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#16094 Identifying patterns of forest hydrologic and biogeochemical fluxes using weather map classification in a Mid-Atlantic deciduous forest

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Delaware Environmental Observing System (DEOS)

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Abstract (#16094):
The partitioning of precipitation within the forest canopy into throughfall and stemflow is controlled by biotic and abiotic factors, which include storm characteristics (e.g., intensity, duration, and magnitude) and canopy structural parameters. Our research uses novel applications of weather map classification to relate synoptic scale weather patterns to the surface environment. A daily synoptic calendar was developed in the Mid-Atlantic to categorize the subcanopy hydrologic and biogeochemical fluxes during storm events in an eastern deciduous forest.
Synoptic classification identified 6 low pressure systems, 4 high pressure systems, 1 cold front, 3 northerly flow regimes, 3 southerly flow regimes, and 5 weak patterns. The low pressure systems were commonly associated with the largest average flux-based enrichment ratios of solutes in throughfall and stemflow compared to rainfall solute concentrations. Low pressures such as the Weak Coastal Low, centered off the Mid-Atlantic coast with easterly winds over the study region, were associated with large rainfall events with moderate intensities falling over a long period of time. This combination of meteorological conditions allowed complete washoff of antecedent atmospheric deposition and maximum canopy leaching as storm systems of this magnitude were able to wet the entire canopy. The lowest flux-based enrichment ratios occurred during cold fronts and weak southwest flow regimes, which were both characterized by moderately high rainfall amounts that occurred over short periods of time (i.e., < 0.5 days) with high intensities (i.e., > 5 mm h^{-1}). As a result, the water from these storm systems passed through the forest canopy very quickly and with minimal contact time thus resulting in minimal enrichment of throughfall and stemflow. The distinct chemical signatures of synoptic types provide evidence that this novel application of storm classification in forest hydrology is useful for estimating hydrologic and nutrient fluxes in eastern forests and modeling forest water and nutrient budgets in response to changing precipitation characteristics in the region.

Introduction:

Deciduous forests represent a significant land cover classification in much of the temperate US and contribute meaningful ecosystem services such as carbon sequestration, water and air purification, storm water management, recreational retreats, in addition to providing valuable timber products. These services are constrained by forest health, which can be measured via several parameters including net primary production and biomass accumulation, evapotranspiration, resiliency to disturbance, and forest nutrient balances. These services are ultimately constrained by the external climate from which forests derive water and nutrients. Within the forest canopy, there are distinct pathways in which precipitation and nutrients reach the forest floor and move throughout a watershed, including throughfall and stemflow (Figure 1). These pathways may become enriched with nutrients and other solutes via washoff of dry deposition during antecent dry periods or canopy leaching (Lovett and Lindberg 1984), which is defined as the removal of substances from plant surfaces by the action of aqueous solutions (Tukey 1970), such as rainfall. Changes in precipitation characteristics such as magnitude, duration, and intensity or in overall storm tracks have the potential to alter the movement of water and nutrients in forests.

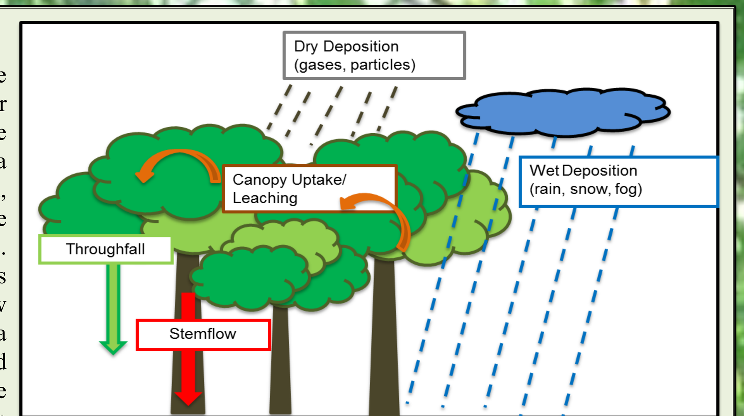


Fig. 1 Throughfall, rainfall that passes through the forest canopy and is deposited to the forest floor, may or may not come in contact with the forest surfaces, has minimal residence time, and exhibits a large degree of spatial variability (André et al. 2011). Stemflow, rainfall that has been captured by the forest canopy and funneled down woody surfaces to be deposited at the base of the trunk, has much longer residence time, more strongly influenced by canopy architecture and bark morphology, contributes disproportionately to nutrient cycling based on hydrologic flux (Levia et al. 2011).

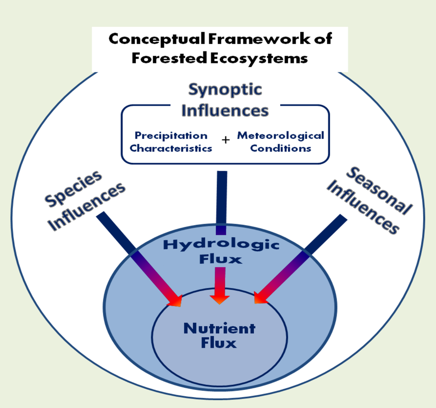


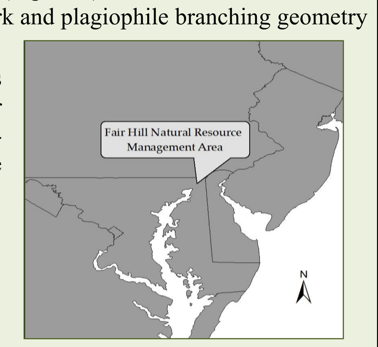
Fig. 2 Conceptual framework of the transformation of water and nutrients by the forest canopy.

Synoptic classification is a tool used to represent diverse atmospheric variables as a single synoptic type, allowing researchers to relate large-scale atmospheric circulation to regional- and small-scale surface environments in a simplified manner. Subcanopy hydrologic and nutrient fluxes are intimately connected to the larger synoptic setting under which the storm events occur (Figure 2). It is widely recognized among the synoptic community that stagnant anti-cyclonic conditions with origins in pollution emission areas result in the highest rates of surface pollutant deposition and accumulation (Fernau and Samson 1990). Geographic proximity to pollution sources has also been shown to enhance pollutant deposition in forested ecosystems (Skeffington et al. 2012) although this process is tightly linked to atmospheric circulation patterns (Avila and Alarcón 1999). Beyond identifying source regions for storm events, no known studies have used storm classification to understand subcanopy hydrologic and nutrient pathways. **It is hypothesized that the classification of synoptic types via principal components analysis and cluster analysis will reduce the number of variables and provide a method to more easily distinguish between fundamentally different storm events and the subsequent response of subcanopy hydrologic and nutrient fluxes during such events.** The ability to relate large-scale atmospheric circulation to the surface environment has been successfully completed in the past in instances of air pollution and surface response. This study will be the first of its kind to relate atmospheric circulation to subcanopy forest fluxes.

Site Description

The research presented here was collected at Fair Hill Natural Resources Management Area (FH-NRMA) in northeastern Maryland (39°42'N, 75°50'W). The research plot is located within a 12 hectare forested catchment with a stand density of 225 trees ha^{-1}, a stand basal area of 36.8 $m^2 ha^{-1}$, a mean diameter at breast height (DBH) of 40.8 cm, and a mean tree height of 27.8 m. The forest canopy is comprised of *Liriodendron tulipifera* L. (yellow poplar), *Fagus grandifolia* Ehrh. (American Beech), *Acer rubrum* L. (red maple), and *Quercus alba* L. (white oak). The dominant canopy trees are approximately 80-100 years old (Figure 2) and have a leaf area index (LAI) of 5.3 $m^2 m^{-2}$. *Fagus grandifolia* has smooth bark and erectophile branching geometry. *Liriodendron tulipifera* has rough bark and plagiophile branching geometry (Figure 3).

Climate is primarily humid maritime with well-defined seasons. Frontal systems derived from mid-latitude cyclones characterize autumn, winter, and spring precipitation while convective systems dominate summertime precipitation. Mean 30-year annual precipitation is approximately 1200 mm; summer (JJA) is the wettest season (324 mm) and winter (DJF) is the driest (274 mm) on average, although precipitation falls consistently throughout the year (MD Climatologist Office, 2008). Average temperature is 21.7°C in summer and 1.1°C in winter.



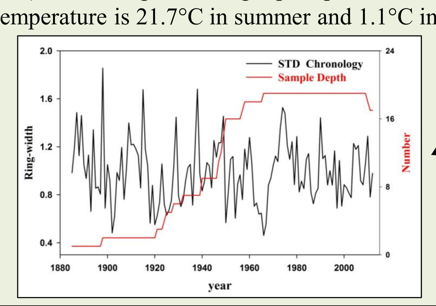


Fig. 3 Standard tree-ring chronology constructed from canopy-dominant *L. tulipifera* at the research site. Maximum tree age is 120 years.

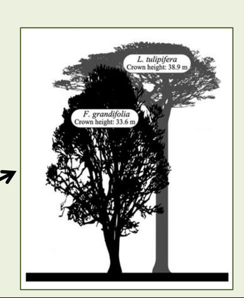


Fig. 4 Interspecific canopy architecture and geometry differences. In addition, *F. grandifolia* has extremely thin, smooth bark and *L. tulipifera* has extremely rough, thick bark. (Van Stan et al. 2011)

Materials & Methods:

Forest Biogeochemistry:
Throughfall and stemflow hydrologic measurements were collected at 5-minute intervals using Texas Electronics TE525MM tipping bucket gages interfaced with a Campbell Scientific CR1000 datalogger. Two tipping buckets each were placed under *Fagus grandifolia* Ehrh. (American beech) and *Liriodendron tulipifera* L. (yellow poplar) canopies to measure throughfall. Three trees of each species were fitted with 31.8 mm vinyl tubing cut longitudinally that drained into the remaining six tipping buckets to monitor stemflow.

Throughfall and stemflow solute samples were collected manually using inert polyethylene containers within 24 hours of the completion of a storm event. Solute collectors were deployed in the same manner as the hydrology-monitoring tipping buckets. Samples were filtered to remove particulates larger than 0.45μm and stored at 4°C until analyzed for Na^+, Mg^{2+}, K^+, Ca^{2+}, NH_4^+, SO_4^{2-}, NO_3^-, Cl^-, Al^{3+}, Si, TN, DON, and DOC at the College of Environmental Science and Forestry at the State University of New York in Syracuse, NY.

Fig. 5 Biogeochemistry samples: Precipitation, Throughfall (2), Litter Leachate (2), and Stemflow (2).

Meteorology:
Meteorological measurements were collected at 5-minute intervals with a Delaware Environmental Observing System (DEOS) station in a nearby clearing at FH-NRMA. The DEOS station monitors general meteorological conditions and rainfall.

Synoptic Climatology:
Synoptic classification is a practical tool used to represent a variety of atmospheric variables through a simple classification scheme relating large-scale atmospheric circulation to regional- and small-scale surface environments. A daily synoptic calendar (Siegert et al., *in review*), has been employed that classifies the synoptic setting from 1946 to present using the eigenvector-based approach outlined in Yarnal (1993).

Fig. 6 Throughfall and stemflow hydrologic sampling.

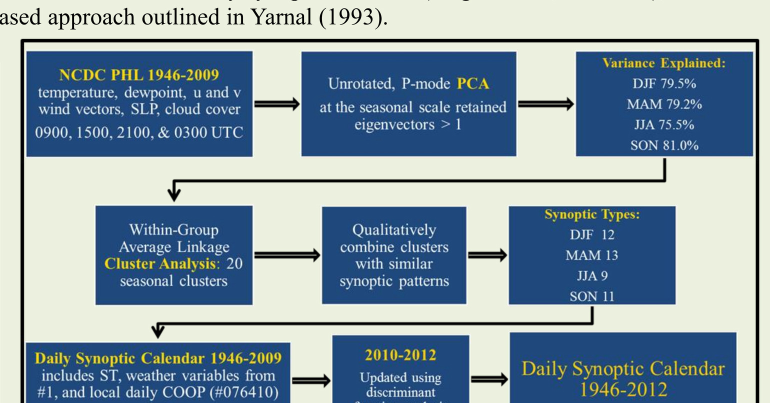


Fig. 7 Synoptic calendar development (1946-2009) and annual updating (2010-2012) methods.

Fig. 8 DEOS station and precipitation chemistry collector.

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FOREST HYDROLOGY & BIOGEOCHEMISTRY

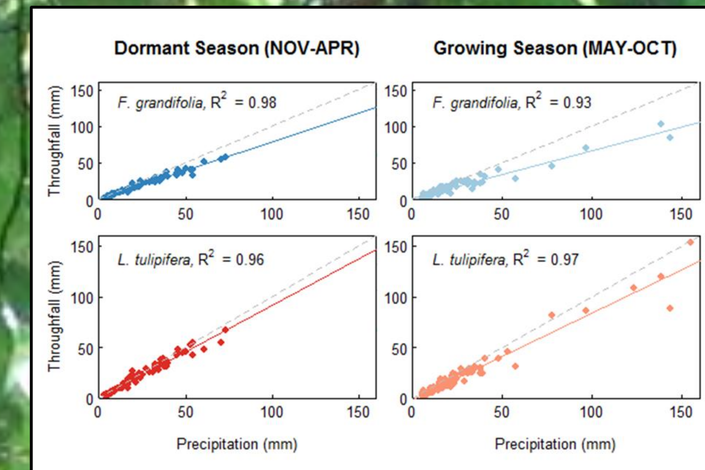

Fig. 9 Hydrologic partitioning of throughfall in relation to precipitation magnitude. Blue panels denote F. grandifolia and red panels denote L. tulipifera. Darker hued panels denote fluxes observed during the dormant season (NOV-APR) and lighter hued panels denote fluxes observed during the growing season (MAY-OCT).

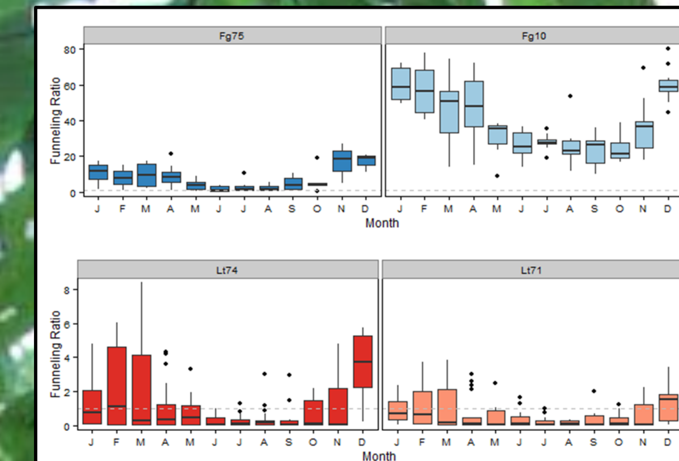

Fig. 10 Monthly boxplots of tree-specific stemflow funneling ratio (FR). The horizontal black line indicates median FR, boxes indicate the range of FR that fall within the first and third quartiles, whiskers represent FRs that fall within 1.5 times the interquartile range, and circles represent outliers. The horizontal dashed gray line indicates FR = 1, where stemflow volume is the same as rainfall over the tree basal area. (Siegert and Levia 2014)

	pH	Cl^- (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	DOC (mg/L)	DON (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)
PRECIPITATION	6.39[a]	1.04[a]	1.99[a]	2.12[a]	1.17[a]	0.38[a]	3.30[a]	1.23[a]	1.60[a]	2.33[a]
THROUGHFALL										
F. grandifolia	6.45[a]	1.37[a] (1.5)	1.87[a] (1.4)	4.78[b] (10.0)	1.29[a] (1.3)	0.62[ab] (1.7)	8.25[b] (2.5)	0.78[a] (1.1)	4.64[b] (5.0)	3.64[b] (2.1)
L. tulipifera	6.39[a]	1.40[a] (1.5)	1.61[a] (1.4)	9.35[c] (16.5)	1.80[a] (1.9)	1.02[b] (2.8)	17.61[c] (5.4)	1.63[a] (1.7)	2.34[ab] (1.6)	3.53[b] (2.5)
STEMFLOW										
F. grandifolia	5.87[b]	1.88[ab] (33.5)	0.89[b] (16.9)	8.76[b] (167.1)	1.82[a] (29.7)	0.65[b] (28.2)	15.94[b] (60.4)	2.23[a] (30.5)	7.46[b] (77.5)	9.42[b] (99.9)
L. tulipifera	6.03[b]	1.97[b] (3.5)	0.84[b] (1.7)	16.43[c] (25.6)	3.00[b] (5.8)	1.67[c] (7.4)	46.69[c] (21.9)	4.93[a] (5.6)	3.37[c] (2.2)	7.77[b] (12.0)

Table 1 Statistical differences between pH and solute concentrations in precipitation, throughfall, and stemflow. Different letters denote statistically different population means between species [Note: comparisons were made between species, but not between throughfall and stemflow]. Enrichment ratios are given in parentheses. Analysis performed with student's T-test in R.

RESULTS & DISCUSSION:

- *Throughfall hydrology* is largely controlled by precipitation amount, although the presence of foliage decreases throughfall and increases interception.
- *Stemflow hydrology* is much more variable. Foliage reduces stemflow funneling capabilities in both species. Total stemflow generation is much greater in smoother-barked species, but also more variable and less constrained by rainfall characteristics. Smaller trees are more efficient at capturing and converting rainfall to stemflow.
- *Throughfall biogeochemistry* is significantly different from rainfall for K^+, Mg^{2+}, DOC, NO_3^-, and SO_4^{2-}. Interspecific differences were observed for K^+ and DOC. Enrichment ratios were relatively small, except for K^+.
- *Stemflow biogeochemistry* is significantly different from rainfall in all solutes except DON. Interspecific differences were observed for K^+, Ca^{2+}, Mg^{2+}, DOC, and NO_3^-. Solute concentrations (when significantly different) were greater in *L. tulipifera* stemflow although enrichment ratios were greater in *F. grandifolia*.

SYNOPTIC CLIMATOLOGY

Synoptic Classification	Season	N	N (%)	Rainfall (mm)	Duration (h)	Intensity (mm h^{-1})	Wind Direction
Low Pressure							
L1- Strong Coastal Low	DJF	118	0.5	6.3 (2.4)	6.4	0.6	NE
	MAM	59	0.2	10.3 (6.1)	8.3	1.1	
L2- Weak Coastal Low	DJF	330	1.3	10.5 (6.6)	8.8	0.9	E
	MAM	246	1.0	13.4 (10.2)	10.3	1.1	
	SON	201	0.8	11.9 (6.9)	8.3	1.1	
L3- Great Lakes Low	DJF	386	1.6	4.7 (0.5)	3.9	0.6	W
	MAM	180	0.7	3.0 (0.0)	2.5	0.5	
	JJA	123	0.5	3.7 (0.8)	2.2	1.0	
	SON	204	0.8	3.4 (0.0)	2.2	0.6	
L4- Midwest Low	DJF	696	2.8	4.5 (0.0)	3.7	0.5	S
	MAM	443	1.8	7.8 (2.3)	4.9	1.0	
	SON	179	0.7	7.5 (0.8)	4.2	1.1	
L5- New England Coastal Low	MAM	118	0.5	0.7 (0.0)	1.0	0.2	NW
	SON	131	0.5	5.7 (1.3)	4.4	0.8	
L6- Southeast Canadian Low	JJA	312	1.3	0.4 (0.0)	0.3	0.1	N
High Pressure							
H1- Strong Overhead High	DJF	169	0.7	0.0 (0.0)	0.1	0.0	-
	MAM	135	0.6	0.3 (0.0)	0.5	0.1	
	SON	313	1.3	0.0 (0.0)	0.0	0.0	
H2- Overhead High	DJF	462	1.9	1.1 (0.0)	1.7	0.2	-
	JJA	163	0.7	0.0 (0.0)	0.0	0.0	
	SON	1381	5.6	0.2 (0.0)	0.2	0.1	
H3- Weak Overhead High	DJF	535	2.2	1.8 (0.0)	2.5	0.3	-
	MAM	620	2.5	0.2 (0.0)	0.2	0.1	
H4- New England High	DJF	412	1.7	5.2 (0.8)	4.9	0.6	E
	SON	680	2.8	5.1 (0.3)	4.0	0.6	
Cold Front							
F1- Cold Front	DJF	177	0.7	2.9 (0.0)	3.0	0.4	NW
	MAM	790	3.2	1.6 (0.0)	1.4	0.3	
	JJA	901	3.7	2.0 (0.0)	1.0	0.6	
	SON	399	1.6	1.8 (0.0)	1.2	0.4	
North/Northwest Flow							
N1- Northerly Flow	MAM	226	0.9	3.0 (0.0)	3.1	0.4	N
N2- Strong Northwest Flow	DJF	1085	4.4	0.3 (0.0)	0.6	0.1	NW
N3- Northwest Flow	DJF	748	3.1	1.1 (0.0)	0.9	0.2	NW
	MAM	704	2.9	0.2 (0.0)	0.4	0.1	
	SON	755	3.1	0.7 (0.0)	0.7	0.1	
South/Southwest Flow							
S1- Southwest Flow	DJF	919	3.8	1.2 (0.0)	1.4	0.2	SW
	MAM	1416	5.8	2.2 (0.0)	1.6	0.4	
	SON	697	2.8	2.8 (0.0)	1.9	0.5	
S2- Weak Southwest Flow	JJA	1400	5.7	1.2 (0.0)	0.6	0.4	SW
	SON	1104	4.5	2.8 (0.0)	1.7	0.6	
S3- Southerly Flow	JJA	1471	6.0	5.8 (0.3)	2.2	1.3	S
Weak Patterns							
W1- Weak Pattern	MAM	680	2.8	4.7 (0.3)	3.7	0.7	-
W2- Weak Southerly Flow	MAM	547	2.2	3.6 (0.5)	3.9	0.5	-
W3- Weak Upper Trough	JJA	208	0.8	14.6 (7.1)	6.5	2.0	-
W4- Zonal Flow Aloft	JJA	432	1.8	0.2 (0.0)	0.1	0.1	-
W5- Southern Trough Aloft	JJA	1045	4.3	2.8 (0.0)	1.8	0.5	-
Tropical Systems							
TS- Tropical System		91	0.4	28.0 (13.0)	9.4	2.6	-

Table 2 Inter-seasonal synoptic classification comparisons and descriptions. Mean rainfall values are given with median values in parentheses. Rainfall intensity was calculated from values across all storms, not from mean rainfall quantities and duration. (Siegert et al. *in review*)

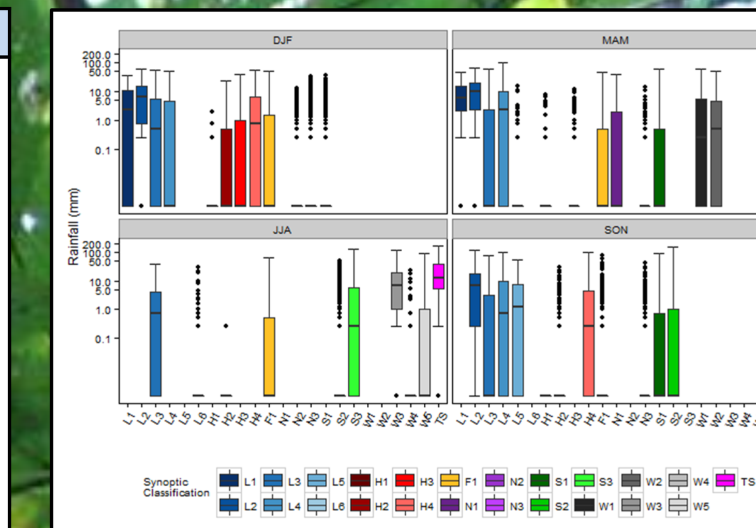

Fig. 11 Boxplot distribution of rainfall observed in each synoptic classification by season from 1956 to 2012. Median rainfall is plotted as the horizontal black bar, the first through third quartile precipitation values are contained within the box, the 1.5 interquartile precipitation values are contained within the range of the whiskers, and the outliers are plotted as black circles. (Siegert et al. *in review*)

RESULTS & DISCUSSION:

- 22 unique weather conditions were identified in the Mid-Atlantic.
- The largest precipitation-producing classifications were not restricted to low pressure systems, but rather to weather patterns with access to marine moisture sources from the Atlantic Ocean and easterly (on-shore) winds to transport the moisture inland.
- Applications of the synoptic calendar to hydroclimatology are numerous but limitations do exist. One of the largest sources of error in any weather classification scheme is the temporal scale. For daily classification, weather patterns may extend beyond the 24-hour period, multiple fast-moving patterns may occur in a single day, or the pattern may overlap between two 24-hour periods.
- More than 20,000 days were classified therefore the majority of the classifications accurately reflect the true atmospheric and precipitation conditions.

SYNTHESIS: MERGING THE FOREST AND THE ATMOSPHERE

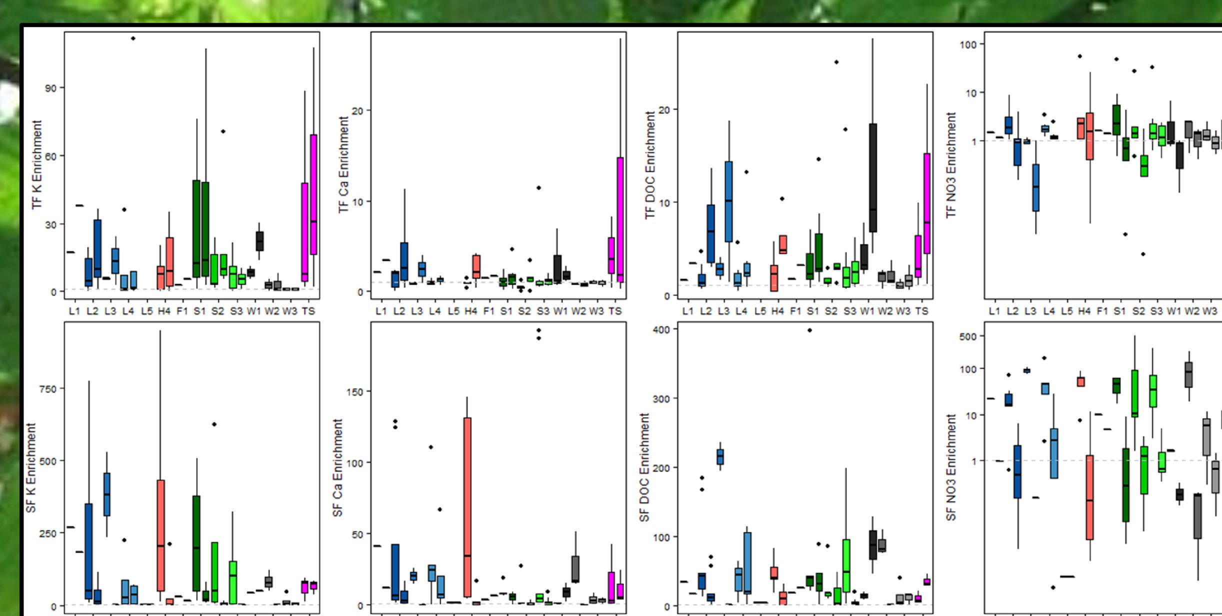

Fig. 12 Paired boxplot distribution solute enrichment in throughfall (top panels) and stemflow (bottom panels). Left boxplots represent collections from *F. grandifolia* and right boxplots from *L. tulipifera*. Primary sources for each solute is: canopy leaching (CL) for K^+; CL and dry deposition (DD) for Ca^{2+}; wet deposition (WD) and canopy uptake (CU) for NO_3^- (Lovett and Lindberg 1984); and DD for DOC (Arisci et al. 2012). Horizontal grey line at 1 indicates no net solute change between precipitation and throughfall/stemflow pathways.

	K^+	Ca^{2+}	Mg^{2+}	Na^+	Cl^-	SO_4^{2-}	NO_3^-	DON	DOC
Precipitation									
Largest	W3	S2	W2	W2	W2	W2	W2	L3	W3
Smallest	L1	L1	W1	L1	W1	L2	S1	L5	W1
***F. grandifolia* Throughfall**									
Largest	S1 (L5)	W1 (S3)	W1 (L5)	W1 (W2)	L2 (W2)	L2 (L5)	H4 (S3)	S1 (L2)	W1 (S3)
Smallest	W3 (L4)	S2 (L1)	L4 (L1)	L3 (W3)	S2 (W3)	S2 (F1)	L3 (F1)	F1 (W1)	W3 (L4)
***L. tulipifera* Throughfall**									
Largest	L1 (L5)	L2 (L3)	L2 (L3)	W2 (W2)	W2 (W2)	L2 (L5)	H4 (W2)	L2 (L2)	W1 (L3)
Smallest	W3 (L4)	W2 (W1)	W3 (L4)	S2 (W1)	W3 (W1)	W3 (F1)	L3 (L5)	F1 (L4)	W3 (L5)
***F. grandifolia* Stemflow**									
Largest	L3 (W3)	H4 (H4)	S3 (W3)	L2 (W2)	W2 (W2)	L2 (H4)	L2 (W2)	L2 (L2)	L3 (L3)
Smallest	W3 (L1)	W1 (F1)	W1 (F1)	F1 (F1)	W1 (F1)	W1 (F1)	W1 (F1)	W3 (F1)	W3 (L1)
***L. tulipifera* Stemflow**									
Largest	L1 (L5)	L4 (L5)	W1 (L5)	L2 (W2)	L2 (W2)	L2 (L5)	L4 (S3)	W1 (L2)	W1 (W1)
Smallest	W2 (L1)	L3 (L1)	L3 (L1)	L3 (L1)	L3 (W1)	L3 (S2)	L5 (L5)	W2 (L1)	L3 (L1)

Table 3 Summary of synoptic types with the largest and smallest solute concentrations (mg/L) with enrichment ratios in parentheses. Precipitation values are concentrations (mg/L) only.

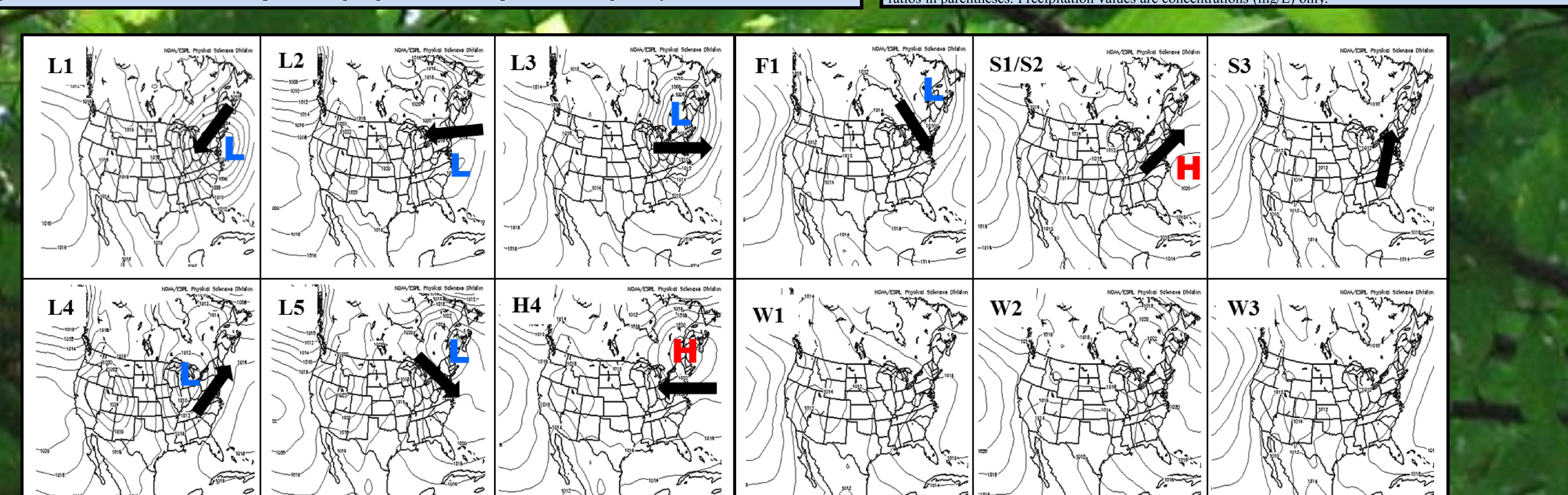

Fig. 13 Sea level pressure maps of storm events sampled during the 2007 to 2012 study period. Wind direction over the study region is indicated by black arrows.

RESULTS & DISCUSSION:

- Synoptic classification can be applied to forest hydrologic and solute fluxes to reduce the number of independent meteorological variables. Differences in solute flux between storm classifications is evident and may be used to estimate forest nutrient inputs.
- *Solute concentrations in precipitation* were largest during W2, a weakly defined weather pattern associated with localized precipitation. The study site is situated in a large metropolitan region, so local air masses may be enriched with pollutants and aerosols. Solute concentrations were lowest during several synoptic types, especially L1, a strong coastal low. Associated with offshore winds, this pattern has limited access to anthropogenic solute sources and may also exhibit solute dilution due to large rainfall quantities.
- *Solute concentrations in throughfall and stemflow* were commonly greatest in L2, a weaker coastal low. This pattern is associated with large quantities of rainfall that are able to saturate the forest canopy and maximize wash-off of antecedent dry deposition and canopy leaching. Solute concentrations were occasionally lowest in synoptic types associated with southerly/southeasterly flow (*e.g.,* S2, W1, W3). These air masses are likely less influenced by anthropogenic activities than those from the west and northwest (*i.e.,* the strongly industrialized regions of the U.S.) and may not have the capacity of saturate the forest canopy.
- *Enrichment ratios in throughfall and stemflow* were commonly smallest during F1 (cold front), W1, and L1 patterns. Cold front patterns were associated with fast moving storms that moved through the forest canopy very quickly, resulting in minimal residence time and canopy leach potential. W1 patterns were also associated with high intensity rainfall events in addition to low initial solute concentrations in precipitation. L1 patterns also had very low initial precipitation solute concentrations, which could reduce enrichment potential.
- As there are several pathways for throughfall and stemflow biogeochemistry to be altered (*i.e.,* dry deposition, canopy leaching/uptake), future research efforts will be aimed towards separating biogeochemical flux components and whether this may lead to even better classification results.

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