantifying both throughfall and spatial heterogeneity in canopy structure.
- Objective 2: Understand how fluxes of precipitation, groundwater, and surface water affect salinity in hummocks and adjacent swales.
- Objective 3: Understand the sources of waters available to and used by baldcypress on coastal swamp hummock-swale topography.
- Objective 4: Understand the systematic error from cryogenic extraction device, the efficacy of extraction water from wood, and whether active carbon - commonly used to reduce volatile organic compounds (VOCs) - caused fractionation.

1.6 References

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CHAPTER 2. SPATIAL VARIABILITY OF THROUGHFALL AMOUNT AND ISOTOPIC COMPOSITION UNDER A HARDWOOD FOREST CANOPY

2.1 Abstract

Micro-scale dynamics in throughfall influence soil moisture and other subcanopy processes. Stable isotopes of water can help identify the pathways, sources, and residence time of rainfall to give clues to the physical processes of forest canopy interception. The objective of this study was to examine whether the canopy structure relates to throughfall amount and isotopic variation by quantifying both throughfall and spatial heterogeneity in canopy structure. Throughfall amount was spatially correlated with canopy structure, such as distance to the nearest tree, crown coverage, and crown length. Spatial patterns of throughfall amount were consistent in time but the spatial patterns of stable isotopes were much weaker. Spatial autocorrelation was consistent in throughfall amount across events, which suggests fixed controls over patterning of throughfall to the forest floor by the canopy. Complexity in isotopic composition suggested that routing through the canopy, intra-storm isotopic variation, isotopic exchange, and evaporation interacted to affect the stable isotopic composition. The throughfall process does correspond with the canopy structure enough to strongly influence throughfall amount but only weakly influence isotopic composition.

2.2 Introduction

The interception of precipitation and transport through the canopy is a function of vegetation heterogeneity (Levia et al., 2011). Canopy structure modifies deposition, storage, and redistribution of water, yielding spatial variability in amount and chemical composition of throughfall (Durocher, 1990; Raat et al., 2002; Zimmermann et al., 2009). However, throughfall

properties are not only a function of the canopy, but also of meteorological conditions, so the spatial pattern of throughfall is a product of a complex and dynamic suite of processes.

Tracers, namely naturally occurring stable isotopes, are important tools for disentangling throughfall processes (Allen et al., 2014). Isotopic composition of throughfall is affected by fractionation, mixing, and exchange within the canopy (Saxena, 1986; Ikawa et al., 2011; Kato et al., 2013) and spatially and temporally varying transmission of water through the canopy (a.k.a. “selection”, Dewalle and Swistock, 1994). Moreover, isotopic processes are superimposed on temporally varying isotopic composition of precipitation (Brodersen et al., 2000) from weather conditions (Dansgaard, 1964), which also affect interception loss (Llorens et al., 1997).

Temporally persistent spatial patterns in throughfall amount suggest the canopy is a fixed structural control (Keim et al., 2005; Staelens et al., 2006). In contrast, persistent spatial patterns in isotopic composition have not been observed (Allen et al., 2015), which suggests that complexity from evaporation, exchange, and selection is important (Xu et al., 2014). Altogether, the apparent complexity of throughfall isotopic composition highlights the poor understanding of the interception process. Coupled measurements of spatial variability of isotopic variations with measurements of canopy structure can provide more insight into processes occurring in the canopy than have previous studies focusing on temporal variability.

In this study, we examined the relationship between throughfall (TF) isotopic variations and canopy structure, specifically 1) we measured amount and isotopic composition (^{18}O and ^2H) with 100 TF collectors in a 0.05 ha plot for five events to examine spatial variability, and 2) we compared these TF observations to canopy structural characteristics.

2.3 Methods

2.3.1 Study site

The study site was bottomland hardwood forest in the floodplain of the Mississippi River, at the LSU Reproductive Biology Center, near St. Gabriel, Louisiana, USA. The forest was about 42 years old, established after abandonment of an agricultural field, and is an even-aged stand of deciduous species (*Acer rubrum*, *Carya aquatica*, *Celtis laevigata*, *Fraxinus pennsylvanica*, *Quercus texana*, and *Ulmus americana*) with basal area of 24.3 m²/ha (Moerschbaeher, 2012). Trees had a mean diameter of 18.3 cm and mean height 10 m.

2.3.2 Throughfall sampling

A single plot of 22 × 22 m was established (Figure 2-1). 100 cups fitted with funnels 7 cm radius were mounted 100 cm above the ground at randomly determined locations. Five storms were sampled during the leafed period in 2011 and 2012. Samples for isotope analysis were collected in 20 ml glass bottles with plastic caps and zero headspace. All cups were dry and clean before each storm and emptied fully within 30 hours after each storm. A controlled experiment indicated fractionation within the cups was maximum 1.2‰ for δD and 0.2‰ for $\delta^{18}O$ (-0.4‰ for d).

2.3.3 Stable isotopes

Throughfall samples were analyzed for stable isotopes using laser absorption spectroscopy (DLT-100, Los Gatos Research, Mountain View, CA). Results were converted to $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$, in which δ indicates the deviation of ^{18}O or 2H from Vienna-Standard Mean Ocean Water (VSMOW) (Gonfiantini et al., 1993), R_{sample} is the isotope ratio ($^{18}O/^{16}O$ or $^2H/^1H$) of the sample, and R_{standard} is the isotope ratio of the standard. Deuterium excess (d) was calculated by displacement from the global meteoric water line (GMWL),

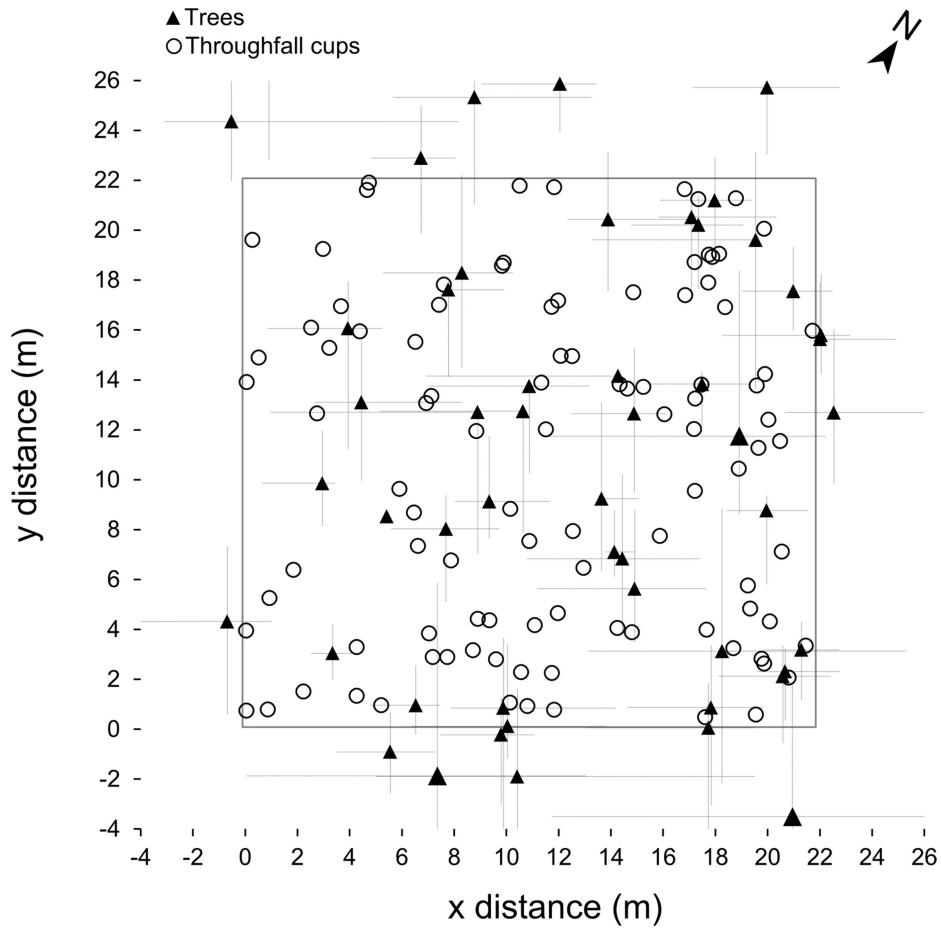


Figure 2-1. Spatial locations of throughfall collectors and trees on the study plot. The plot boundary is indicated by box. Tree crown extent is indicated by lines at the four cardinal directions.

$d = \delta D - 8 \times \delta^{18}\text{O}$; variations in d help distinguish water sources because they arise from non-equilibrium evaporation and condensation (Dansgaard, 1964).

2.3.4 Canopy structure

Each tree in the plot and adjacent to the plot was measured for diameter at breast height, total height, and crown length (total height – height to base of the crown). Each individual crown was described by its extent in each of the four cardinal directions and crown length as the distance between tree height and the bottom branch. A total of 48 trees were measured in and around the plot.

Canopy coverage over each individual cup was determined with vertical images taken by a digital SLR camera on an overcast day in June and analyzed using image processing software ImageJ. Analysis of canopy coverage was of a 1 m diameter patch in the center of the photo (2.86 degrees at 20 m height).

2.3.5 Statistical methods

Analyses were carried out on values rank-transformed per storm event because of highly non-normal distribution of throughfall. Ranks were linearly transposed to a 1 to 100 scale in cases where samples were missing. Time stability plots (Raaijmakers et al., 2002) were used to compare the data at individual cups across events for temporal consistency of spatial patterns. Tukey tests were applied to test the differences of means among cups. The spatial autocorrelation of throughfall was quantified using variograms, which compare semivariance ($\gamma_h = \sum \frac{(z_x - z_{x+h})^2}{2n(h)}$; where z_x is the value at location x and z_{x+h} is the value at location h distance apart) by lag (distance apart). Analyses were done using Excel, R, and MATLAB. Lag reflects the distance in paired samples that values are no longer reflecting similar correlation as they have at shorter distance; thus, the paired samples are showing randomness at lag distance.

2.4 Results

2.4.1 Spatial variability of throughfall

The mean throughfall for each storm event varied from 2.0 to 36.1 mm (Table 2-1; Figure 2-2). There was some temporal persistence in throughfall amount (Figure 2-3); the median rank amount at most (85%) cups was statistically different from at least one other cup and 3% were different from at least 30 other cups (Figure 2-3). Variograms of throughfall ranked amount had a characteristic range of ~2-4 m per storm, but the range of the mean rank across the entire study

was only ~0.5 m (Fig. 2-4, A-F). Experiment-wide patterns were less distinct than event-based (Figure 2-5, A-F).

Table 2-1. Stable isotopic compositions and amount in throughfall from five events.

Event	Date	Slope ($\delta D/\delta^{18}O$)	Throughfall amount (mm)	δD	$\delta^{18}O$	d
		Mean \pm S.D. (‰)				
TF36.1	22-Aug-11	1.3	36.1 ± 7.5	6 ± 1	-0.9 ± 0.4	12.7 ± 2.7
TF9.9	30-Aug-12	6.9	9.9 ± 2.5	-13 ± 6	-3.1 ± 0.8	11.9 ± 2.0
TF5.2	6-Jun-12	0.8	5.2 ± 1.2	-4 ± 2	-1.1 ± 0.8	4.6 ± 6.4
TF3.7	28-Oct-11	2.7	3.7 ± 0.9	7 ± 3	-0.6 ± 1.0	11.5 ± 5.6
TF2.0	12-Jun-12	2.9	2.0 ± 0.7	-12 ± 8	-0.6 ± 2.1	-7.0 ± 12.1

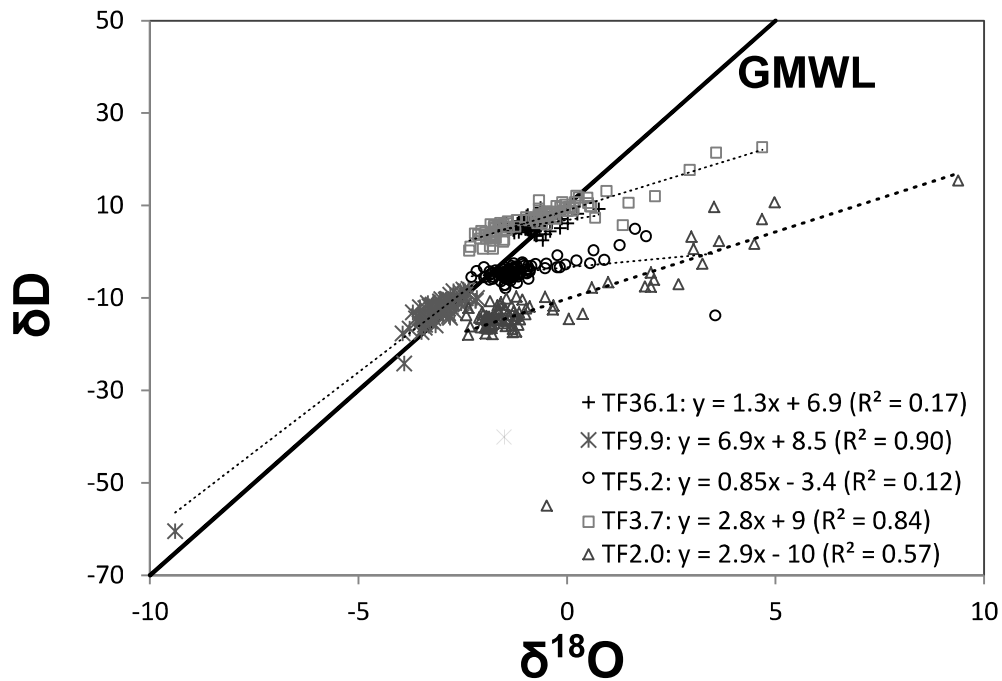


Figure 2-2. Isotopic water lines of throughfall for five rainstorms at St. Gabriel, LA during June 2011 to 2012.

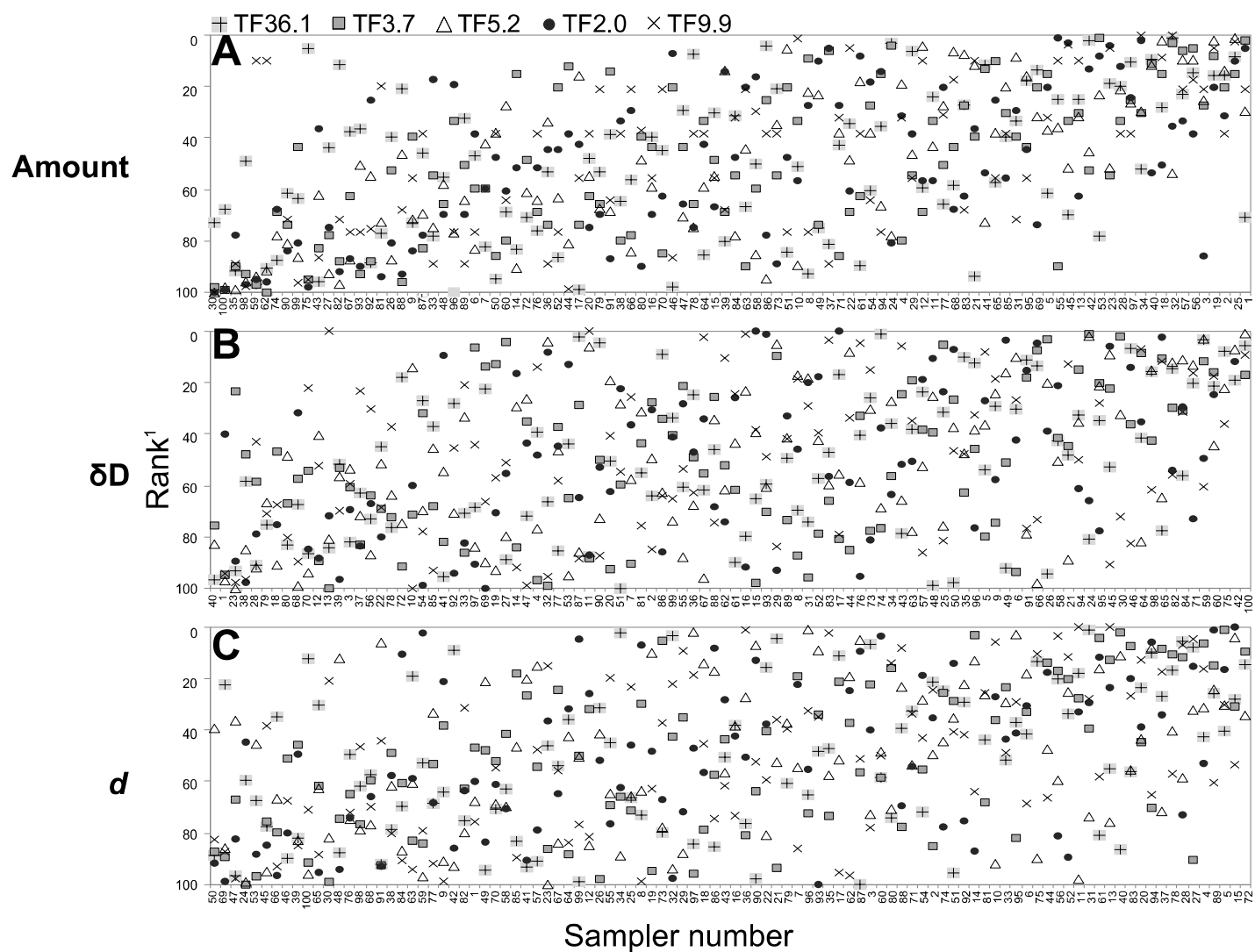


Figure 2-3. Time stability plots of throughfall amount (A) and isotopic composition (δD -B; d -C) across five rainstorms. Symbols directly above or below each other show variation for a cup among events. Sampler number (x-axis) is ordered by the mean ranked values for parameters.

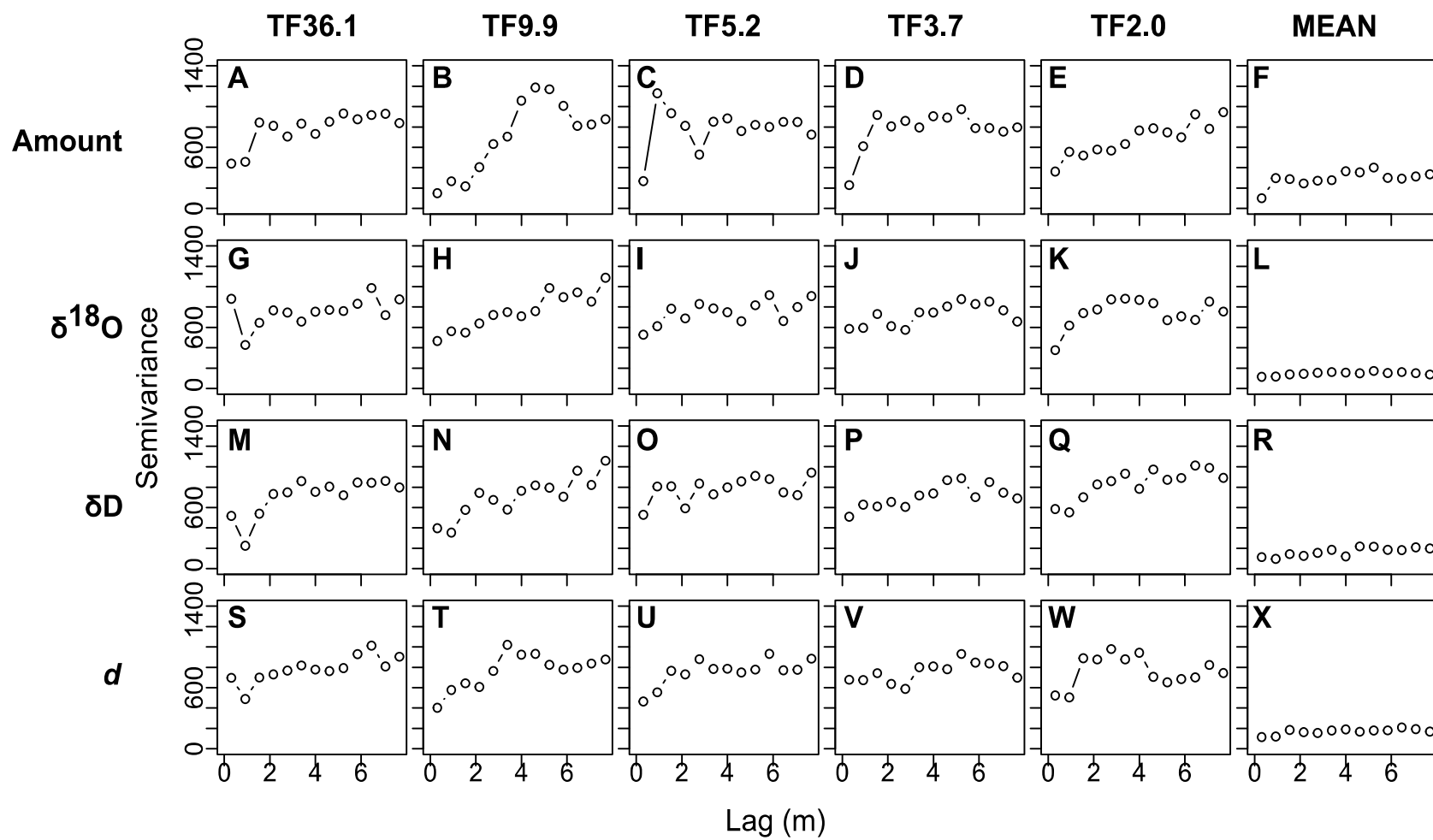


Figure 2-4. Variograms of rank-transformed throughfall amount (A-F) and isotopic composition ($\delta^{18}\text{O}$: G-L; δD : M-R; d : S-X) of throughfall in five events.

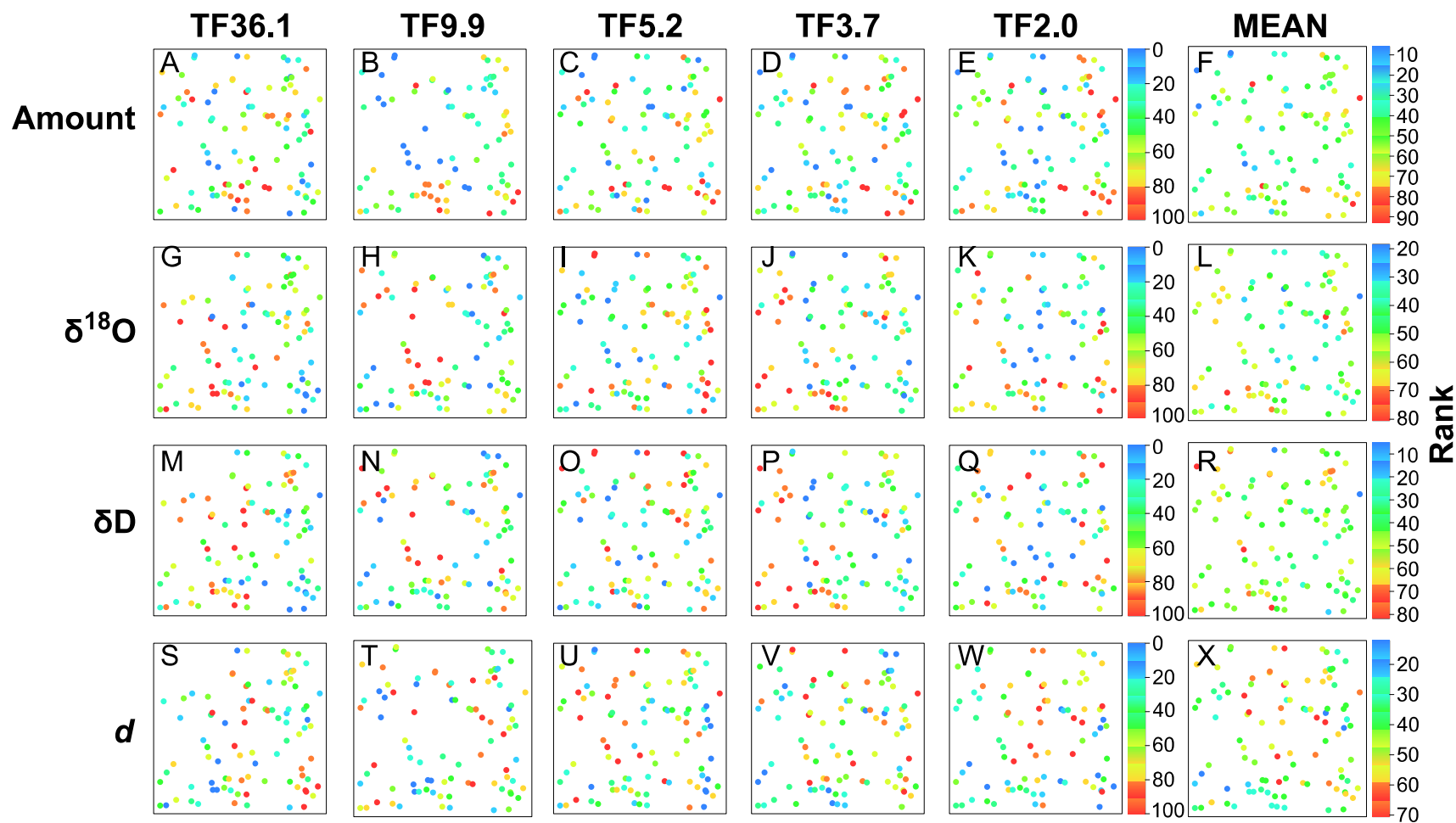


Figure 2-5. Spatial plots of rank transformed values of throughfall amount (A-F), $\delta^{18}\text{O}$ (G-L), δD (M-R), and d (S-X) across four rainstorms. Each dot represents throughfall sampler where rank 1 (dark blue) represents the highest value and rank 100 (red) represents the lowest value.

2.4.2 Spatial variability of isotopic composition

Throughfall was variable within each event demonstrating interception effects (Figure 2-2). In contrast to throughfall amount, Tukey tests revealed no differences in mean rank by cup for δD , $\delta^{18}O$, or d ; and time stability plots showed substantially less temporal persistence for isotopic composition (Figure 2-3, B,C). Variograms of mean-rank isotopic composition across all events showed no structure, but there was structure evident in some individual events (Figure 2-4G-X). Ranges (lag of at which sill is reached) for individual events were ~2-6 m when a sill (maximum variance) was identifiable. There were no clear differences in the spatial structures of δD , $\delta^{18}O$, and d —they all showed similar, weak spatial structure per event that did not persist among events to create identifiable structure at the experiment scale.

2.4.3 Canopy structure

Crown coverage above throughfall collectors ranged from 2 to 100% (Figure 2-6, A), and crown length ranged from 0 to 33 m (Figure 2-6, B). The variogram of canopy coverage showed increasing variance with lag, with sills identifiable at ~3 m or ~7 m (Figure 2-7).

2.5 **Effect of canopy structure on spatial patterns of throughfall**

2.5.1 Amount

Throughfall amount was influenced by canopy coverage and crown length (Figure 2-8). Throughfall amount was greater away from tree trunks ($\rho = 0.15$, $p < 0.0001$; Figure 2-8, A), under less canopy cover ($\rho = -0.30$, $p < 0.0001$; Figure 2-8, B), and under shorter crowns ($\rho = -0.40$, $p < 0.0001$; Figure 2-8, C). Throughfall amount varied more under a closed canopy than in less covered areas (Figure 2-8, A-C).

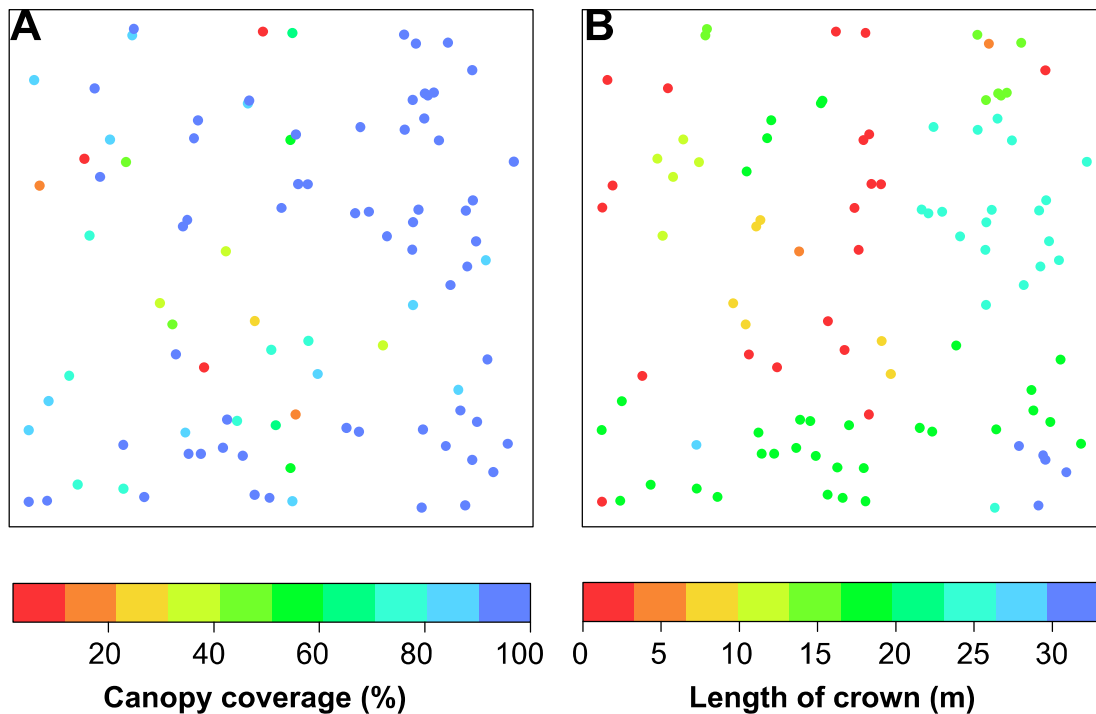


Figure 2-6. Spatial condition of (A) crown coverage and (B) crown length above each throughfall sampler (colored dot).

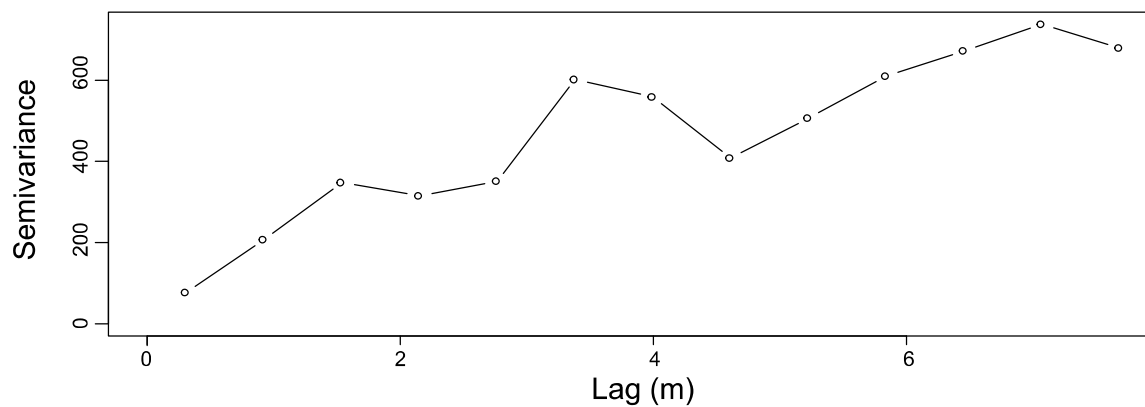


Figure 2-7. Variogram of crown coverage; this showed that the crown coverage is spatially correlated at least at a range of 3 or 7m.

2.5.2 Isotopic composition

The isotopic composition of throughfall was correlated with canopy structure, but less so than was throughfall amount (Figure 2-8). Long crown lengths and high canopy coverage were

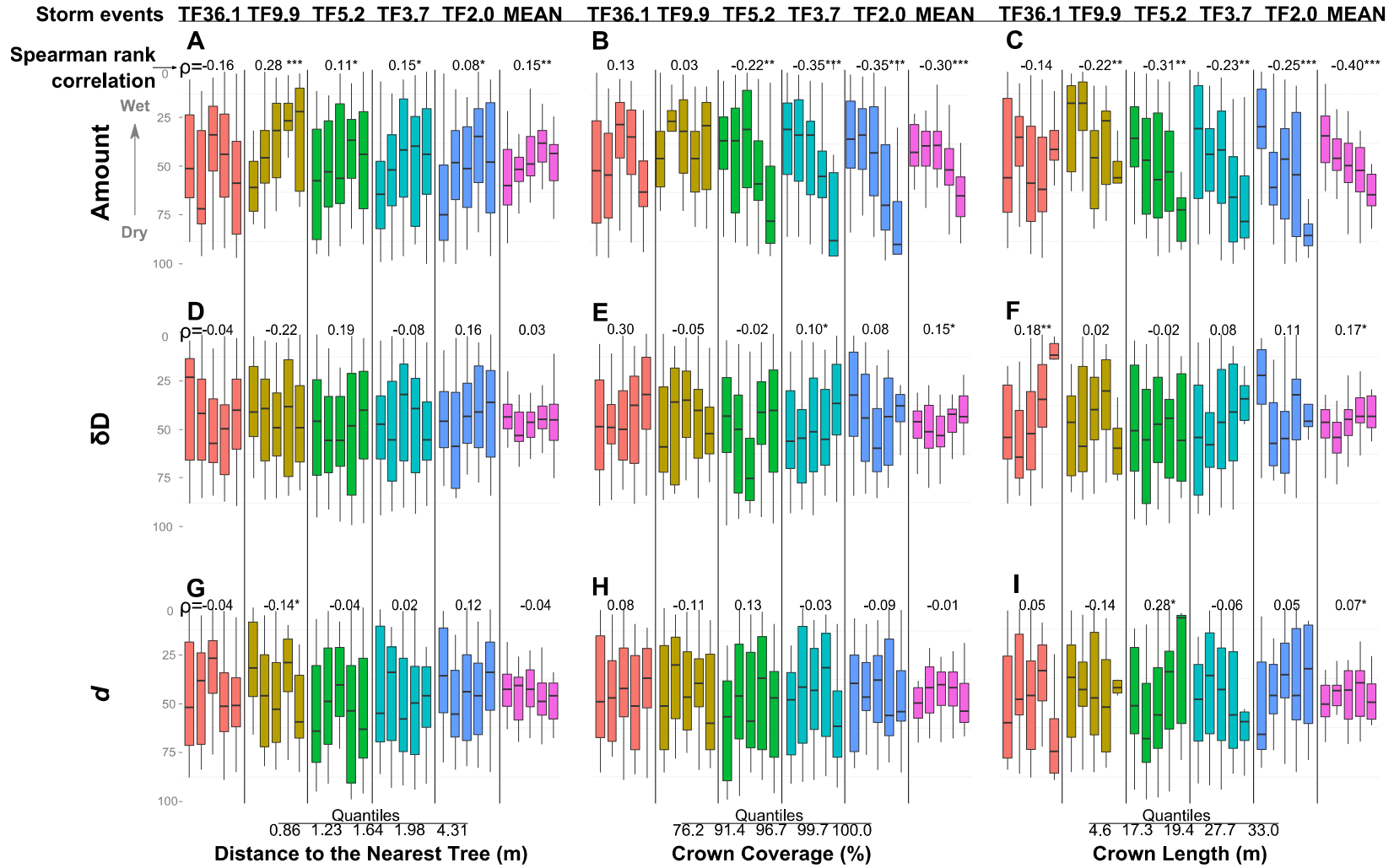


Figure 2-8. Boxplots of the relationships between rank-transformed throughfall variables (amount: A-C; δD : D-F; d : G-I) and three forest structure variables for each of five storms (boxplot clusters of the same color) and for the mean rank across storms. Each box is a quantile (20 throughfall samplers). Spearman rank correlations (ρ) were shown above each boxplot. Rank 1 shows the highest value.

both weakly associated with heavier δD (Figure 2-8, E, F), but these relationships were weaker or absent for d (Figure 2-8, H, I). These relationships were inconsistent for individual rainfall events. For example, long crowns were strongly related to heavier δD only in one storm; the relationship for the remainder was weaker or absent (Figure 2-8, F).

Heavy throughfall amount was correlated with lower δD (Table 2-2). However, this relationship did not hold for each storm, and there was poor correlation between rank throughfall and rank isotopic composition for $\delta^{18}O$ and d in all storms and experiment wide.

Table 2-2. Correlation between throughfall amount and its associated stable isotopic compositions from each storm event.

Variable of each storm	Throughfall event					
	TF36.1	TF9.9	TF5.2	TF3.7	TF2.0	Mean
δD	-0.14	-0.23*	-0.28**	-0.17	0.01	-0.23**
$\delta^{18}O$	-0.20	-0.14	-0.13	-0.15	0.18	-0.18
d	0.12	-0.03	0.04	0.14	-0.16	0.00

2.6 Discussion

Canopy coverage and the crown length were related to spatial variability of throughfall amount more so than distance to tree. However, this relationship applied much less for isotopic composition, and there were only occasional hints at canopy control over spatial variability of isotopic composition. Similarly, variograms of throughfall amount were generally more structured at both the storm and experiment level for throughfall amount than for isotopic composition, and stability plots showed more persistence for amount than isotopic composition. Taken together, these results show low temporal stability in stable isotopes from collected water samples while the amount of rainfall remained more stable, suggesting that a suite of exchange, redistribution, and selection processes for water occurred within canopy (Xu et al., 2014) to give less predictability to the chemical composition of throughfall.

One of the factors explaining why isotopic composition of throughfall is more spatially varied is the selection effect. Under complex crowns, residence time in the canopy and mixing within the canopy creates complex behavior of throughfall. In previous work, droplets of the latter part of the rainfall are often thought to be trapped in the canopy (Xu et al., 2014), and the rainfall from that part of the storm never becomes throughfall, as selection effect. Because rainfall varies in isotopic composition through time, the selection effect may result in either high depletion or enrichment in the throughfall (Celle-jeanton et al., 2004). This selection process is generally expected to have greater effect under dense and thick canopies (Llorens and Gallart, 2000; Staelens et al., 2006, 2008; Allen et al., 2014).

There was a generally strong and consistent spatial pattern in throughfall with variograms having identifiable sills. In contrast, isotopic composition showed much less structure to the variograms. Hence, the processes that redistribute the rainfall spatially may not all operate on the same time scale to produce spatial variability of isotopic composition.

As rainfall passes through the canopy on vegetative surfaces, isotopic exchange of throughfall within vapor layer is likely (Kendall, 1993) and the net effect is to mute spatial patterns of isotopic composition (Liu et al., 2008; Xu et al., 2014). It is possible that during the rainfall, small, splash droplets form that are important for total interception losses (Murakami, 2006; Dunkerley, 2009). When splash droplets contribute to throughfall, gaps would have higher throughfall volume (as we observed) and the drops consist of old water and new water combined (Nanko et al., 2011). The expected effect of this process may be also to mute spatial patterns because of this mixing, and also because of enhanced vapor interactions by the smaller drops.

The crown variograms showed a sill at lag ~ 3 m, which matched with the mean crown radius of 2.9 m and also corresponds to mean distances from collectors to tree stems (mean 2 m).

(Keim et al., 2005) observed that variograms of throughfall amount corresponded to crown sizes, but in our forest the relationship was weak: individual storms had ranges of 2–6 m for amount and isotopic composition was similar where any patterns were evident. Thus, crown size was related to patterns of both amount and isotopic composition of throughfall, but with much more complex processing of throughfall than is implied by simple correspondence among these variables.

2.7 Conclusion

Throughfall amount was spatially correlated with canopy structure, such as distance to the nearest tree, crown coverage, and crown length. Spatial patterns of throughfall were consistent in time but the patterns were much weaker for stable isotopes. Spatial autocorrelation was consistent in throughfall amount across events, which suggests fixed controls by the canopy. Complex patterns in isotopic composition of throughfall suggested that routing through the canopy, intra-storm isotopic variation, isotopic exchange, and evaporation interacted to affect the composition. The throughfall process does correspond with the canopy structure enough to strongly influence throughfall amount but only weakly influence isotopic composition.

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CHAPTER 3. HYDROLOGICAL EXCHANGE IN HUMMOCKS IN A FORESTED, DELTAIC SWAMP

3.1 Abstract

Hummocks support clusters of trees a few centimeters above surrounding swales at the saltwater-freshwater transition zone. To examine how hummocks support trees in an otherwise inhospitable wetland, naturally occurring stable isotopes of water and salinity were used as tracers to understand water fluxes in pore spaces. Water samples were collected from suction lysimeters placed in four hummocks surrounded by permanently flooded swales. Hummocks were frequently inundated. Surface water in the swales surrounding hummocks was similar to throughfall in isotopic composition, which suggested mixture from rainfall events. Salinity of groundwater under hummocks increased with soil depth, was higher than in the swales, and fluctuated little over time. Salinity, $\delta^{18}\text{O}$, and $\delta^2\text{H}$ in porewater varied more in the shallow open water than in groundwater. The shallow subsurface of hummocks is a zone characterized by slow dilution and episodic salinization rather than slow salinization and episodic flushing. Rainfall and frequent inundation by generally low-salinity water flushed salts and maintained lower salinity in upper layers. Thus the baldcypress forest overall occupies a nonsaline site, but the episodic influxes followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season.

3.2 Introduction

Forested deltaic swamps at the transition of forest-marsh mosaics are often characterized by microtopographic variation as hummock-and-swale topography (HST). The tops of hummocks are typically vegetated, less than 0.5 m above mean water level, and formed mainly by organic accretion (Duberstein and Conner, 2009). In HST, trees are generally restricted to

hummocks (Rheinhardt and Hershner, 1992), or at least preferentially established on hummocks (Huenneke and Sharitz, 1986; Light et al., 2007), especially when inundation of swales is for more than half of the growing season (Day et al., 2007; Duberstein and Conner, 2009).

The elevation of hummocks above mean water level usually promotes tree survival by providing refuge from hypoxia and flood stress (Dommain et al., 2010; Courtwright and Findlay, 2011). However, flood stress does not limit tree growth in some forested HST (Duberstein et al., 2013); other factors such as erosion in hollows (Day et al., 2007) or seedling recruitment (Huenneke and Sharitz, 1986; Peterson and Baldwin, 2004) appear to control plant distribution in some cases. Mechanisms that control plant growth and distribution vary depending on whether HST is formed in a relatively stable landform, such as peat bogs (Malmer and Wallén, 1999) or along stable coasts (Rheinhardt and Hershner, 1992), as opposed to their formation in submerging landforms such as rapidly subsiding deltas (DeLaune et al., 1994).

In many coastal wetlands, salinity is important in structuring vegetation communities in general, but the interaction of salinity and flood stressors in controlling plant communities in HST is not understood. Salinity has been found to favor formation of HST in at least one location (Stribling et al., 2007), but the mechanism is not well understood and the phenomenon has not been described in forested wetlands.

One place where the interaction between flooding and salinity is ecologically important is in the delta of the Mississippi River, where the forest-marsh boundary is controlled by flooding and salinity (Allen et al., 1996; Krauss et al., 2009; Day et al., 2012) and recent rapid subsidence has caused widespread increased flooding and saltwater intrusion (Boesch et al., 1994). In marginal environments, trees occupy hummock tops as is typical of HST. However, it is not clear

whether hummocks are most important as refuge from flood stress, salinity stress, or both (Middleton, 2000).

The hydrologic and salinity regimes of hummock interiors control the suitability for plants. Hummocks are more suitable for tree growth generally, but the reasons for this remain unclear in many places, including our study site in the Mississippi River delta. We hypothesize that two alternative regimes may dominate hummock hydrology and salinity (Figure 3-1). When evapotranspiration (ET) exceeds precipitation, net flux of swamp water into the hummock subsurface likely increases salinity because of evaporative concentration (e.g., Bauer-Gottwein et al., 2008; Gardner, 2009). Alternatively, when precipitation exceeds ET, subsurface salinity likely decreases because of flushing by net flux out of the hummock. It is important, therefore, to examine which mechanism applies to this hummock system to understand the role of hummocks in vegetative communities.

3.3 Objective

The objective of this study was to determine how fluxes of precipitation, groundwater, and surface water affect salinity in hummocks and adjacent swales. Specifically, we examined whether there is a difference in the salinity regimes of hummocks as compared to swales, using stable isotope tracers to distinguish water flow paths.

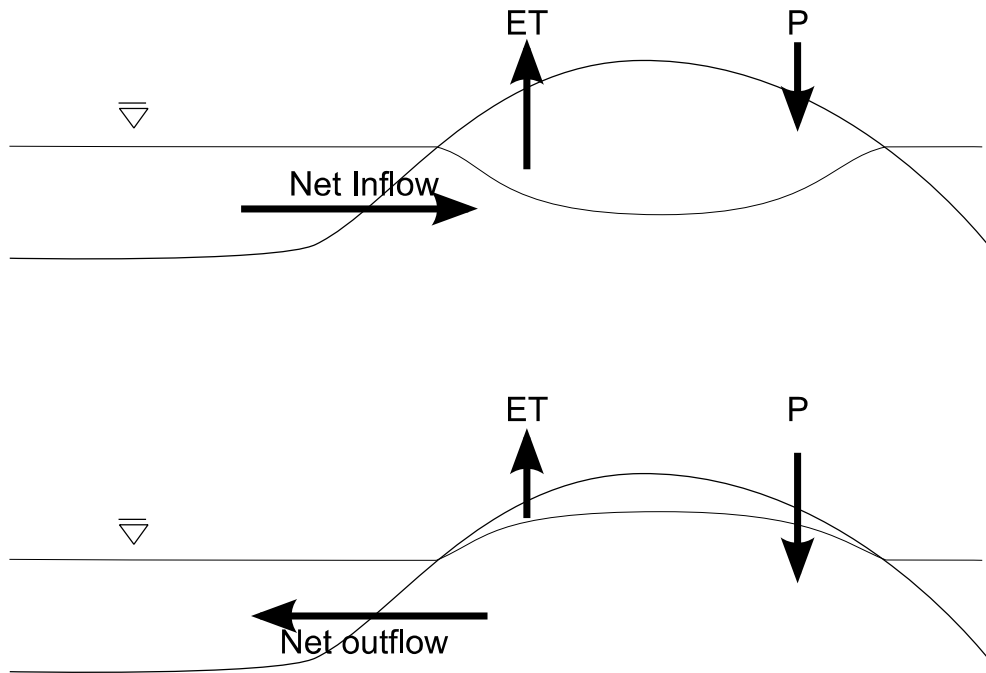


Figure 3-1. Conceptual water budget scenarios in hummocks ecosystem: (Top) Salinity accretion occurs in unsaturated hummocks under evapotranspiration and limited inundation; (Bottom) coarse pore space in hummocks allows gravity drainage and leaches salt from precipitation.

3.4 Methods

3.4.1 Study Site

This study took place in Jean Lafitte National Historical Park and Preserve of Barataria Basin, between Lake Salvador and Bayou Segnette, in the Barataria Basin of Louisiana, USA (29.756 N, 90.146 W; Figure 3-2). Site elevation is less than 0.5 m msl (Jiang and Middleton, 2011) near the transition between forested, baldcypress (*Taxodium distichum*) swamp and non-forested marsh and ~100 m from the site characterized previously (Krauss et al., 2009). The site is on young, deltaic sediments and subsiding at a rate of approximately 3-5 mm/y (Lane et al., 2006) from compaction of shallow, deltaic deposits (Törnqvist et al., 2008).

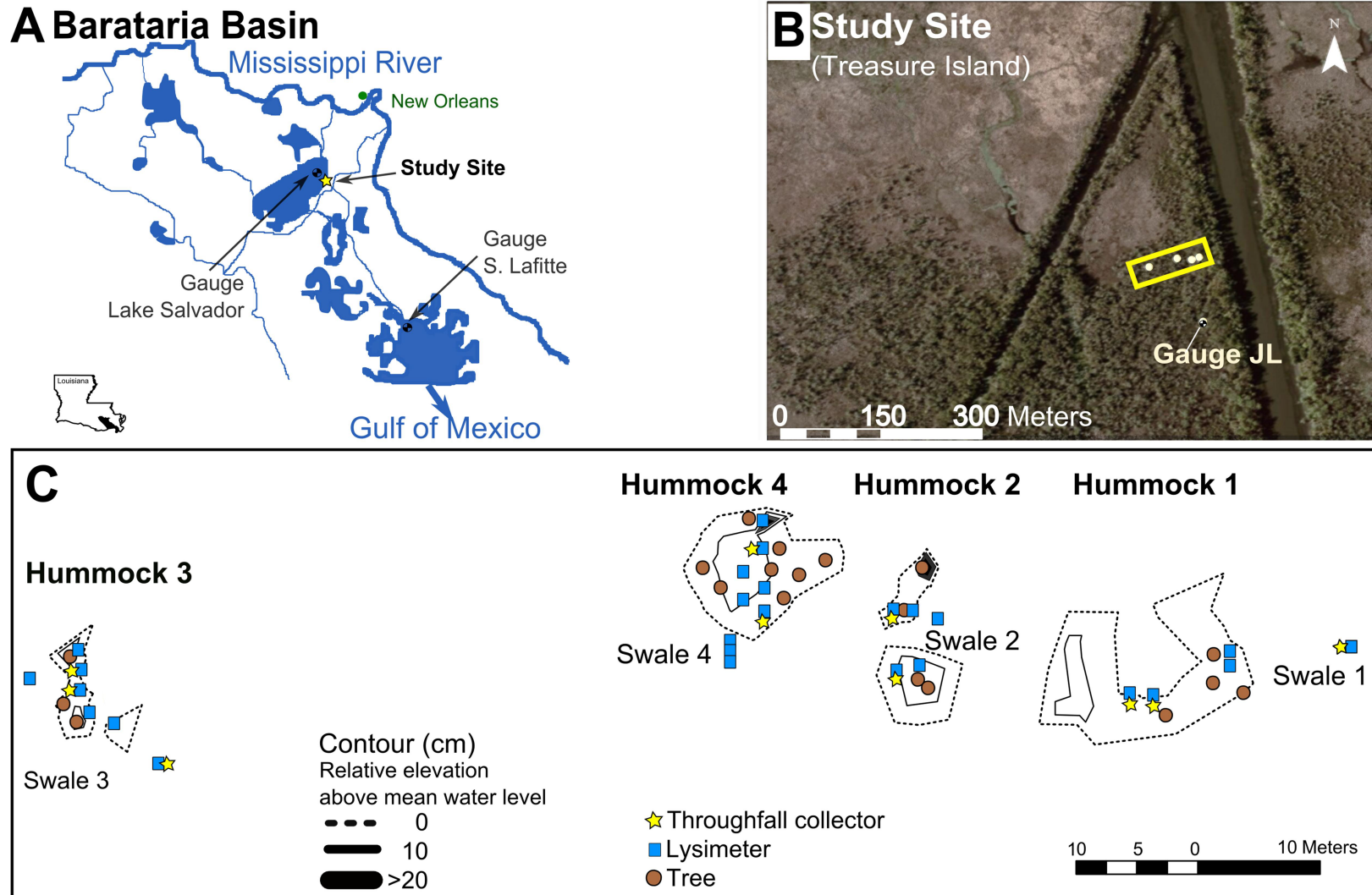


Figure 3-2. The study area: (A) Barataria Basin showing gauging stations; (B) Jean Lafitte National Historical Park and Preserve (Treasure Island); and (C) contour map of study hummocks, locations of trees, throughfall collectors, and lysimeters.

The site is characterized by occasional hydrologic connection to the Barataria estuary associated with rain events or high tides driven by wind (Krauss et al., 2009). The Barataria Basin experiences a micro-tidal influence from the Gulf of Mexico, and water level and salinity vary due to lunar and wind tides, lateral inflows, and rainfall in the Barataria Basin (Swarzenski, 2003; Habib et al., 2007; Inoue et al., 2008). Salinity increases seasonally during water deficit in the late spring (Sklar, 1983) and in the fall associated with accumulated ET and low discharge from the Mississippi River (Baumann, 1987). High salinity events are caused by occasional tropical cyclones (Conner et al., 2007) and by droughts that allow saltwater intrusion (Habib et al., 2007; Day et al., 2012). Total rainfall amount was 754 mm during April-1 to Oct-31 in 2011 sample period, compared to average 1006 mm during the same period between 1981 and 2010 (Daly et al., 1994; PRISM; www.prism.oregonstate.edu).

The soil is fine-textured, fluid muck, mapped by the USDA Soil Conservation Service as very-fine, smectitic, nonacid, hyperthermic Typic Hydraquents of the Barbary series. Organic matter is ~60% at the surface but declining with depth to mineral muck, and bulk density < 0.3 g/cm³ in the top 20 cm and generally < 1 g/cm³ throughout (Conner et al., 2007; Krauss et al., 2009; Jiang and Middleton, 2011). Hummocks are organic accumulations of detritus and living roots that contain frequent large internal voids above the mineral muck at their bases. Swales are highly fluid and the surface is a poorly defined transition from floating and suspended organic matter to fluid, organic-rich mineral muck.

Vegetation on hummocks comprises trees and shrubs, including baldcypress, *Morella cerifera*, *Triadica sebifera*, *Acer rubrum* var. *drummondii*, and *Sabal minor*. Floating and emergent herbaceous species occupy the swales, including *Sagittaria lancifolia*, *S. latifolia*,

Eleocharis fallax, *Sphagnum* spp., *Schoenoplectus americanus*, *Decodon verticillatus*, *Alternanthera philoxeroides*, *Polygonum punctatum*, and *Typha* spp. (Nolfo-Clements, 2006).

Water levels were recorded about 100 m from the study site with a water level recorder inserted approximately 1 m into the soil (Infinities USA, Port Orange, FL, USA) and reporting at hourly intervals (Figure 3-3, A). Salinity and water level data were obtained from USGS gauges in Lake Salvador (USGS 073802375) and Barataria Waterway (USGS 292859090004000) (Figure 3-3, A, B). Rainfall during the study was interpolated from nearby stations (Daly et al., 1994; PRISM; www.prism.oregonstate.edu).

Four hummocks were selected for measuring detailed site hydrology. Site topography was measured by topographic survey (TOPCON, Topcon Positioning Systems, Inc. Livermore, CA USA). Relative elevation was referenced to the mean water level in 2011 at the nearby water level recorder, which was estimated to be ~30 cm above mean sea level based on assuming equal water surface elevation at the study site and in nearby Lake Salvador during high water events (Figure 3-3, A). Hummocks were from 15 to 58 cm above mean water level (47-90 cm msl) and individual hummocks were 7.6 - 47.6 m² in area (Table 3-1). The approximate surface elevation of the swales was approximately 14 cm below the mean water level, or 18 cm msl. Jiang and Middleton (2011) measured swamp floor elevation nearby at ~10 cm msl.

3.4.2 Water sampling

Water samples were collected from surface water (SW) in swales and in the saturated zone beneath swales and hummocks (ground water, GW) using suction lysimeters. Lysimeters were 1.7 cm PEX[®] tubing, capped at the top and open at the sampling end but plugged with plastic scouring pad to prevent ingress of sediment. Lysimeters were installed by pushing them

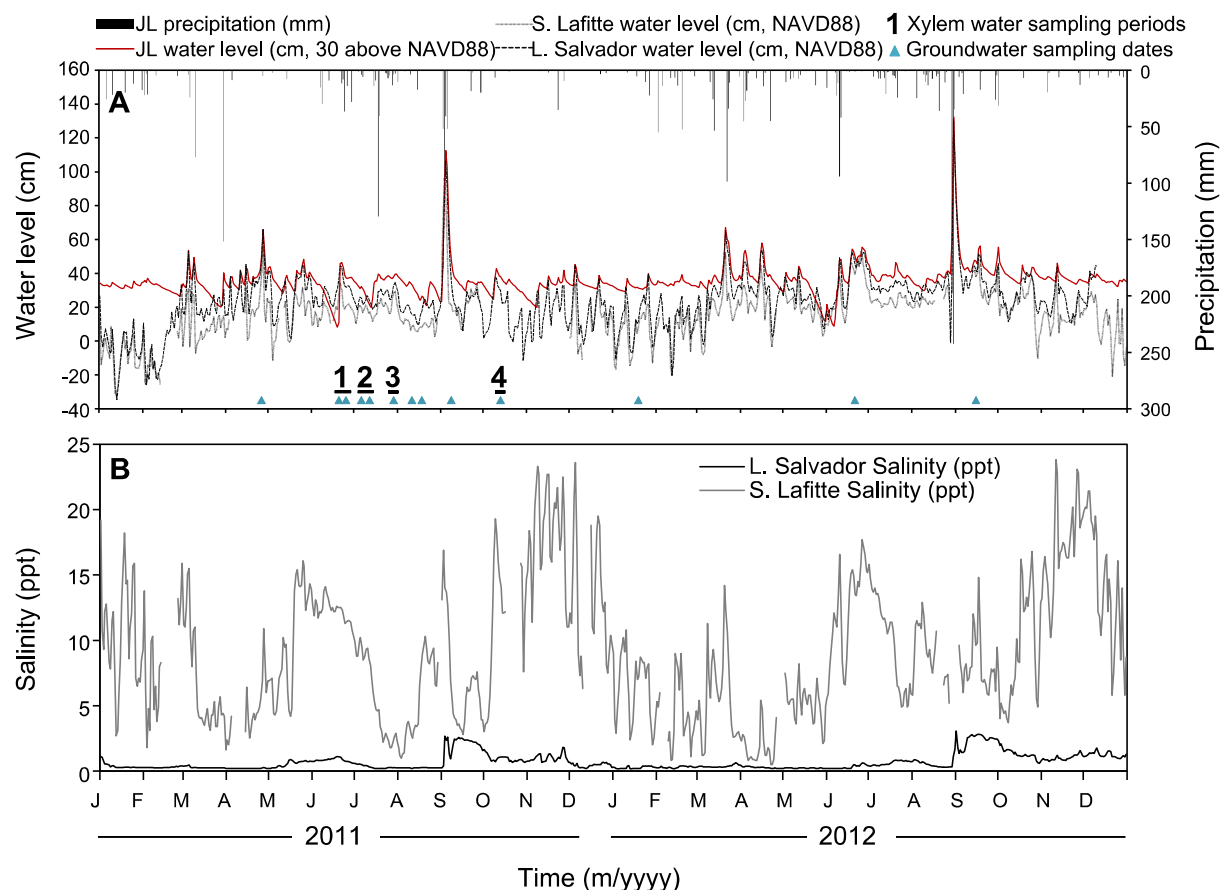


Figure 3-3.(A) Precipitation and water level of the study site and nearby water bodies in the Jean Lafitte National Park and Preserve in 2011 and 2012; (B) Salinity fluctuations in the Barataria waterway and Lake Salvador near Lafitte, LA.

Table 3-1. Characteristics of study hummocks in Jean Lafitte NHPP.

Hummock	Relative elevation (cm)		Area (m ²)	Time submerged (%)	
	Maximum	Mean		Completely	> 50% area
1	15	4	32	8	42
2	59	6	8	<1	30
3	20	6	10	5	11
4	40	13	48	1	31

into the soil using a cone-shaped steel rod. Using a hand pump, lysimeters were purged at a maximum suction of about 80 kPa before acquiring water samples. Lysimeters were installed at nominal depths of 10, 30, 60 and 90 cm below the relative mean water level. Four to six lysimeters were within each hummock depending on our ability to install lysimeters through

roots and undecomposed woody debris. At least one lysimeter was in each adjacent swale, depending on whether soil strength was sufficient to support installations (Figure 3-2).

Meteoric water was collected from 11 throughfall (TF) collectors on forested hummocks and above the water surface in swales. Each collector was 14 cm in diameter and contained 1 cm of mineral oil to avoid evaporation and isotopic fractionation of TF prior to analysis. All water samples were collected in 20 ml glass vials with zero headspace to prevent isotopic equilibration with headspace water vapor.

3.4.3 Analyses

We measured salinity of samples by proxy using electrical conductivity (EC300, YSI Inc. Yellow Springs, OH). Isotopic composition was analyzed using liquid water isotopic analyzer, LWIA (Los Gatos Research Inc. Mountain View, CA), which uses laser absorption spectroscopy. The values were transformed with reference to a Vienna Standard Mean Oceanic Water, $\delta = R_{\text{sample}} / R_{\text{standard}} - 1$, where δ indicates deviation from the standard, R_{sample} is the heavy isotope ratio ($^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$) of the sample, and R_{standard} is the heavy isotope ratio of the standard. Deuterium excess (d) was calculated by displacement from the Global Meteoric Water Line (GMWL, Dansgaard, 1964) as $d = \delta\text{D} - 8 \times \delta^{18}\text{O}$.

Laser spectroscopy is sensitive to contamination by organic compounds likely to exist in our samples (West et al., 2010), so a spectral contaminant identifier (Brian Leen et al., 2012) was used to flag likely problem samples; these were then analyzed by isotope-ratio mass spectrometry instead.

Sources of water to hummocks and their associated uncertainties were identified based on the mass balance of concentration of multiple tracers (Christophersen et al., 1990). We used a dual-tracer approach under a general mixing model based on mass balance of the tracer

concentration, where we assumed that source waters were (1) groundwater (as measured in swales), (2) throughfall, and (3) surface water. From this separation analysis, estimated values were tested whether they matched with original values for accuracy as to identify valid sources (Hooper et al., 1990). Uncertainties exist in the concentrations of tracers within each source and between sources (Meyer, 1975; Genereux, 1998) which may be reduced by applying standard error with large sample size (Phillips and Gregg, 2001). To model the uncertainty, the variance, ω_y^2 , of each tracer, y , was estimated from the contribution of the partial variance in that tracer from each source, x :

$$\omega_y^2 = \left(\frac{\partial y}{\partial x_1} \cdot \omega_{x_1}\right)^2 + \left(\frac{\partial y}{\partial x_2} \cdot \omega_{x_2}\right)^2 + \left(\frac{\partial y}{\partial x_3} \cdot \omega_{x_3}\right)^2.$$

The contribution of each source was then estimated with uncertainty (Appendix 7.2.1; Daly et al., 1994; Genereux, 1998).

3.5 Results

3.5.1 Hydrologic regime of the study site

Water levels in the study area rarely responded substantially to rainfall events; instead, high water events at the study site occurred in conjunction with high water events in the estuary in response to coastal wind and storms, including surges from two tropical cyclones (Figure 3-3, A). This surface connectivity to the estuary appeared to occur when the water level was more than ~5 cm above mean water level for the swamp (~35 cm msl). There was slow recession of water level between connectivity events, and low water in the study site occurred near the ends of long periods of low water in the estuary.

Water level remained within 5 cm of the mean 34% of the time during the study period. Hummocks were flooded from 2 to 27% of the time due to fluctuating water levels from -25.6 to

90.8 cm mwl (Table 3-1; Figure 3-4). Water level rose more than 5 cm above the mean 11% during this same period (Figure 3-4), and the majority of these events occurred when the water level in the estuary was also high. Thus, inundation of hummock tops normally occurred only when lateral connectivity with Lake Salvador was high.

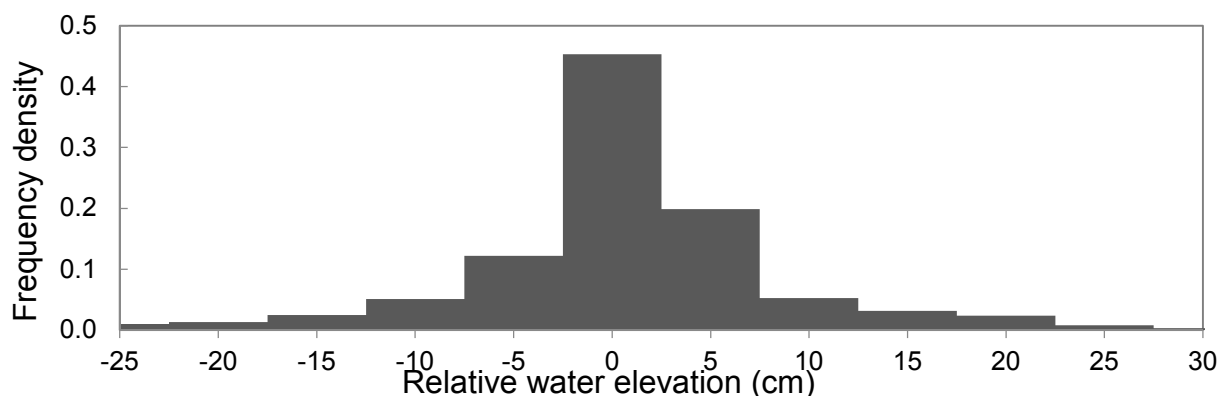


Figure 3-4. Frequency density of water level of Treasure Island study area, Jean Lafitte NHPP from 2011 to 2012. Relative elevation zero is mean over the entire period and is near 30 cm msl.

3.5.2 Salinity variation

Salinity of pore water in hummocks and swales was higher than throughfall and surface water throughout the experiment (Figure 3-5, E,M v.s. A, I; Table 3-2). There was generally a salinity gradient out of the soil into the water column; accordingly, salinity was generally slightly greater at depth in both hummocks and swales. Salinity in pore water in swales was slightly lower (mean 2.0 ppt) than in hummocks (mean 2.3 ppt).

Salinity of the soil and free water in the study site remained generally higher than in the neighboring open water of Lake Salvador, (Figures 3-5 column 1 v.s. 3-3, B). There was a salinity gradient out of the study site into Lake Salvador except during storm surge events and low water periods.

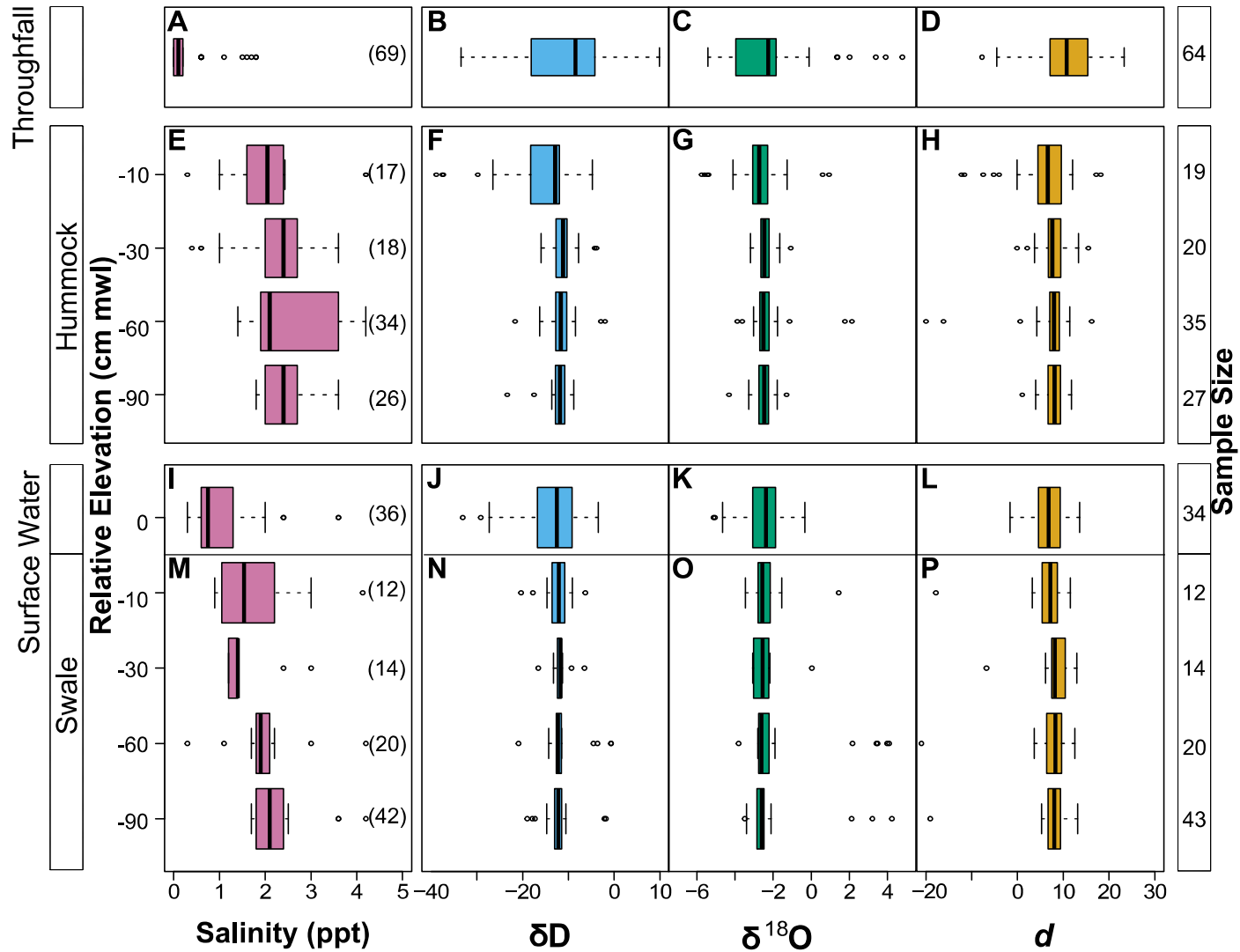


Figure 3-5. Salinity and stable isotopic composition of meteoric (row 1), surface (0 cm in row 3), and subsurface water in hummocks (row 2) and swales (row 4). Repeated measurements at the same locations and depth increments were pooled.

Table 3-2. Isotopic composition of selected water sources, April 2011 to September 2012.

Sources	Sample size	δD	$\delta^{18}O$	d	Salinity
		-----Mean \pm S.D. (‰)-----			Mean \pm S.D. (ppt)
Throughfall	64	-10.8 \pm 9.3	-2.7 \pm 1.7	11.2 \pm 9.4	0.5 \pm 6.3
Surface Water	34	-13.6 \pm 6.7	-2.6 \pm 1.0	7.0 \pm 3.8	-2.9 \pm 3.4
Groundwater in Swale	89	-12.0 \pm 3.6	-2.3 \pm 1.4	6.1 \pm 8.6	-2.7 \pm 3.4
Groundwater in Hummock	101	-11.8 \pm 3.0	-2.4 \pm 0.8	7.4 \pm 4.5	-1.9 \pm 2.1

3.5.3 Tracers of water sources to hummocks

Isotopic composition of water δD and $\delta^{18}O$ in the groundwater (GW) of hummocks were similar to those of swales: mean δD values were -11.8‰ and -11.9‰, respectively; mean $\delta^{18}O$ values were -2.2 ‰ and -2.4 ‰ respectively. Composition of groundwater did not vary by depth beneath the surface except the shallowest depth (-10 cm bin). Water in the shallowest samples was generally slightly more depleted in δD and $\delta^{18}O$, had slightly lower d-excess, and was slightly more temporally variable than deeper samples (Figure 3-5, column 2, 3).

3.5.4 Separation analysis of water sources

Deuterium and salinity dominated the first two components, respectively, of a principal components analysis of water chemistry for all samples in the study, and thus provide the best basis for source separation (i.e. better than any combinations that included $\delta^{18}O$ or d ; Figure 3-6). There was good separation among these sources in salinity, but less so in δD (Figure 3-7). Groundwater under hummocks was a mixture of approximately -30% throughfall, 99% surface water, and 31% groundwater when considered over the entire study. Negative estimated contribution of throughfall indicates a structural deficiency in the source analysis, in that the tracers and sources are not sufficient to constrain the observed composition of hummock water (Figure 3-7).

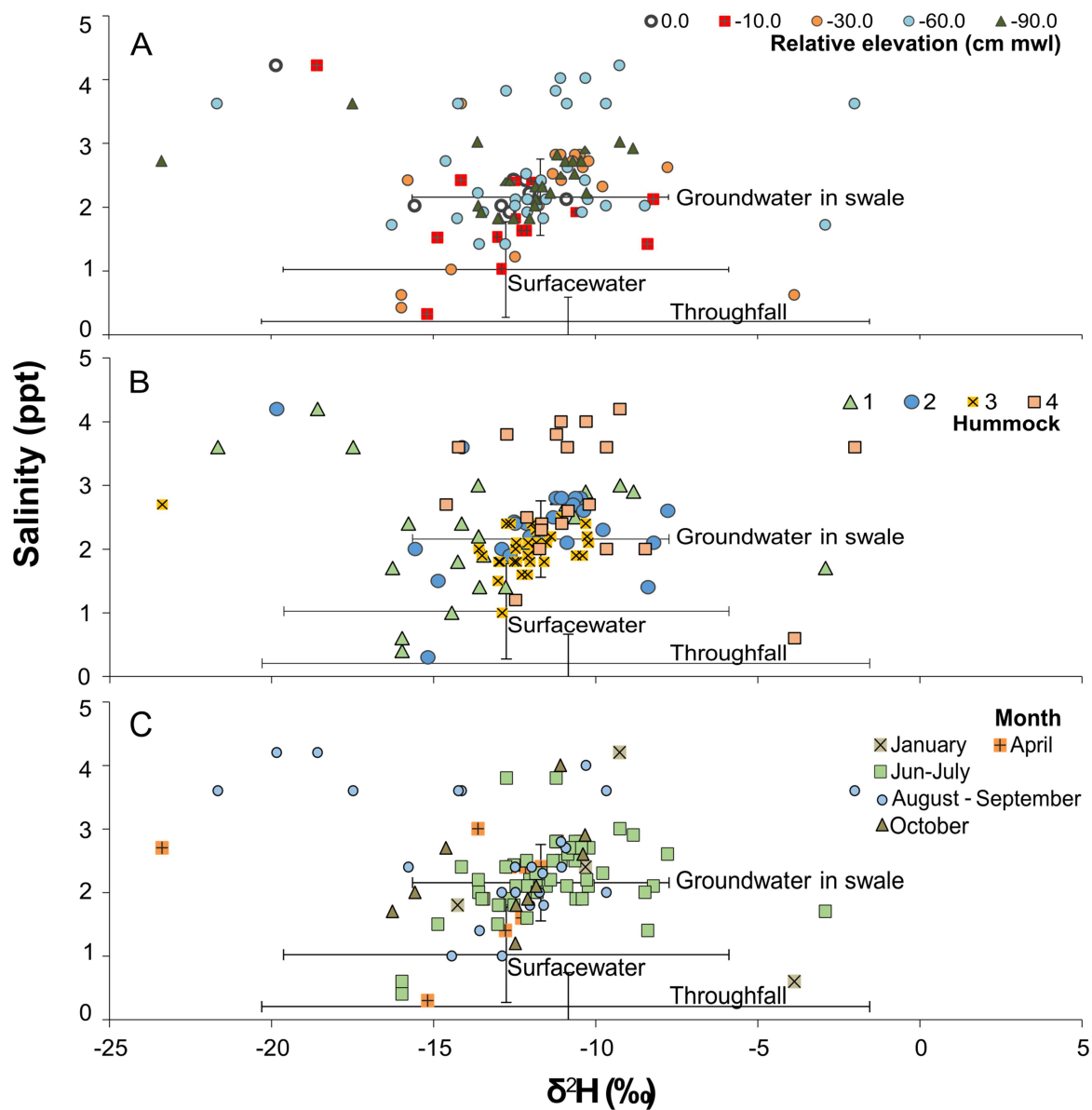


Figure 3-6. Salinity and deuterium of pore water in hummocks; vertical lines represent the standard deviation of salinity by water source and horizontal lines represent the standard deviation of deuterium by water source: grouped by (A) relative elevation, (B) hummock, and (C) time period.

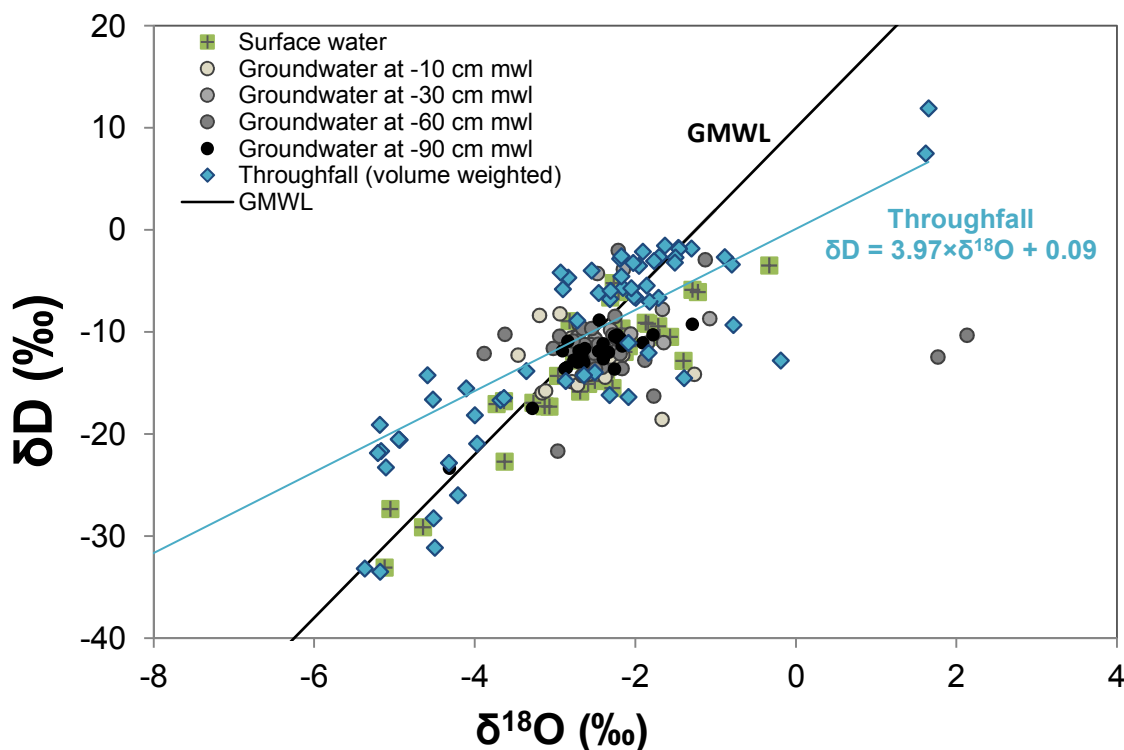


Figure 3-7. Isotopic composition of water sources, April 2011 to September 2012. GMWL is the global meteoric water line: $\delta\text{D} = 8 \times \delta^{18}\text{O} + 10$. “mwl” is mean water level.

3.6 Discussion

Water in both hummocks and swales maintained an upward gradient of salinity throughout the study, and groundwater salinity generally exceeded surface water salinity. Thus, vertical mixing in the shallow subsurface was apparently rare, flux exchange between hummocks and swales occurred only occasionally, and diffusion of salts toward the surface water dominated. Lower deuterium excess and salinity of the shallow soil water suggests evaporation is not causing high salinity in the surface soils. This is in contrast to other studies in which evapotranspiration enriched the isotopic composition of water and increased salinity in marshes (Wang et al., 2007; Tosatto et al., 2009).

Solute transport is slow under low flow conditions and in the permanently saturated groundwater zone under very low flow gradients (Hillel et al., 1998). Thus, salinity likely migrated through diffusion, suggesting a long residence time.

Although not measured in this study, previous work in the estuary suggests that salinity in the swamp originated from episodic saltwater intrusion during drought and storm surges (DeLaune et al., 1987; Battaglia et al., 2009; Day et al., 2012). Salinity readily increases under dry conditions in hummocks, and deeper in the soil than what is normally exposed (Figure 3-4). Once water levels recover, there is little mechanism for removal of these salts other than diffusion into the overlying water column and slow leaching by exchange of that water between the swamp and the open water of the estuary. Salinity in hummocks and swales appears to behave similarly to rooted vs. floating marsh as described by (Swarzenski and Swenson, 1994). In rooted marshes and hummocks there is greater variation in space and steeper vertical gradients in salinity. These patterns are consistent with less exchange between sediments and the water column in hummocks.

Salinity of Lake Salvador (the upper estuary near Treasure Island) did not fluctuate as much as the estuary farther south. This muted salinity is related to freshwater inputs from surrounding land, which has been shown to be important for maintaining low salinity in the upper Barataria Basin (e.g. Figure 3-3; Inoue et al., 2008). The Treasure Island study site is acting as part of that watershed by maintaining salinity lower than the estuary in general. Thus the baldcypress forest overall occupies a nonsaline site, but the episodic influx followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season.

In previous work, Baumann (1987) suggested precipitation has been suggested as the major freshwater input in this area. However, isotopic evidence from this study does not indicate that throughfall was a dominant source of water. The fluctuation in water level instead was closely associated with that of adjacent Lake Salvador during episodic periods of connectivity, and between periods of connection to the existing shallow water reservoir on the surface and near subsurface was sufficient to overwhelm rainfall events and remain dominant as the water source to hummocks.

3.7 Conclusions

Overall, salinity was slightly higher in groundwater in hummocks than in swales, but with substantial heterogeneity both within and among hummocks. The shallow subsurface of hummocks is a zone characterized by slow dilution and episodic salinization rather than slow salinization and episodic flushing. Rainfall and frequent inundation by generally low-salinity water flushed salts and maintained lower salinity in upper layers. Groundwater below 60 cm in hummocks and 30 cm in swales was essentially decoupled from surface water because the water level rarely drops below -15 cm. Thus the baldcypress forest overall occupies a nonsaline site, but the episodic influx followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season.

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CHAPTER 4. BALDCYPRESS AVOIDS THE COMBINED STRESSORS OF SALINITY AND FLOODING IN THE HUMMOCK AND SWALE TOPOGRAPHY OF COASTAL LOUISIANA

4.1 Abstract

Microtopographic variability in forested wetlands, especially in hummock and swale terrain, may mitigate salinity and flooding stressors in trees perhaps by altering access to fresh water. We examined sources of water using stable isotopes of water as tracers. We measured concentrations of ^2H and ^{18}O in the xylem of baldcypress (*Taxodium distichum* (L.) Rich.) and in the vadose zone (i.e. unsaturated root zone), ground water, surface water, and throughfall. . During the growing season hummocks were occasionally partially submerged but were completely submerged 1 to 6 % of the growing season by such events. Throughout the growing season, salinity in hummocks was greatest (~ 2.5 ppt) in the saturated zone below 30 cm was more variable near the surface. Mean salinity in the vadose zone was 0.7 ppt. Surface water and throughfall had similar isotopic composition and were less saline than groundwater. Low variation in groundwater salinity and isotopic composition suggested long residence time and limited exchange with surface water. Water taken up by the baldcypress (xylem water) had an isotopic signature similar to water in the vadose zone and unlike other measured sources. This study indicates that trees rely on hummocks as refugia from higher salinity environments in the flooded portions of hummocks and in the swales.

4.2 Introduction

Baldcypress (*Taxodium distichum* (L.) Rich.) is the most prevalent tree species within the coastal forested wetlands of the southeast coast of the U.S. that receives both tidal and riverine input (Conner and Day, 1988; Allen et al., 1996; Chambers et al., 2005). Baldcypress can tolerate low salinity, but salinity reduces regeneration success (Pezeshki et al., 1996; Krauss et

al., 1999, 2009). Clusters of baldcypress and its associates may adapt to tidal flooded wetlands even with occasional episodic saltwater intrusion (Day et al., 2007; Krauss and Duberstein, 2010). However, it is unknown why some baldcypress seem to be able to live in coastal swamps with chronic levels of salinity upon elevated areas, hummock-swale terrain (HST).

4.2.1 Responses of baldcypress to freshwater and saline flooding

Site conditions for baldcypress generally include frequent or extended flooding because it tolerates flooding, but it is replaced by less tolerant species in less flooded conditions.

Adaptations to flooding enable baldcypress to tolerate flooding without major growth decreases (Allen et al., 1996; Oren et al., 1999; Krauss et al., 2009, 2012). Thus, baldcypress is considered a flood-tolerant species, but long-term, stagnant flooding is a stressor (Pezeshki, 1991; Pezeshki et al., 1996; Anderson and Pezeshki, 2001).

Aside from flooding, coastal baldcypress often experience stress from salinity. However, the limits of salinity tolerance vary by life stage. Several studies have suggested that baldcypress seedlings tolerate low levels of salinity (up to 4 ppt) (Pezeshki, 1990; Allen et al., 1994, 1997; Conner, 1994; Krauss et al., 1999). Studies of responses to salinity by mature trees are limited because it is difficult to measure salinity in conjunction with flooding and other stressors needed to quantify overall growth conditions, and plant growth is not a simple, additive response to multiple stressors (Niinemets, 2010). In coastal areas the spatial distribution of baldcypress generally follows variations in mean soil pore water salinity, with forests generally occupy soils with less than 2-3 ppt salinity (Krauss et al., 2007). Baldcypress can survive pulses of greater salinity, such as 21 ppt after tropical storm surge (Conner and Inabinette, 2003). Even when hydrological variation compensates for flooding stress (such as soil aeration in HST; Duberstein et al., 2013), salinity stress often remains a stressor.

4.2.2 Shift of water use in trees

Trees root systems exploit needed resources depending on availability of advantageous conditions (e.g. White et al., 1985). Baldcypress in coastal wetlands, which experience multiple stressors and occupy a varying environment, may systematically exploit favorable soils. Non-halophytes, such as baldcypress, do not have a known mechanism to exclude salt, so water source selection may occur by selective root occupation of favorable sites. It remains unclear whether baldcypress can persist in chronically semi-saline, flooded wetlands by enduring unfavorable conditions or through avoidance by using other water sources.

Frequently, coastal baldcypress are located on hummocks in hummock-swale topography (Huenneke and Sharitz, 1986), but it is not clear whether this preferential occupation in coastal wetlands is caused by flooding, salinity, or both. In hummock-swale topography, there is an interaction between salinity and flooding because of complex hydrologic patterns (Chapter 3). Thus, HST geomorphology may affect baldcypress survival.

4.2.3 Water sources of plants

Stable isotopes of water are a method for identifying source water for plants (Roden et al., 2000; Stratton et al., 2000; Dawson et al., 2002; Sekiya and Yano, 2002; Schoonmaker et al., 2007) because the xylem most often passively transports water from the soil matrix to the leaves in response to water potential gradient. While both relative humidity and air temperature influence the fractionation of water in the leaves, such changes do not occur with water uptake from root to shoot along xylem conduits. Hence, xylem sap is relatively consistent along the path and reflects the water sources to roots (Washburn and Smith, 1934; Dawson and Ehleringer, 1991, 1993; Walker and Richardson, 1991; Ehleringer and Dawson, 1992; Thorburn et al.,

1993). By measuring the isotopic composition of water in the xylem and multiple potential sources of water in the environment, the tree water use can be identified.

4.3 Objectives

Our general objective for this study was to determine the sources of waters available to and used by baldcypress on coastal swamp hummock-swale topography in an attempt to explain continued existence in areas of higher salinity on hummock-swale topography.

4.4 Methods

4.4.1 Approach

We used a two-isotope approach under a general mixing model, where we assume the water available to baldcypress is soil water from the vadose zone, groundwater, and throughfall. We sampled water from these sources and from tree xylem to determine the water sources to trees.

4.4.2 Study site

This study took place in Jean Lafitte National Historical Park and Preserve of Barataria Basin, between Lake Salvador and Bayou Segnette, in the Barataria Basin of Louisiana, USA (29.756 N, 90.146 W; Figure 4-1). Site elevation is less than 0.5 m msl (Jiang and Middleton, 2011) near the transition between forested, baldcypress (*Taxodium distichum* (L.) Rich) swamp and non-forested marsh and ~100 m from the site characterized previously (Krauss et al., 2009). The site is on young, deltaic sediments and subsiding at a rate of approximately 3-5 mm/y (Lane et al., 2006) from compaction of shallow, deltaic deposits (Törnqvist et al., 2008).

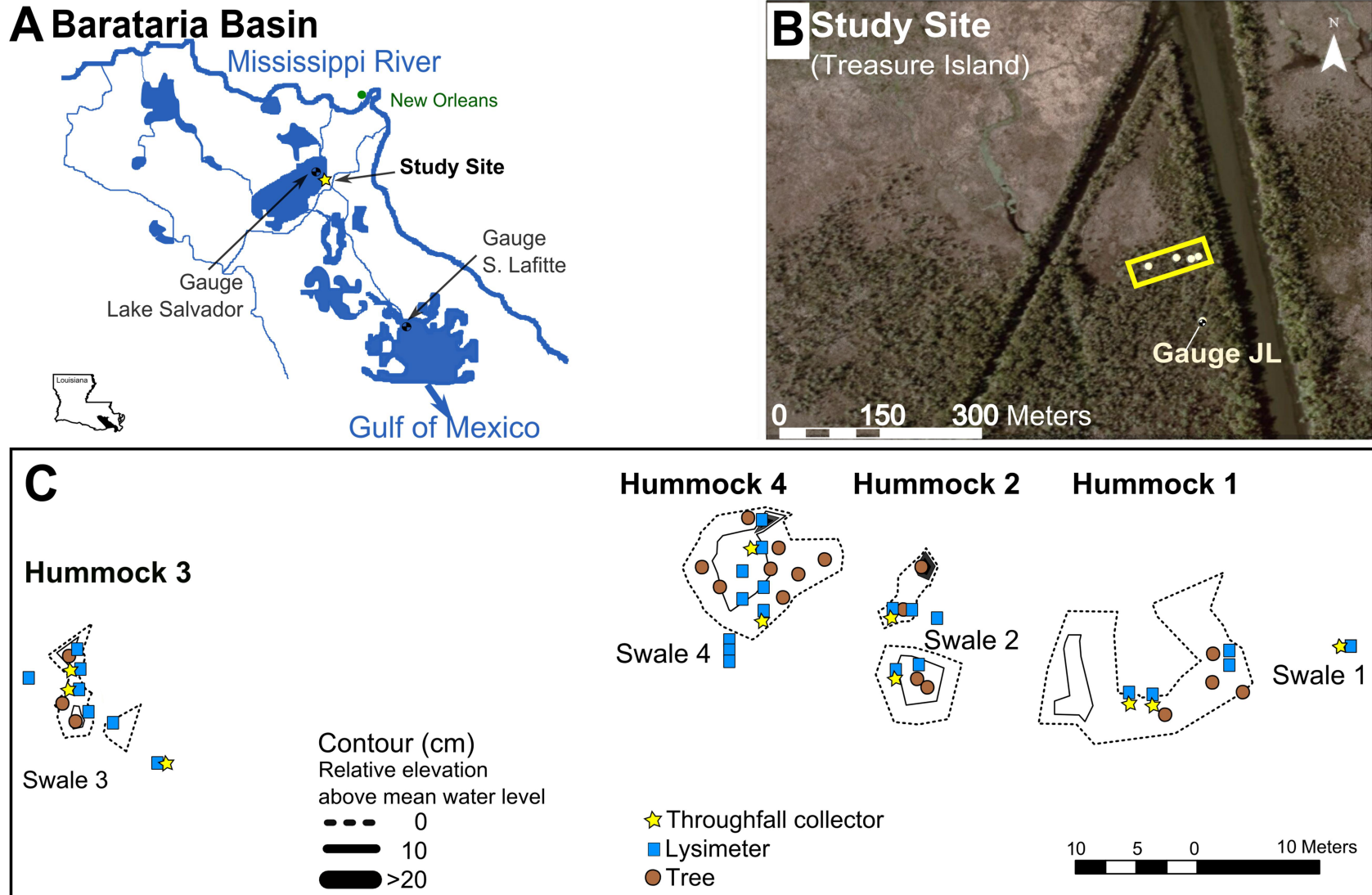


Figure 4-1. The study area: (A) Barataria Basin showing gauging stations; (B) Jean Lafitte National Historical Park and Preserve; and (C) contour map of study hummocks, showing locations of trees, throughfall collectors, and lysimeters.

The site is characterized by occasional hydrologic connection to the Barataria estuary associated with rain events or high tides driven by wind (Krauss et al., 2009). The Barataria Basin experiences a micro-tidal influence from the Gulf of Mexico, and water level and salinity vary due to lunar and wind tides, lateral inflows, and rainfall in the Barataria Basin (Swarzenski, 2003; Habib et al., 2007; Inoue et al., 2008). Salinity increases seasonally during water deficit in the late spring (Sklar, 1983) and in the fall associated with accumulated ET and low discharge from the Mississippi River (Baumann, 1987). High salinity events are caused by occasional tropical cyclones (Conner et al., 2007) and by droughts that allow saltwater intrusion (Swarzenski, 2003; Habib et al., 2007; Inoue et al., 2008). Total rainfall amount was 754 mm during April-1 to Oct-31 in 2011 sample period, compared to average 1006 mm during the same period between 1981 and 2010 (Daly et al., 1994; PRISM; www.prism.oregonstate.edu). The soil is fine-textured, fluid muck, mapped by the USDA Soil Conservation Service as very-fine, smectitic, nonacid, hyperthermic Typic Hydraquents of the Barbary series. Organic matter is ~60% at the surface but declining with depth to mineral muck, and bulk density $< 0.3 \text{ g/cm}^3$ in the top 20 cm and generally $< 1 \text{ g/cm}^3$ throughout (Krauss et al., 2009; Jiang and Middleton, 2011). Hummocks are organic accumulations of detritus and living roots that contain frequent large internal voids above the mineral muck at their bases. Swales are highly fluid and the surface is a poorly defined transition from floating and suspended organic matter to fluid, organic-rich mineral muck.

Vegetation on hummocks comprises trees and shrubs, including baldcypress, *Morella cerifera*, *Triadica sebifera*, *Acer rubrum* var. *drummondii*, and *Sabal minor*. Floating and emergent herbaceous species occupy the swales, including *Sagittaria lancifolia*, *S. latifolia*,

Eleocharis fallax, *Sphagnum* spp., *Schoenoplectus americanus*, *Decodon verticillatus*, *Alternanthera philoxeroides*, *Polygonum punctatum*, and *Typha* spp. (Nolfo-Clements, 2006).

Water levels were recorded about 100 m from the study site with a water level recorder inserted approximately 1 m into the soil (Infinities USA, Port Orange, FL, USA) and reporting at hourly intervals (Figure 4-2, A). Salinity and water level data were obtained from USGS gauges in Lake Salvador (USGS 073802375) and Barataria Waterway (USGS 292859090004000) (Figure 4-2, A, B). Rainfall during the study was interpolated from nearby stations (Daly et al. 1994; PRISM; www.prism.oregonstate.edu).

Four hummocks were selected for measuring detailed site hydrology. Site topography was measured by topographic survey (TOPCON, Topcon Positioning Systems, Inc. Livermore, CA USA). Relative elevation was referenced to the mean water level in 2011 at the nearby water level recorder, which was estimated to be ~30 cm above mean sea level based on assuming equal water surface elevation at the study site and in nearby Lake Salvador during high water events (Figure 4-2, B). Hummocks were from 15 to 58 cm above mean water level (47-90 cm msl) and individual hummocks were 7.6 - 47.6 m² in area (Table 4-1). The approximate surface elevation of the swales was approximately 14 cm below the mean water level, or 18 cm msl. (Jiang and Middleton, 2011) measured swamp floor elevation nearby at ~10 cm msl. The approximate surface elevation of the swales was approximately 14 cm below the mean water level, or 18 cm msl. Hummocks were flooded up to 4% of the time due to fluctuating water levels from -25.6 to 90.8 cm (Figure 4-2).

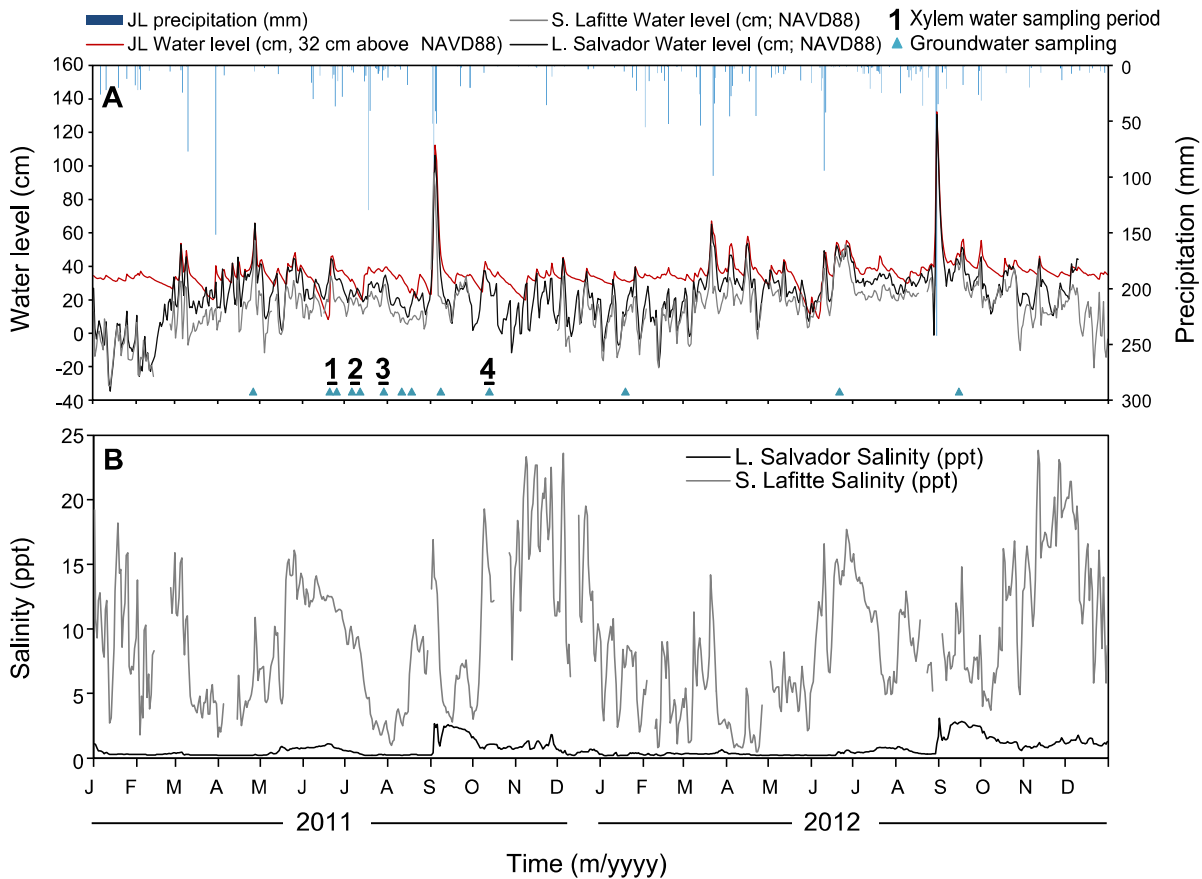


Figure 4-2. Precipitation and water level of the study site in the Jean Lafitte National Park and Preserve in 2011.

Table 4-1. Characteristics of hummocks and the sampled baldcypress.

Hummock	Maximum height of hummock ¹ (cm)	Hummock ² area (m ²)	Number of trees (n)	Tree height (m)	Crown ² area (m ²)	DBH (cm)
				Mean \pm S.D.		
1	15.0	31.7	4	20 \pm 3	21 \pm 5	30 \pm 7
2	58.5	7.6	3	16 \pm 3	8 \pm 8	22 \pm 5
3	19.7	9.8	1	24 \pm n.a.	22 \pm n.a.	22 \pm n.a.
4	40.0	47.6	5	24 \pm 4	23 \pm 12	27 \pm 4

¹ Relative height of each hummock was compared with the mean water level during April – November 2011.

4.4.3 Field Measurements

Baldcypress sample trees included all baldcypress trees on Hummocks 1, 2, and 3, and the five largest baldcypress on Hummock 4. For all sampled trees, we measured diameter, sapwood area, tree height, and vertical crown length (Table 4-1).

Ground water (GW), vadose zone water (VW), surface water (SW), and throughfall were sampled across the growing season during four sample periods (Figure 4-2, A). Data were pooled across the growing season to quantify range and variability of source waters for use by trees. Suction lysimeters were used to collect groundwater samples at various depths (10, 30, 60 and 90 cm) with respect to the relative mean water level (30 cm higher than the seawater level). Lysimeters were 1.7 cm PEX[®] tubing, capped at the top and open at the sampling end but plugged with plastic scouring pad to prevent ingress of sediment. Lysimeters were installed by pushing them into the soil using a cone-shaped steel rod. Using a hand pump, lysimeters were purged at a maximum suction of about 80 kPa before acquiring water samples. We deployed four to six lysimeters within each hummock depending on our ability to install lysimeters at specified depths. We deployed a least one in each adjacent swale depending on whether soil strength was sufficient to support installations (Figure 4-1). We measured salinity of all soil water and throughfall samples by proxy using electrical conductivity (EC300, YSI Inc. Yellow Spring, OH). Within each hummock, we collected soil samples at 10 cm depth when the soil was not saturated in the vadose zone. Soil samples were stored in glass vials, kept on ice; brought back to the lab and frozen for later cryogenic distillation and salinity analysis. After cryogenic distillation analysis were completed, soil samples were dried at 105°C, then meshed, and soaked in water equal to 20 times the weight of the dry soil. Total soluble salinity of the resulting

solution was measured by proxy using electrical conductivity (EC300, YSI Inc. Yellow Spring, OH; Rhoades et al., 1989).

Surface water (SW) was free water collected in swales whenever that occurred. Meteoric water was collected from 11 throughfall (TF) collectors on forested hummocks and above the water surface in swales. Each collector was 14 cm in diameter and contained 1 cm of mineral oil to avoid evaporation and isotopic fractionation of TF prior to analysis. All water samples were collected in 20 ml glass vials with zero headspace to prevent isotopic equilibration with headspace water vapor.

4.4.3.1 Xylem water samples

Xylem water was used to assess the source of water use by baldcypress. Across the growing season, we sampled xylem water from 15 baldcypress trees in four sample events (Figure 4-2). Sapwood and heartwood tissues were pooled for each sample to help obtain enough water for analysis. A total of 41 samples were collected. To sample xylem water, cores were taken from each sampled tree. Cores were taken using a 5.15 mm increment borer; bark, cambium, and phloem tissue were discarded. All samples were sealed and transported to the lab for later cryogenic extraction of water.

4.4.3.2 Water extraction from xylem and soil samples

Water in the xylem tissue and soil samples was extracted using cryogenic vacuum distillation (CVD), following the procedures detailed by (Ehleringer and Osmond, 1989; Ehleringer et al., 2000; West et al., 2006). Samples were heated above 100°C in a 90-milliTorr vacuum using a hot saline water bath. Vapor condensed by cooling with liquid nitrogen (−196°C). Water samples were then collected upon thawing. This extraction apparatus was made

to reduce the leakage and condensation along the transfer tube, by using a U-shaped tube in the liquid nitrogen (Chapter 5). With this design, mean extraction efficiency (percent extracted) was $98 \pm 2\%$. Maximum extraction efficiency was achieved within 5 hours of onset of heating (West et al., 2006). We added activated charcoal to samples to reduce later analytical errors from volatile organic compounds (West et al., 2006; Chapter 5).

4.4.4 Analysis of isotopic composition

Isotopic composition of ^{18}O and D (deuterium) in water samples from all sources were analyzed using laser-absorption spectroscopy (DLT-100, Los Gatos Research Inc. Mountain View, CA). When the ablation spectrum indicated contamination with methanol or ethanol (Brand, 2010; Schultz et al., 2011), water, samples were also analyzed using isotope ratio mass spectroscopy (Thermo Delta V Advantage).

Errors could come from distillation, volatile organic carbon in samples, and application of activated carbon, which we found to be negligible (Chapter 5). The largest source of error is likely isotopic fractionation from incomplete extraction and exchange in wood or soil, but these were minimized by high fraction of mass recovery (Chapter 5).

Results were converted to $\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$, in which δ indicates the deviation of ^{18}O or ^2H from Vienna-Standard Mean Ocean Water (VSMOW) (Gonfiantini et al., 1993), R_{sample} is the isotope ratio ($^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$) of the sample, and R_{standard} is the isotope ratio of the standard. Deuterium excess (d) was calculated by displacement from the global meteoric water line (GMWL), $d = \delta\text{D} - 8 \times \delta^{18}\text{O}$; variations in d help distinguish water sources because they arise from non-equilibrium evaporation and condensation (Dansgaard, 1964).

4.5 Results

4.5.1 Water levels

Water level at the site fluctuated between -18 cm and 81.7 cm above mean water level (mwl; Figure 4-2, A). During the growing season, water level remained between 0 and 5 cm 48% of the time. Comparatively, water level exceeded 5 cm only 9% of the 2011 growing season. Water level of the study site was synchronized with that of Lake Salvador when the lake water level exceeded 35.7 cm msl and there was no consistent correlation between precipitation and site water level fluctuations (Chapter 3).

4.5.2 Salinity variation of the hummock-swale terrain

Salinity in the unsaturated portion of the hummocks (vadose zone) was 0.7 ± 0.4 ppt (Figure 4-3, H). Within the normally saturated portion of hummock soil, the mean pore water salinity at -10 cm mwl was 1.4 ppt, while the mean salinity of the entire saturated portion of the hummock soil was 1.9 ppt (Figure 4-3). Mean surface water salinity in the surrounding swales was 1.2 ppt (Figure 4-3), while mean salinity within the soils of swales was 1.8 ppt (Figure 4-3, T). Salinity generally increased with depth (Figure 4-3, L, T). The mean salinity of the throughfall samples was 0.2 ppt (Figure 4-3, A).

4.5.3 Water sources for baldcypress

Variations in stable isotopic (δD , $\delta^{18}O$, and d) compositions of throughfall, xylem water, and vadose water were large relative to groundwater (Figure 4-4). Stable isotopic composition of groundwater of hummocks and swales was similar to each other, was less varied than surface water, and generally on the mwl. Vadose zone water was distinct from other water sources, lying generally below the mwl (Figure 4-4) and with lower d .

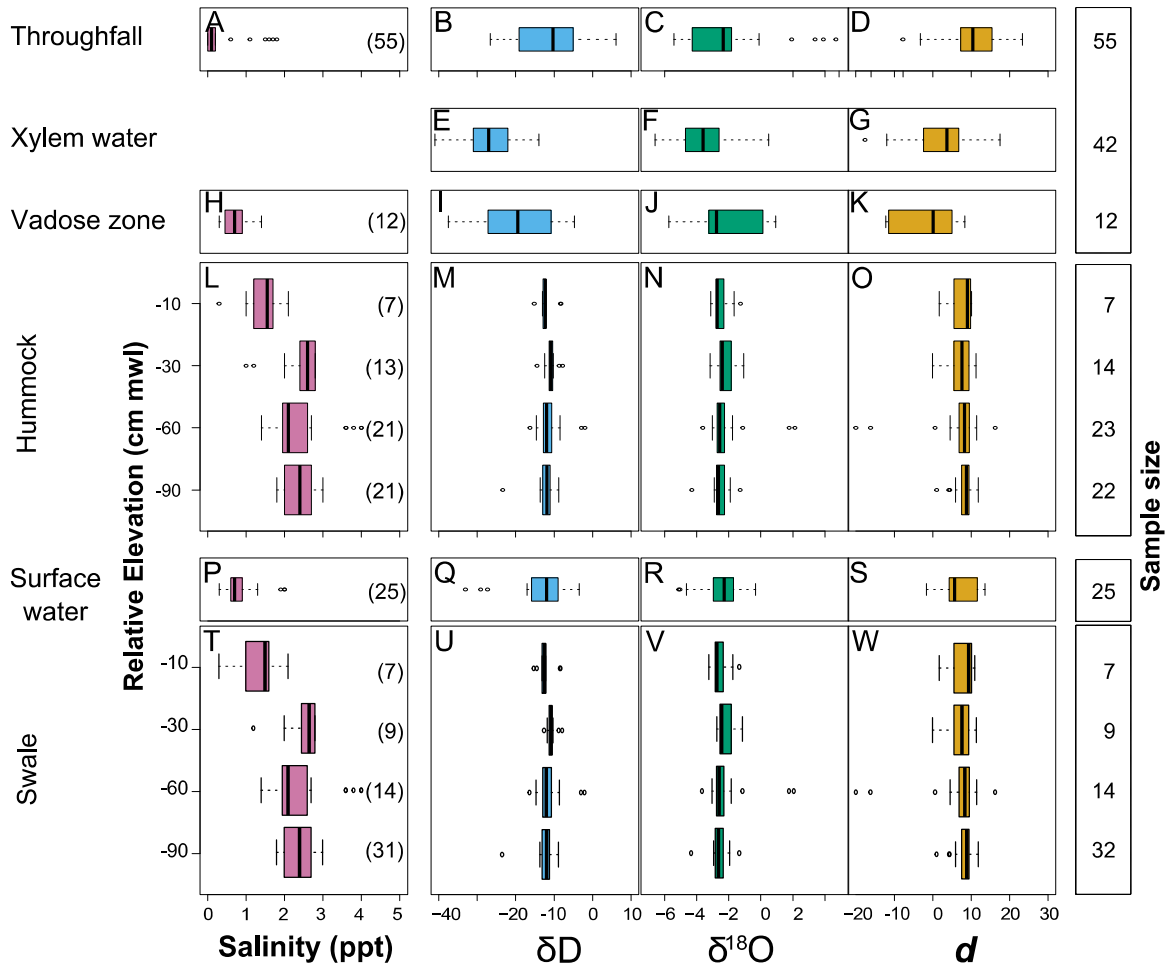


Figure 4-3. Salinity and stable isotopic composition of throughfall (row 1), xylem water (row2), porewater from vadose zone (row3), surface water (row 5), and groundwater from hummocks (row 4) and swale (row 6). Repeated measurements on the same spatial locations as well as same soil depth increment were pooled. Box number on the right indicates sample sizes; numbers in parentheses represent sample size for salinity. Each box shows median and interquartile ranges, as well as outliers (circles). Samples were collected during April to October, 2011 in Treasure Island, Jean Lafitte NHPP, LA.

Isotopic composition of xylem water (XW) was more like VW than any other measured water sources at the site (Figure 4-4). Deuterium excess (d) of VW and XW were also generally lower than d of SW, GW, and TF sources, but similar to each other (Figure 4-4).

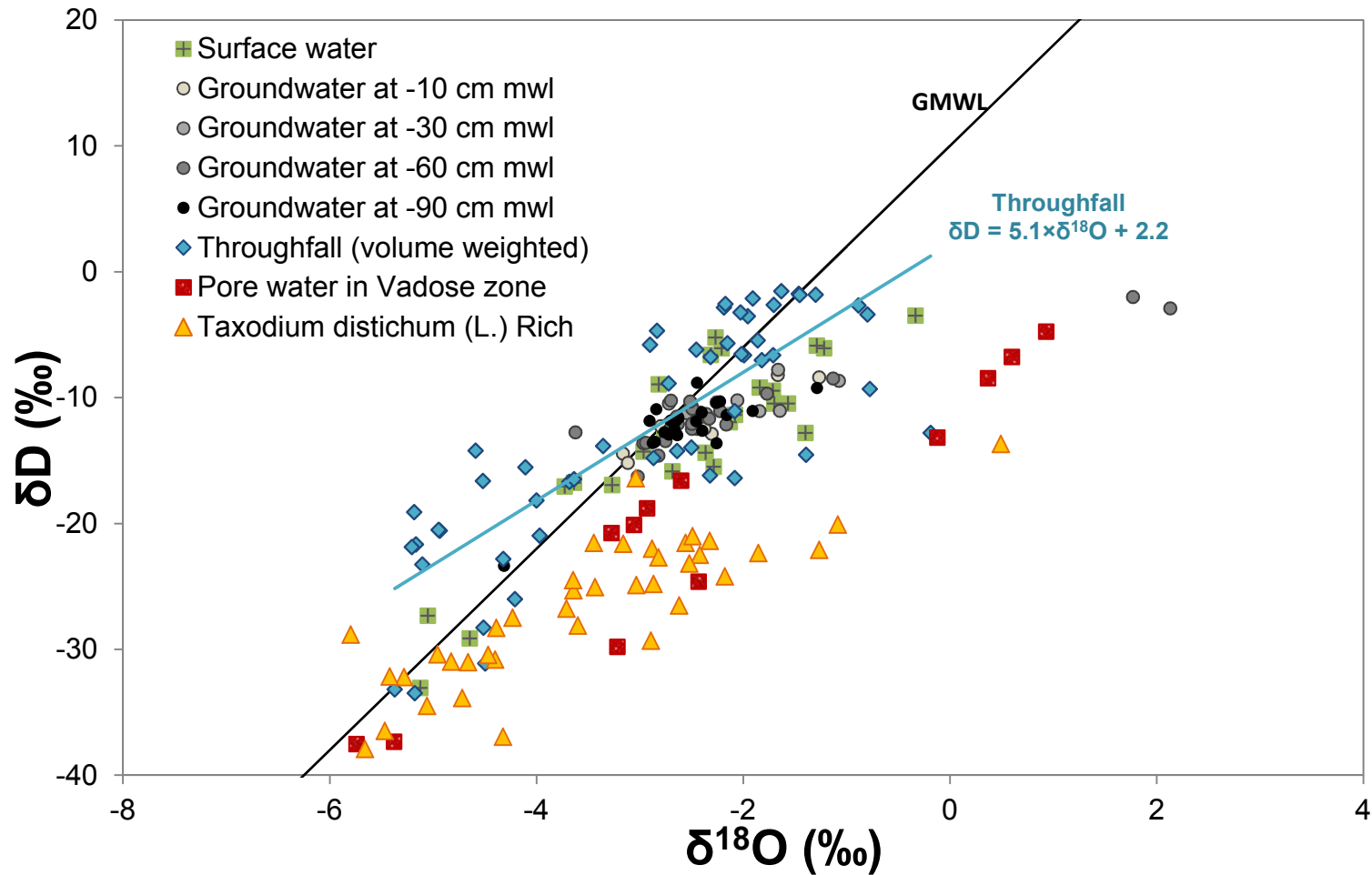


Figure 4-4. Isotopic composition of several water sources throughout sampling seasons, April to October 2011 including surface water, volume weighted-throughfall, xylem water of baldcypress, pore water of hummocks in vadose zone and saturated zone (relative elevation -10 to -90 cm from mean surface water level of the entire data). Global Meteoric Water Line (GMWL; $\delta D = 8 \times \delta^{18}O + 10$, Dansgaard 1964).

4.6 Discussion

4.6.1 Water sources for baldcypress in HST

Xylem water stable isotopes were more similar to water in the vadose zone (non-saturated zone of the hummock) than other measured water sources. Although there is some minor overlap in isotopic composition of XW with that of throughfall and surface water, most of the XW samples are outside the range of anything observed in those sources. Therefore baldcypress on hummocks appear to use water primarily from the vadose zone.

The isotopic composition of VW, and thus XW, is difficult to interpret physically. Simple evaporation and condensation of other measured water pools is not sufficient to explain deviation mainly as lower δD and similar $\delta^{18}O$ from other samples. A similar deviation was observed by (Brooks et al., 2010) and interpreted as derived from evaporation of isotopically light precipitation that was preferentially retained because of its timing at the end of the dry season. It is possible that we observed a similar process, by which the soils retain some distinctly light precipitation that is subsequently modified by evaporation. However, we have no data to suggest this is likely, and can only conclude that the isotopic composition of VW is a complex result of some combination of selective retention by soils, evaporation, diffusion, and condensation.

In our study we combined heartwood and sapwood samples to capture enough water for isotopic analyses. The most likely effect of combining sapwood and heartwood samples in our study is to mute measured temporal variation in isotopic composition in xylem water, and to measure the integrated isotopic regime of growing conditions. (Ritchie and Hinckley, 1971) suggested that during droughts and subsequent wetter periods differences in contribution of exchange of water between the sapwood and heartwood can occur, and that trees integrate water sources depending on soil water availability over the season. White et al. (1985) found no

difference in δD in sapwood and heartwood of baldcypress from three swamp sites in Arkansas. The degree of exchange between sapwood and heartwood remains unclear for baldcypress especially under less flooded environments or saline flooding. In this study, we extend the scope to long-term response of baldcypress which may have included variation from radial exchange.

At the Jean Lafitte site increased soil salinity in deeper zones does not likely influence the bulk of the active fine roots that are restricted to the higher elevation and less frequently saturated part of the hummocks. Vadose zone salinity was low and it remained unsaturated for the majority of the growing season, which appears to have created the most favorable conditions for roots. Similarly, Colón-Rivera et al. (2014) suggested that roots of *Pterocarpus officinalis* were concentrated in the shallow soil on hummocks and that water uptake was mostly from this zone.

4.6.2 Avoidance of high salinity in hummocks

The use of VW by baldcypress in HST topography on our site appears to be the mechanism by which it avoids salinity and flooding stresses in the soil below hummocks and swales. In general, roots of trees in forested wetlands are known to occupy the shallow soil (e.g., (Jones et al., 2000)), and the same is apparently true in hummocks. At our study site, the hummocks were composed mainly of organic matter with very high concentration of living roots. The results of this work suggest that roots within the vadose zone of the hummock provide the primary uptake of water for baldcypress and that concentration of root growth in the hummocks is a feedback between the trees and their growing environment whereby the maintenance of hummocks by high root growth also provides a favorable environment for the trees.

The shallow subsurface of hummocks is a zone characterized by slow dilution and episodic salinization rather than slow salinization and episodic flushing (Chapter 3). Rainfall and

frequent inundation by generally low-salinity water flushed salts and maintained lower salinity in upper layers. The baldcypress forest overall occupies a nonsaline site, but the episodic influx followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season.

The fact that baldcypress growing on hummocks did not use the groundwater suggests it can avoid salinity and flood stresses at least for large portion of time. Historically, baldcypress is intolerant to chronic saline flooding at higher than 2 ppt, which is a threshold less than mean groundwater salinity of 2.5 ppt at the study site. Baldcypress may be restricted to the upper part of hummocks because higher salinity only involves short-term salinity pluses that are survivable by baldcypress.

4.6.3 Role of hummocks in sustainability of coastal forested wetlands

While baldcypress on the hummocks in our study are currently able to access freshwater in the vadose zone, continued local subsidence and sea level rise will likely increase flooding and salinity in the long term and eventually reduce the sustainability of baldcypress.

Microtopography in the coastal zone of the Mississippi Delta makes prediction of HST forest sustainability difficult. The subsidence rate at this site due to compaction of sediments is about 3 to 5 mm/yr (Lane et al., 2006). Combined with eustatic sea level rise predicted to be 4 mm/yr (Church et al., 2013), relative sea level rise is likely to be 7 to 9 mm/yr during the next century. Maintenance of hummocks in a subsiding environment depends on continued accretion, which Kirwan et al. (2010) estimated is likely insufficient to maintain marshes in a low-sediment, micro-tidal estuarine wetland experiencing such high relative sea level rise. We do not yet fully understand the process of hummock formation, how it compares to marsh accretion, and how changes in salinity and flooding alter the rates. Baldcypress in our study site may owe their

existence to the hummocks, but hummock formation in a subsiding delta may not be rapid enough for long-term sustainability of forests.

4.7 Conclusions

Stable isotopes in xylem water of baldcypress were more similar to water in the vadose zone than in other measured water sources. Baldcypress on hummocks appear to use water from the vadose zone where the majority of roots were apparently located and thus could avoid salinity and flooding stresses. Overall the baldcypress forest on our site occupies a nonsaline site, but the episodic influx followed by slow leaching occurs superimposed on a layer of salinity that lies presumably beneath the root zone for most of the growing season. Hummocks may represent short-term refugia, from where local subsidence and sea-level rise will continue to increase exposure to both flooding and salinity.

4.8 References

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CHAPTER 5. TRACING WATER IN COASTAL WETLAND SOILS AND TREES USING LASER SPECTROSCOPY: ERRORS IN CRYOGENIC VACUUM DISTILLATION

5.1 Abstract

Stable isotopes of water have proven useful for identifying water sources for trees in many environments. But application of this technique in coastal wetlands requires greater experimental precision than in some other cases because of small variation in isotopic composition. In a forested wetland of the Mississippi River delta, we used isotopes in sapwood water to distinguish baldcypress trees water use from among sources in hummocks and swales. Cryogenic vacuum distillation (CVD) was applied to extract water from soil and wood samples. Several controlled tests were used to test efficiency, accuracy, and precision of this modified CVD system and analysis using a liquid water isotope analyzer from Los Gatos Research Inc. Results of liquid water extractions showed deviation following the theoretical slope at an offset for ^{18}O , but at a lower slope for ^2H . Error from applying activated carbon in deionized water was -0.8‰ in $\delta^2\text{H}$ and -0.4‰ in $\delta^{18}\text{O}$, which were within internal error of the LWIA analyzer. The greatest error was in extraction from wood, in which there was mean deviation in $\delta^2\text{H}$ of -9.2‰ but no identifiable deviation in $\delta^{18}\text{O}$. This large deviation in $\delta^2\text{H}$ may come from mass error or memory effect in wood. In summary, systematic errors in CVD were smaller than theoretical fractionation and also less than variation in natural waters of this coastal swamp. However, interpreting data from extracted sapwater proved difficult. Errors can be reduced under extraction efficiency greater than 90% and high temperature, but an empirical, systematic or species specific correction for fractionation of ^2H may be appropriate.

5.2 Introduction

Application of water isotopes as tracers in coastal wetland hydrology requires greater experimental precision than in some other cases because fluctuations of water table and mixture of subsurface water occur frequently. In a forested wetland of the Mississippi River delta, we used isotopes in sapwood water to distinguish *Taxodium distichum* (L.) Rich water use among sources in hummocks and swales.

Water in soil and wood samples extracted through CVD underwent fast vaporization and condensation at 100 milli-torr. Kinetic fractionation occurred due to the high gradient in temperature and pressure in which vapor moves from high-temperature source to low-temperature sink unlike equilibrium condition (i.e. Gat et al., 1994; Horita and Wesolowski, 1994; West et al., 2010, 2006). Unknown systematic errors may occur from incomplete extraction within CVD, from partial retention within soil or wood, or from contamination by volatile organic compounds (VOCs). Specimens had previously undergone extraction from field conditions and were low in volatile organic compounds (VOCs) known to contaminate laser spectroscopy: each passed the spectral contamination identifier (Los Gatos Research Inc.; (Schultz et al., 2011; Brian Leen et al., 2012).

5.3 Objectives

To address the systematic error from CVD, observed deviation ($\Delta_{\text{product} - \text{reactant}}$) derived from incomplete extraction was compared with theoretical values. To test the CVD system for coherence with theoretical fractionation, we applied partial (52-100%) extraction on 10 ml deionized water of known isotopic composition placed in the extraction chamber. To test efficacy of extraction from wood, we soaked sapwood core specimens in deionized water, then completed extractions. To test whether activated carbon—commonly used to reduce volatile

organic carbon VOCs—caused fractionation by adding activated carbon 10- 40% by mass to deionized water and analyzing after three days. Finally, we tested whether activated carbon—commonly used to reduce VOCs—caused fractionation by adding activated carbon 10- 40% by mass to deionized water and analyzing after three days.

5.4 Methods

Cryogenic vacuum distillation (CVD, Figure 5-1) was to extract water from soil and wood samples. Several controlled tests were used to test efficiency, accuracy, and precision of this modified system; following analysis used a liquid water isotope analyzer (LWIA) from Los

Gatos Research Inc. $\Delta\delta = \frac{F^{(\frac{1}{\alpha})} - F}{F - 1} * 10^3$, where F as fraction of water remaining in the extraction side; α as the fractionation factor at target temperature.

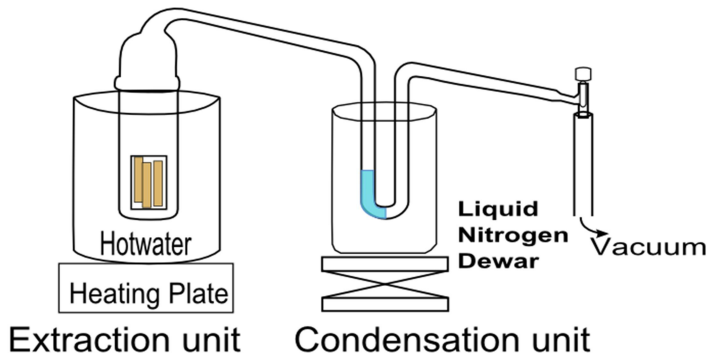


Figure 5-1. Extraction device (modified from Ehleringer and Osmond, 1989; Ehleringer et al., 2000; West et al., 2006).

5.5 Results

Results of liquid water extractions showed fractionation following the theoretical slope at an offset for ^{18}O , but at a lower slope for ^2H (Figure 5-2; Equation 5-1). Fractionation of the di water incomplete extraction experiment showed,

For D: $\Delta = -37.3 f + 0.47$ ($R^2 = 0.76$); for ^{18}O : $\Delta = -5.92 f + 0.50$ ($R^2 = 0.76$). (Equation 5-1)

where $\Delta = \Sigma\Delta(\text{experimental value} - \text{original value}; \text{‰})$; f = fraction remaining (%). Even under maximum extraction efficiency, in which no remaining water exists in the extraction side, fractionation of the possible loss from vapor onto glass wall are 0.47 ‰ in δD and 0.5 ‰ in $\delta^{18}\text{O}$. CVD extraction presents enrichment factor to the final isotopic compositions. Comparing to the analytical errors of the LWIA, which were 2.2 in δD and 0.6 in $\delta^{18}\text{O}$,

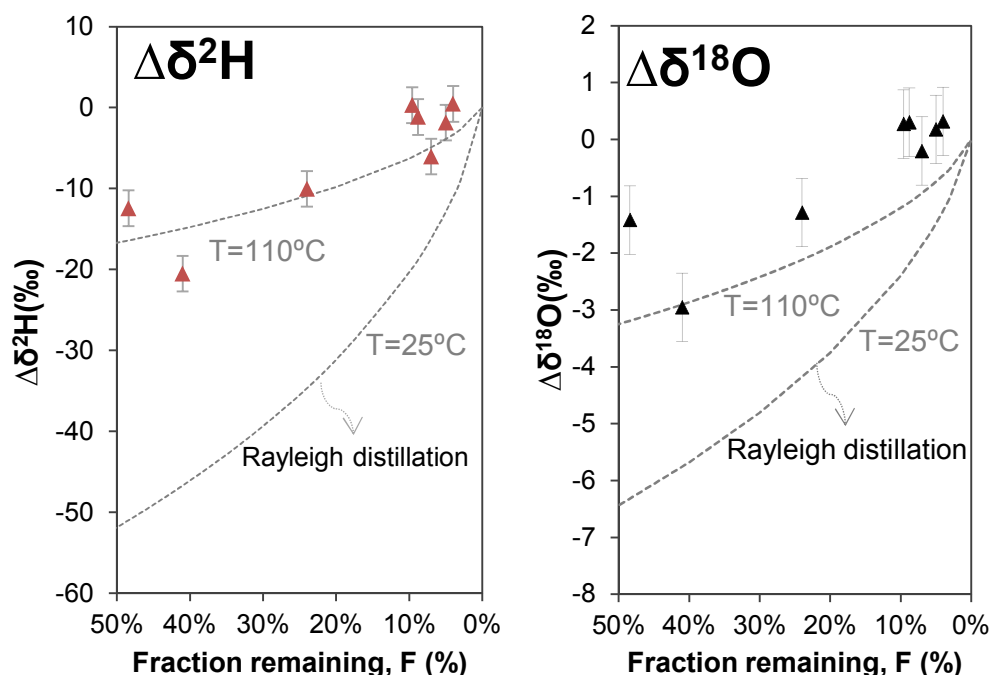


Figure 5-2. Deviation of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ contributed by incomplete extraction (triangles); error bars (standard deviation) show internal error ranges for the LGR-LWIA as experimentally estimated in our lab. Rayleigh distillation curves (dash lines) were derived from under open and evaporating system in which water phase changes between vapor-liquid-solid (Equation 5-1).

Error from applying activated carbon in deionized water was negligible: -0.8 ‰ in $\delta^2\text{H}$ and -0.4‰ in $\delta^{18}\text{O}$ (Figure 5-3). Activated carbon is proved to have certain amount of depletion factor to the final isotopic compositions in our study. However, contaminated samples were not totally removed from organic matter because activated carbon only helped for removing weak

polar compound rather than high polar compounds, such as alcohols, glycols, strong acids and bases (Brand, 2010; Schultz et al., 2011).

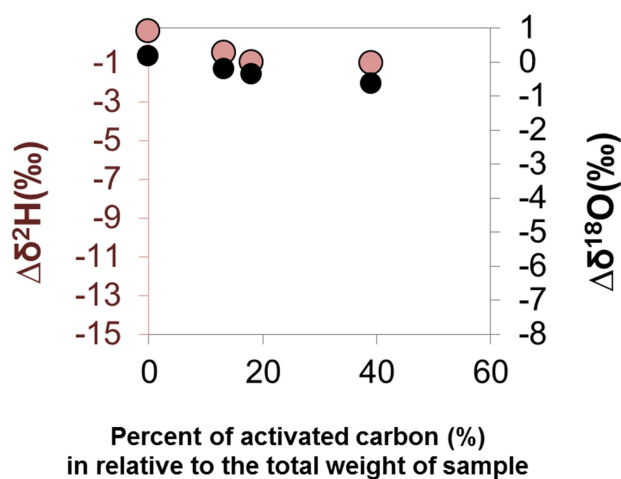


Figure 5-3. Deviation of $\delta^2\text{H}$ (red) and $\delta^{18}\text{O}$ (black) contributed by activated carbon in deionized water.

Extra errors from characteristics of the sample: The greatest error was in extraction from wood, in which there was fractionation in $\delta^2\text{H}$ by up to 11‰ compared to undetectable fractionation in $\delta^{18}\text{O}$ (Figure 5-4). Examining the extracted water from rewetting wood in DI water, fractionation increased in higher extraction for isotopic deuterium composition and significantly different from original DI value ($P < 0.005$).

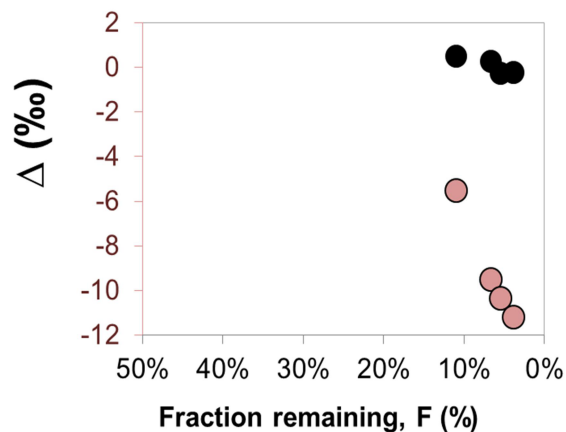


Figure 5-4. Deviation of $\delta^2\text{H}$ (red) and $\delta^{18}\text{O}$ (black) contributed and blank test on rewetted wood.

5.6 Summary

Results of liquid water extractions showed deviation following the theoretical slope at an offset for ^{18}O , but at a lower slope for ^2H (Figure 5-2). Error from applying activated carbon in deionized water was negligible (Figure 5-4). The greatest error was in extraction from wood, in which there was a mean deviation in $\delta^2\text{H}$ - 9.2 ‰ but no identifiable deviation in $\delta^{18}\text{O}$ (Figure 5-3). This large deviation in $\delta^2\text{H}$ may come from mass error or memory effect in wood (Koeniger et al., 2011). Yet comparing to other studies over the standard deviation, our result showed 2.5 ‰ in $\delta^2\text{H}$ and 0.38 ‰ in $\delta^{18}\text{O}$ (Table 5-1). Yet, error in $\delta^2\text{H}$ is rather unpredictable (i.e. Schmidt et al., 2012). In summary, systematic errors in CVD were smaller than theoretical fractionation and also less than variation in natural waters of this coastal swamp. Errors can be reduced under extraction efficiency greater than 90% and high temperature, but an empirical, systematic or species specific correction for fractionation of ^2H may be appropriate.

Table 5-1. Comparison of CVD extraction studies.

Authors	Extraction method	Isotope analyzer	Sample type	Standard deviation	
				$\delta^2\text{H}$	$\delta^{18}\text{O}$
Araguás-Araguás et al. (1995)	CVD	IRMS	Clayey soil	3.0	0.30
West et al. (2006)	CVD	IRIS IRMS	Clayey soil	0.7	0.15
Koeniger et al. (2011)	CVD	IRMS	Tree core (<i>Picea abies</i>)	4.7	0.63
Schmidt et al. (2012)	CVD	IRIS IRMS	Twig (beech, oak, pine)	0.5	0.22
This study	CVD	IRIS	Tree core (<i>Taxodium distichum</i>)	2.5	0.38

5.7 References

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CHAPTER 6. CONCLUSIONS AND FUTURE RESEARCH

Throughfall amount was spatially correlated with canopy structure, such as distance to the nearest tree, crown coverage, and crown length. The throughfall process is related to canopy structure enough to strongly influence the amount of throughfall, but canopy structure only weakly influences isotope composition.

Overall, salinity was slightly higher in groundwater in hummocks than in swales, but with substantial heterogeneity both within and among hummocks. The shallow subsurface of hummocks is a zone characterized by slow dilution and episodic salinization rather than slow salinization and episodic flushing. Rainfall and frequent inundation by generally low-salinity water flushed salts and maintained lower salinity in upper layers. Baldcypress on hummocks use water from the vadose zone and thus avoid saline flooding. Generally, the baldcypress forest occupies a nonsaline site, but the episodic influx followed by slow leaching occurs on top of a layer of salinity that lies presumably beneath the root zone for most of the growing season. However, hummocks may represent short-term refugia, from where local subsidence and sea-level rise will continue to increase exposure to both flooding and salinity.

APPENDICES

7.1 Throughfall

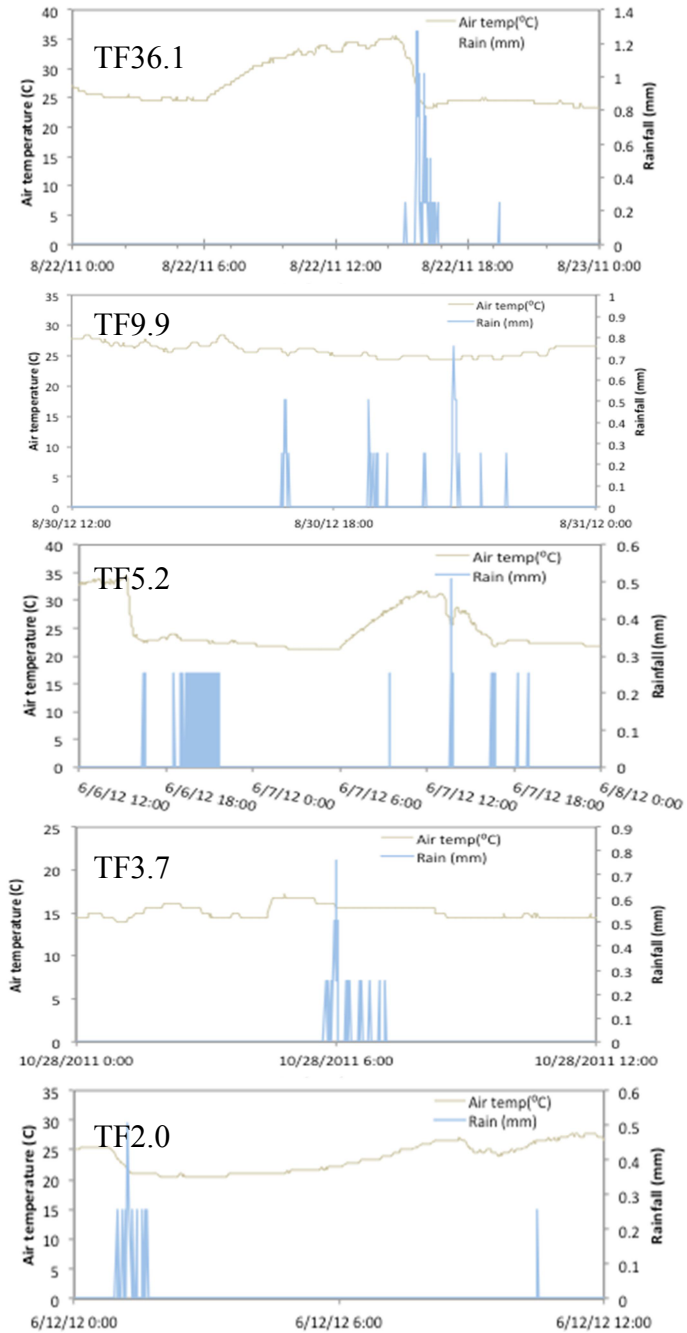


Figure 7-1. Rainfall patterns of each event.

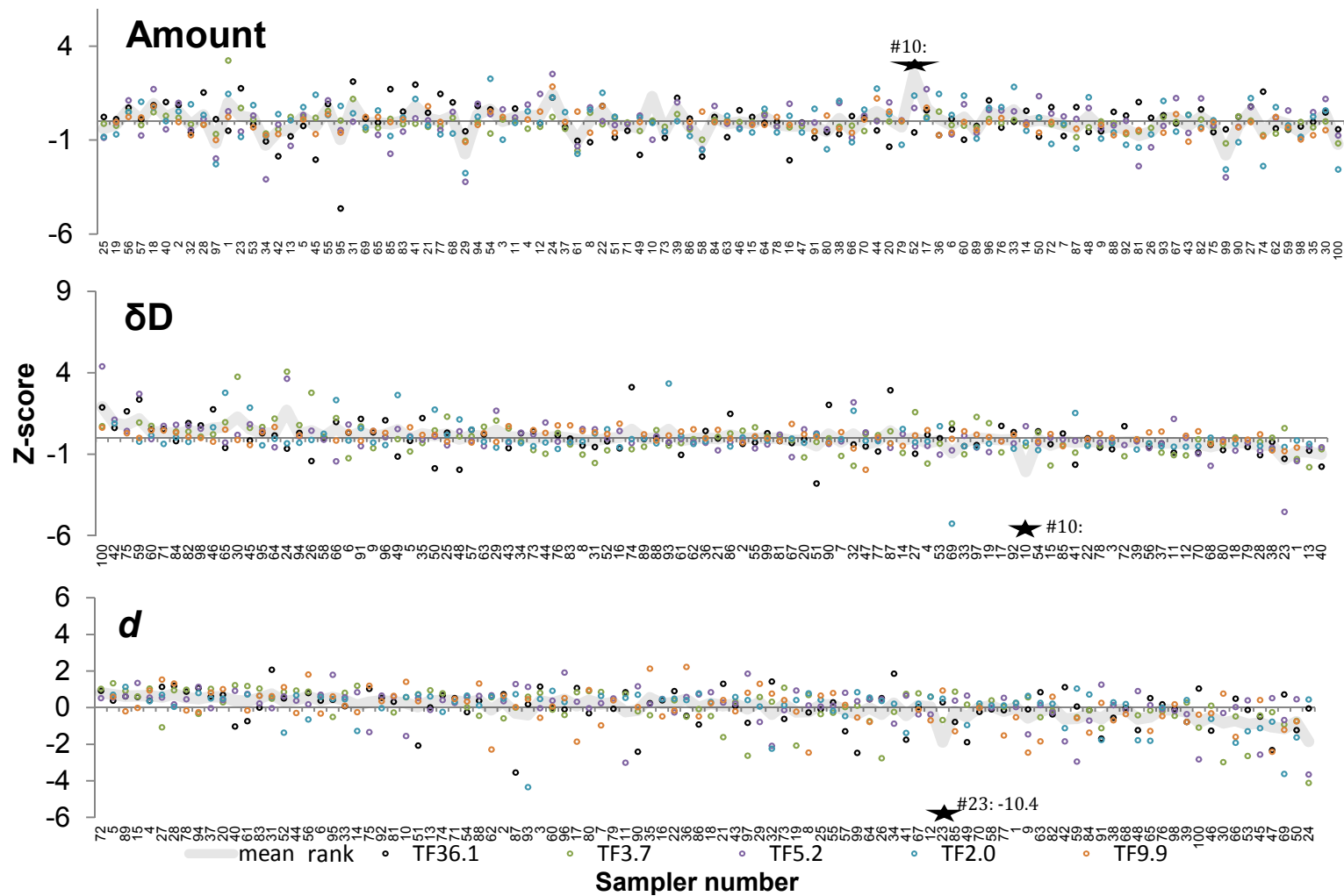


Figure 7-2. Time stability plots for throughfall amount and isotopic compositions (δD and d) across four rainstorms. X-axis showed the order between cups on the mean rank of each variable (the bold shaded lines). Colored dots represented the five events with incomplete observations in a fraction of samples. Y-axis showed normalized values (z-scores) within the same event for three variables. Three extreme values were noted in this figure for which had $> 5SD$.

7.2 Water separation analysis

7.2.1 Water separation analysis

Mass balance of overall quantity of water, as Q_s , and variables, as $A_s, B_s, C_s \dots$ etc., can be described as (Genereaux, 1999):

$$Q_s = Q_1 + Q_2 + Q_3 \rightarrow 1 = f_1 + f_2 + f_3$$

$$A_s = f_1 A_1 + f_2 A_2 + f_3 A_3$$

$$B_s = f_1 B_1 + f_2 B_2 + f_3 B_3$$

Where Q_n represents the proportion of each source and f_n represents the fraction of each source in components 1, 2, and 3. Based on the equations above, f_n can be derived as (Genereaux, 1999):

$$f_1 = \frac{A_s B_2 - A_s B_3 + A_2 B_3 - A_2 B_s + A_3 B_s - A_3 B_2}{A_1 B_2 - A_1 B_3 + A_2 B_3 - A_2 B_1 + A_3 B_1 - A_3 B_2}$$

$$f_2 = \frac{A_s B_3 - A_s B_1 + A_1 B_s - A_1 B_3 + A_3 B_1 - A_3 B_s}{A_1 B_2 - A_1 B_3 + A_2 B_3 - A_2 B_1 + A_3 B_1 - A_3 B_2}$$

$$f_3 = \frac{A_s B_1 - A_s B_2 + A_1 B_2 - A_1 B_s + A_2 B_s - A_2 B_1}{A_1 B_2 - A_1 B_3 + A_2 B_3 - A_2 B_1 + A_3 B_1 - A_3 B_2}$$

7.2.2 Uncertainty analysis

The partial derivatives for each fraction are as follows:

Let $f_1 = C/F, f_2 = D/F, f_3 = E/F$, then the errors for standard deviation grouped in source n are:

$$\omega_{f_1} = \frac{1}{F^2} \left\{ \begin{aligned} &[(B_3 - B_2) \cdot C] \cdot \omega_{A_1} + [(B_3 - B_s) \cdot F - (B_3 - B_1) \cdot C] \cdot \omega_{A_2} + [(B_s - B_2) \cdot F - (B_1 - B_2) \cdot C] \cdot \omega_{A_3} + \\ &[(B_2 - B_3) \cdot F] \cdot \omega_{A_s} + [(A_2 - A_3) \cdot C] \cdot \omega_{B_1} + [(A_s - A_3) \cdot F - (A_1 - A_3) \cdot C] \cdot \omega_{B_2} + \\ &[(A_2 - A_s) \cdot F - (A_2 - A_1) \cdot C] \cdot \omega_{B_3} + [(A_3 - A_2) \cdot F] \cdot \omega_{B_s} \end{aligned} \right\}$$

$$\omega_{f_2} = \frac{1}{F^2} \left\{ \begin{aligned} &[(B_s - B_3) \cdot F - (B_2 - B_3) \cdot D] \cdot \omega_{A_1} + [(B_1 - B_3) \cdot D] \cdot \omega_{A_2} + [(B_1 - B_s) \cdot F - (B_1 - B_2) \cdot D] \cdot \omega_{A_3} + \\ &[(B_3 - B_1) \cdot F] \cdot \omega_{A_s} + [(A_3 - A_s) \cdot F - (B_2 - B_3) \cdot D] \cdot \omega_{B_1} + [(A_3 - A_1) \cdot D] \cdot \omega_{B_2} + \\ &[(A_s - A_1) \cdot F - (A_2 - A_1) \cdot D] \cdot \omega_{B_3} + [(A_1 - A_3) \cdot F] \cdot \omega_{B_s} \end{aligned} \right\}$$

$$\omega_{f_3} = \frac{1}{F^2} \left\{ \begin{aligned} & \left[(B_2 - B_s) \cdot F - (B_2 - B_3) \cdot E \right] \cdot \omega_{A_1} + \left[(B_s - B_1) \cdot F - (B_3 - B_1) \cdot E \right] \cdot \omega_{A_2} + \left[(B_2 - B_1) \cdot E \right] \cdot \omega_{A_3} + \\ & \left[(B_1 - B_2) \cdot F \right] \cdot \omega_{A_s} + \left[(A_s - A_2) \cdot F - (A_3 - A_2) \cdot E \right] \cdot \omega_{B_1} + \left[(A_1 - A_s) \cdot F - (A_1 - A_3) \cdot E \right] \cdot \omega_{B_2} + \\ & \left[(A_1 - A_2) \cdot E \right] \cdot \omega_{B_3} + \left[(A_2 - A_1) \cdot F \right] \cdot \omega_{B_s} \end{aligned} \right\}$$

VITA

She was born in a coastal wetland area in Chingshuei of Taichung city in Taiwan in the year when global environmental movements were initiated around the world. By the time she grew up as a college student of National Taiwan University, she was already enchanted by the beauty forests where half of Taiwan was covered. She then dedicated to examine mechanisms to vegetation change. However, the progress of urbanization, landslide, earthquakes, and typhoons all destructed forests, wetlands as well as cities. Noticing the lack of sources to restore wetlands and the lack of researchers in such field, she was then dedicated to understand ecosystems by joining the Long-Term Ecological Network working on limnology in Academia Sinica. During her work, she also became a life-member for the Taiwan Environmental Information Association as to help increasing awareness of the environmental issues to the public. Now, she realized that the key to restore ecosystems is largely unknown and sometimes debatable. What she understood cannot solve any bit of it. However, while she gained valuable experience along the way, she still found the beauty of resilience in nature and humane.