FINAL REPORT: Improving Land-Surface Modeling of Evapotranspiration Processes in Tropical Forests

1. COVER PAGE

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Project Title:

Improving Land-Surface Modeling of Evapotranspiration Processes in Tropical Forests

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2. EXECUTIVE SUMMARY

Land surface models are used to represent terrestrial processes that shape global climate; examples of these processes include evaporation, plant water use, and photosynthesis. While much progress has been made to improve and refine these models, some hydrological processes are not well captured, which hinders our ability to understand land-atmosphere interactions and ultimately to predict impacts of climate change on water resources. The inadequate representation of evapotranspiration may partly explain why global climate models do not match observed precipitation patterns. Multiple factors contribute to this problem. In moist tropical regions, high humidity, leaf wetness, and cloud cover combine to suppress forest water use and possibly reduce forest growth in ways that are poorly understood. Mountainous areas pose additional difficulties, as standard modeling and measurement techniques are not readily applied in rough terrain.

In this project, we aimed to improve our understanding and modeling of fluxes of water vapor and carbon dioxide to and from tropical forests. To do this, we collected a suite of data from the mountainous rainforest surrounding the Texas A&M Soltis Center in San Ramon, Costa Rica. From 2014 to 2018, a suite of variables were measured, including: in-canopy profiles of water vapor, carbon dioxide, temperature, light, and leaf wetness; transpiration, evapotranspiration, carbon flux, and soil respiration; and local weather conditions. Leaf-scale measurements were used to find photosynthesis rates and derive their parameters. Using this data set, we were able to better quantify the relationships between assimilation and transpiration and their main drivers in tropical forests. These variables were namely available light, vapor pressure deficit, and leaf wetness, but not soil moisture, which exerted no detectable control. We also showed the vertical variability in canopy microclimates and how neglecting forest layers in models may misrepresent overall fluxes.

The data were then used to test and refine evapotranspiration and energy budget formulations in the Community Land Model. Fluxes and energy budget components were compared to simulated values from CLM4.5 and CLM.5. The biggest discrepancies arose from hillslope shading effects, particularly mismatches in afternoon carbon fluxes, with notable differences in transpiration rates and sap flux due to capacitance in large trees. Secondary, but still significant issues included unrealistic leaf wetness and leaf drying rates, as well as air and vegetation temperatures, both of which were likely linked to CLM's formulations controlling wet leaf and sunlit/shaded leaf fractions. Modeling multiple layers in the canopy via the newly released CLM-ml and making adjustments to existing parameters both show promise in resolving these issues.

In total, the project has produced 5 peer-reviewed articles, 24 presentations, 2 theses, 4 public outreach items, and 4 publically available datasets, to date. Additional products are expected pending the completion of an additional thesis. Data has also been shared with several collaborative networks, including PHENOCAM and SAPFLUXNET.

3. ACTIVITIES AND ACCOMPLISHMENTS

A) Overview of Objectives

The major goals of this project, as stated in the original proposal, were to:

- Measure hydrometeorological variables along in-canopy and above-canopy profiles at spatially distributed locations throughout a mountainous forest watershed in Costa Rica.
    - Determine sensible heat, water vapor, and CO_2 fluxes based on both a top-down and a bottom-up approach.
    - Evaluate the influence of canopy wetness, differential drying rates, and in-canopy micrometeorological gradients on the partitioning of transpiration and evaporation.
    - Characterize the contribution of slope and aspect to variations in latent energy fluxes under both wet and dry canopy conditions.
- Revise CLM to improve its estimates of evapotranspiration in tropical forests.
    - Reformulate CLM parameterizations of surface roughness length and flux resistances for montane tropical forests and wet canopy evapotranspiration for all tropical forests.
    - Compare results from the revised CLM model to fluxes measured at the Costa Rica site and those publically available from FLUXNET sites throughout the tropics and in other wet systems.
- Model tropical forests and their interactions with rainfall at regional scales using CLM coupled with an atmospheric model, WRF.
    - Use numerical experiments to determine the influence of evapotranspiration rates on regional scale precipitation.
    - Investigate the resilience of tropical forests to droughts and the dependence on land-atmosphere interactions simulated by models.

B) Description of Activities

<u>Phase 1</u>

During the first phase of the project, we monitored a suite of micrometeorological variables in the forest canopy at the Texas A&M Soltis Center in San Ramon, Costa Rica. The site originally had a meteorological tower, providing baseline atmospheric data from 2010 to the present. In-forest monitoring associated with this project began in late-summer 2014 and continues to the present. Measurements focused on understanding the drivers of transpiration and leaf surface evaporation within the canopy and the variability caused by changing light, water vapor saturation, and wind at varying heights within the forest. Canopy instrumentation was configured such that it measured each canopy zone: the understory or suppressed region, the midstory layer, and the emergent trees (Figure 1). Instruments included a trace gas (CO_2 and H_2O) profile system, two net radiometers, infrared temperature sensors, leaf wetness sensors, and air and soil temperature probes (Table 1). Using the eddy-covariance method, fluxes of trace gases above the midstory clearing were observed; however, due to the non-ideal configuration of the terrain (highly mountainous) and tower (limited height), only a portion of the data met QA/QC requirements. In order to better observe fluxes directly from vegetation, we modified our study to include the use of Grainier-style sap flux sensors, outfitting an array of trees near the tower. Sapflow monitoring began in 2013 and continued until 2017. All observation data through the 2017 calendar year has been processed and subject to QA/QC procedures.

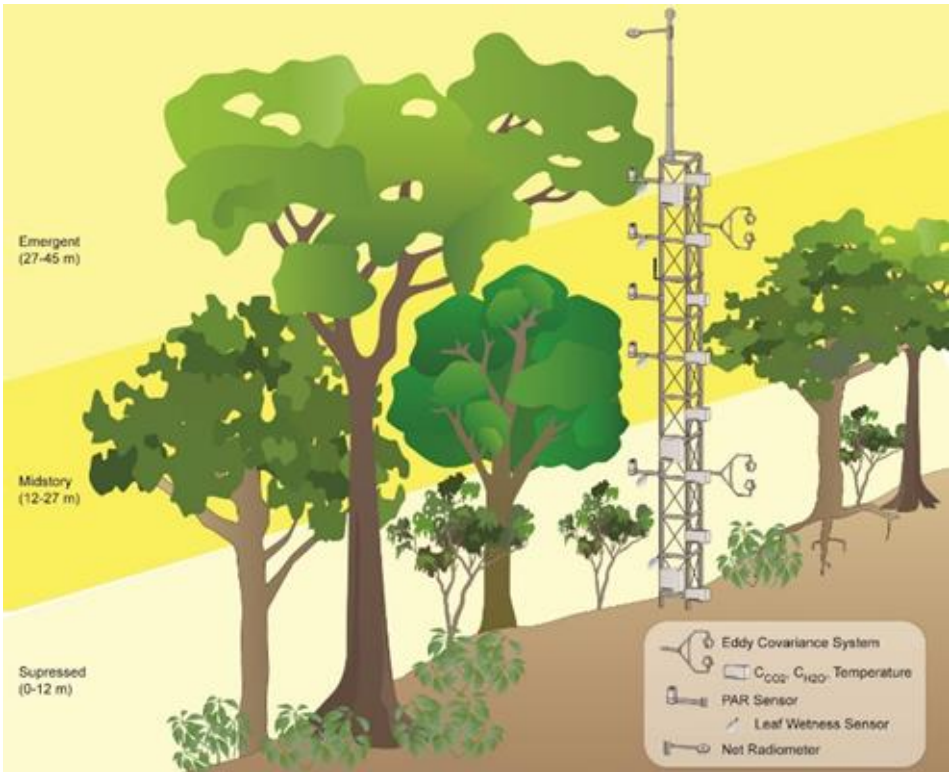

Figure 1: Study plot vegetation layers and canopy tower instrumentation, from Andrews et al.(in prep). The intensity of yellow shading represents approximate light extinction at a given height in the canopy. Predominant wind direction is into the page. Selected symbols obtained from of the Integration and Application Network Library, University of Maryland Center for Environmental Science.

Table 1: Canopy Tower Instrumentation, from Andrews et al. (In Prep)

Sensor	Model	Quantity	Vertical Level (m)	Measured Variables[a]
Three Dimensional Sonic Anemometer	CSAT3[b]	2	11 and 33	U,V,W,P_{air},T_{sonic}
CO_2/H_2O Gas Analyzer	LI-7200[c]	2	11 and 33	CO_2,H_2O
CO_2/H_2O Atmospheric Profile System	AP200[b]	1	1,5,11,16,22,27,33,38	CO_2,H_2O
Temperature	107[b]	8	1,5,11,16,22,27,33,38	T_{air}
Dielectric Leaf Wetness Sensor	LWS[d]	5	3,11,22,33,38	LW
Pyranometer	LI-190SB[c]	5	10,21,27,32,38	PAR
Net Radiometer	CNR1[e]	2	10 and 44	R_{net}
Net Radiometer	NR-LITE2[e]	1	34	R_{net}
Infrared Temperature Sensor	IRTS-P[f]	4	35 (all)	T_{leaf}

[a] U, V, and W = x, y, and z components of wind velocity, P_{air} = air pressure, T_{sonic} = air temperature derived from speed of sound, CO_2 = concentration of carbon dioxide, H_2O = concentration of water vapor, T_{air} = air temperature, LW = leaf wetness, PAR = photosynthetically active radiation, R_{net} = net radiation, T_{leaf} = leaf temperature

[b] Campbell Scientific, Logan, UT, USA; [c] LI-COR Biosciences, Lincoln, NE, USA; [d] Decagon Devices, Pullman, WA, USA

[e] Kipp & Zonen, Delft, The Netherlands; [f] Apogee Instruments, Logan, UT, USA

This portion of the study addressed the first objective, "Measure hydrometeorological variables along in-canopy and above-canopy profiles at spatially distributed locations throughout a mountainous forest watershed in Costa Rica." Results from this portion of the study have been or will be reported in the following peer-reviewed journal articles: Aparecido et al. (2016), Moore et al. (2017), and Andrews et al. (in prep). We have also contributed our data to several multi-site and synthesis studies examining transpiration and ecohydrological processes in the tropics, as reported by: Aparecido et al. (2017a), Moore and Aparecido (2018), and Grossiord et al. (in review). We have archived and made public the final data values as text files in the Texas A&M OAKTrust Digital Repository, a scholarly archive maintained by the university's library. (See "Section 4 – Other Products" for access details.)

Phase 2

During the second phase of this project, we developed a set of simulations in both CLM4.5 and CLM5 to compare the model's performance, at a point-scale, to the measurements at the Soltis Center field station. The simulations were forced with local meteorological data from 2010 to 2017. Critical outputs for comparison were net radiation, transpiration, leaf temperature, ground heat flux, and leaf wetness at diurnal and seasonal scales. In cases where the simulations performed poorly, we examined and altered both parameters and formulations associated with leaf wetness, photosynthesis, and radiative transfer (Figure 2). To address issues with the model's representation of in-canopy process, we created simulations using the new CLM-ml multi-layer canopy flux module (developed by G. Bonan at NCAR). We plan to complete the first comparison of this model with detailed tropical rainforest data, as we are uniquely positioned to provide this analysis.

This phase of the study will complete the second objective, "Revise CLM to improve its estimates of evapotranspiration in tropical forests." Results from this portion of the study have been reported at several conferences (AGU Chapman 2016, AGU Fall 2017). Publications are pending completion of the Ph.D student's doctoral dissertation; we plan to submit two peer-reviewed journal articles within the next six months: Song et al. (2018 – in prep) and Song et al. (2019 – in prep).

Unfortunately, we have, as yet, been unable to complete work relating to the third phase of the project, "Model tropical forests and their interactions with rainfall at regional scales using CLM coupled with an atmospheric model, WRF." It remains pending the hiring of a suitable post-doctoral researcher at PNNL.

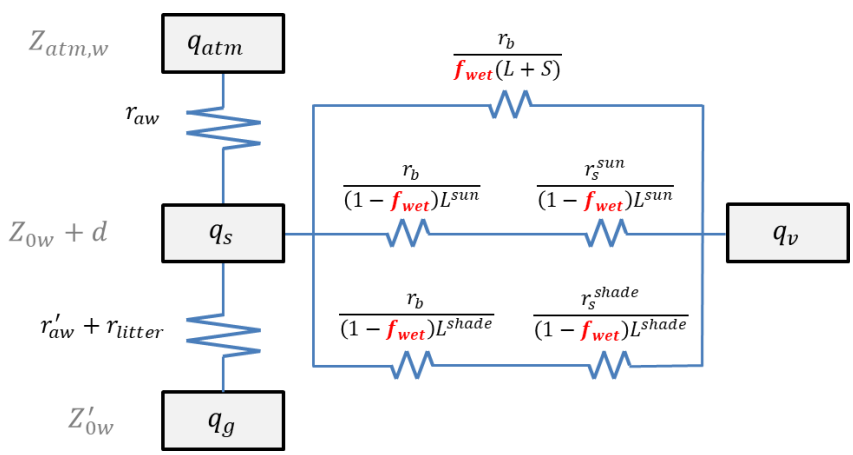

Figure 2: Schematic illustrating control exerted by leaf wetness fraction (f_{wet}) on water vapor (q), as modeled by CLM.

C) Summary of Findings

<u>Drivers of Evapotranspiration in Rainforests</u>

At the site, transpiration measured approximately 500 mm/yr, a fraction of the total mean annual precipitation of 4200 mm/yr. This indicated that the system was "energy limited" and that transpiration was highly suppressed. In this project, we aimed to quantify the strength of this driver and to test the hypothesis that variations in canopy relative humidity and leaf wetness were additional compounding influences. As typical for rainforests, we found that transpiration was indeed significantly dependent on incoming solar radiation for all sizes of trees, while vapor pressure deficit (VPD) explained a significant portion of its additional variability in larger trees (Figure 3). However, these two variables were not sufficient to explain all controls on transpiration. Using leaf wetness data, we were able to identify statistically significant differences in transpiration from trees depending on their current conditions (Figure 4). Wet leaf conditions were associated with a 52% decrease in daily total transpiration, primarily due to the effects on dominant and mid-story trees. Water use by understory trees changed relatively little, due to their more consistently dark, damp environments.

The vertical patterns of these drivers were also apparent in the canopy profiles of water vapor concentration, vapor pressure deficit, photosynthetically active radiation (PAR), and leaf wetness (Figure 5). As depth into the canopy increased, VPD and PAR declined as well, with notable inflection points in the mid-story and near the

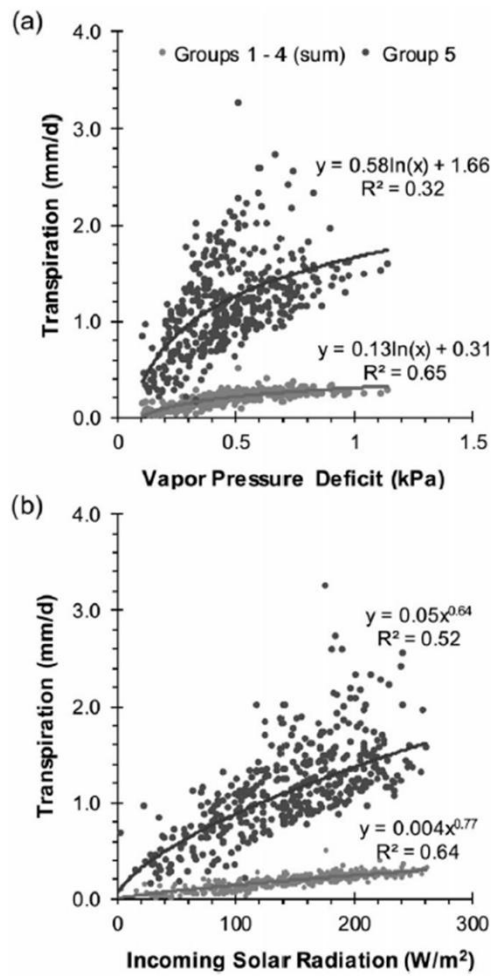

Figure 3: Daily stand transpiration (mm/d) in relation to average vapor pressure deficit (a) and incoming solar radiation (b) partitioned by size class, with small to large trees (light grey) having relatively lower transpiration than the largest trees (dark grey). Reprinted from Moore et al. (2017).

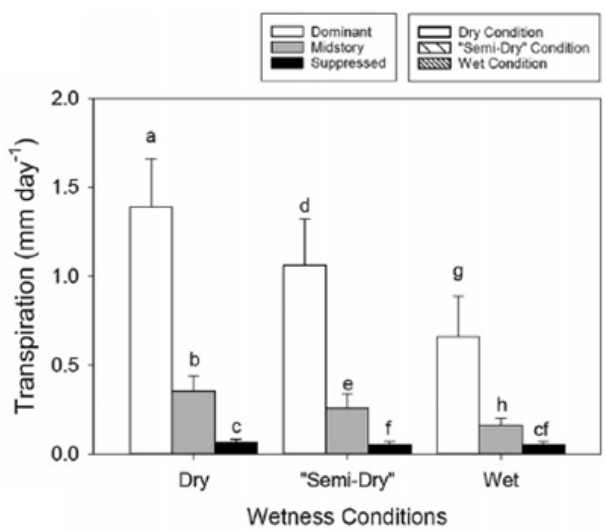

Figure 4: Influence of leaf wetness conditions and tree size/location on stand transpiration, with letters indicating significant differences ($p<0.05$). Reprinted from Aparecido et al. (2016).

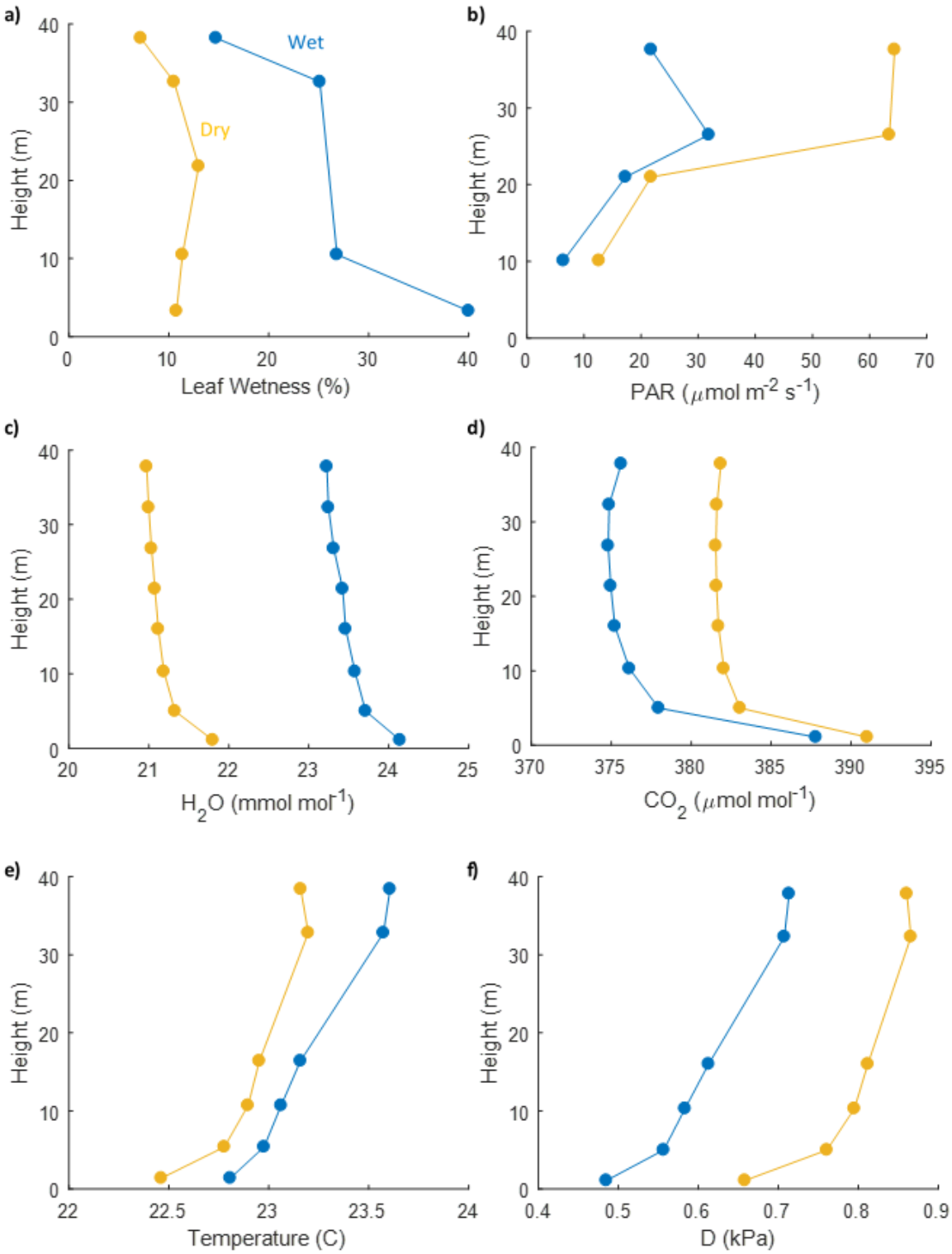

Figure 5: Average vertical sub-canopy profiles of micrometeorological variables during wettest months (June and September) and driest months (March and April) for: a) Percentage Leaf Wetness, b) Photosynthetically Active Radiation (PAR), c) CO2 Concentration, d) H2O Concentration, e) Ambient Air Temperature (Ta), and f) Vapor Pressure Deficit (D). From Andrews et al. (in prep).

forest floor. During the “less wet” season, drivers of transpiration were enhanced. Generally, seasonal differences did not affect the shape of the profile; however leaf wetness was a notable exception. Understory leaves began to experience dry conditions more frequently, although their contribution to total stand transpiration remained minimal.

Leaf-to-Canopy Scale Responses to Wetness

Initial observations suggested differential drying rates not just at various layers of the canopy, but across different tropical tree species. Although not originally an objective of the study, we found that it was critically important to better understand leaf dry-down and its effects on photosynthesis rates. We found significant variability among drying times of leaves from trees common to the Soltis Center forest (Figure 6), with leaf traits such as indented veins, water repellent surfaces, and trichomes (Figure 7) altering these retention times. Contrary to our hypothesis, photosynthesis was not consistently reduced in wet leaves (Figure 8), or even wet amphistomatous leaves. Some species has higher photosynthesis rates when wet, suggesting a preference for the cooler, more humid conditions of the forest understory. In species that did experience reduced photosynthesis when wet, recovery was controlled by the leaf traits that affected drying times, namely water repellency. These findings have mixed implications for the performance of models such as CLM. Here, it is appropriate that formulas of stomatal conductance used for photosynthesis should be decoupled from leaf wetness, and solely rely on vapor pressure deficit and leaf temperature. However, it also suggests that location of leaves within the canopy and variations in these values within the canopy will be influential, making big-leaf and sun/shade leaf formulations less reliable.

Figure 7: Examples of leaf water retention in species found at the Soltis Center: a) water channeled through indented veins, b) water beading on repellant surface, c) thin film of water on adherent surface, and d) leaf tip wetness on a trichome covered surface. Reprinted from Aparecido et al. (2017).

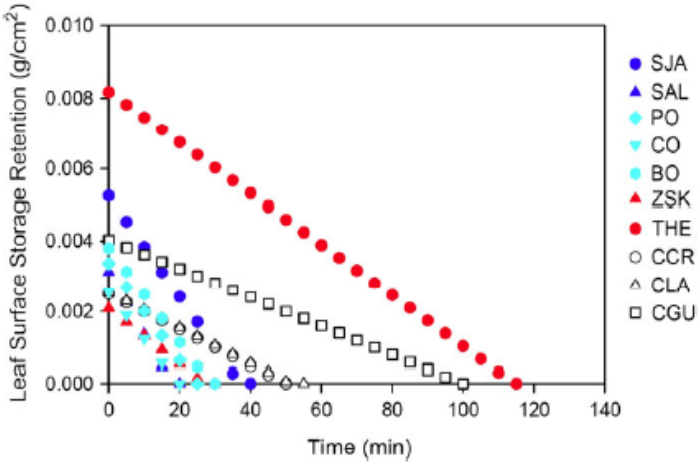

Figure 6: Laboratory dry-down curves for tropical species (filled shapes) and savanna species (open shapes). Reprinted from Aparecido et al. (2017).

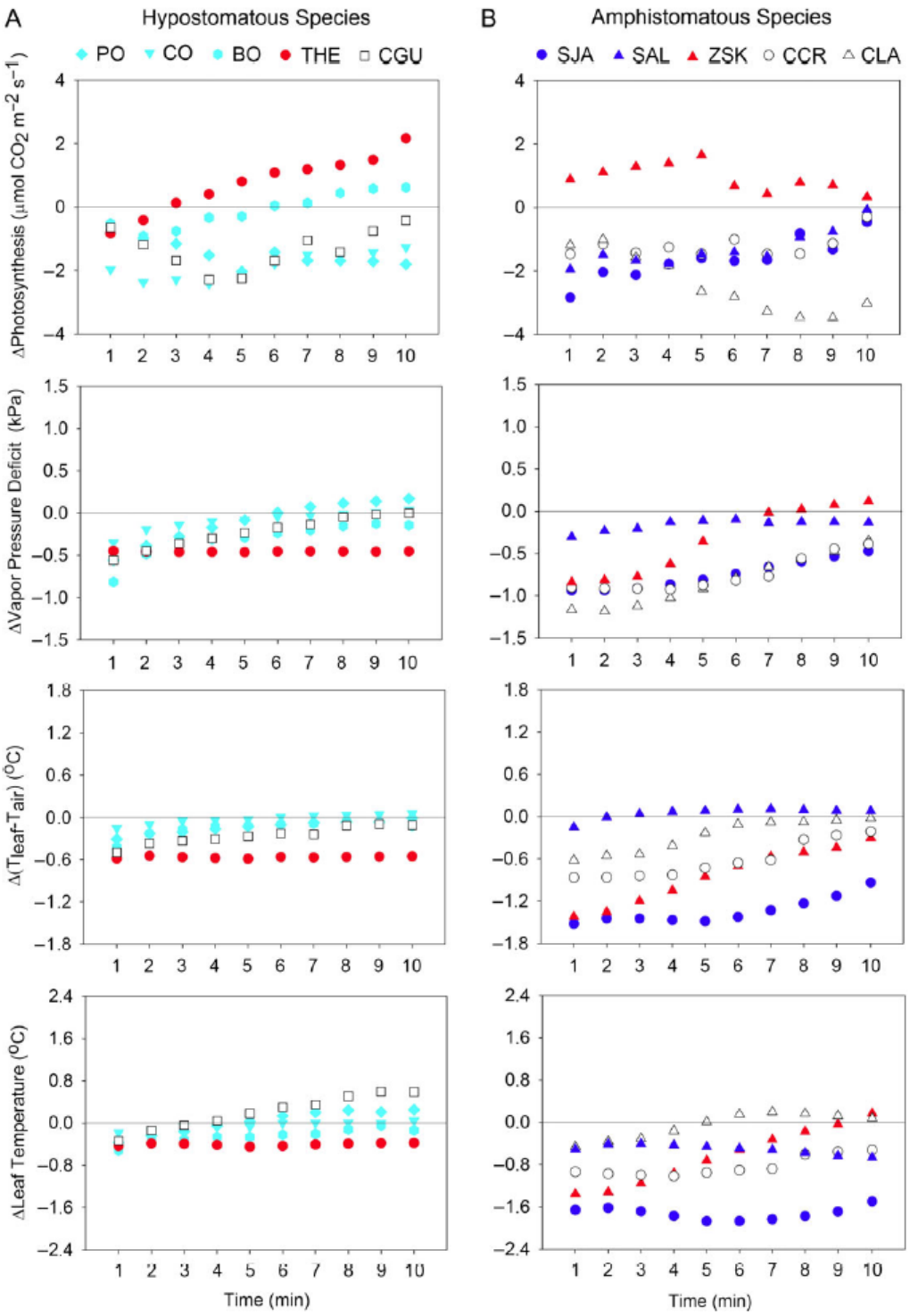

Figure 8: Normalized average photosynthetic response of the sampled species after a simulated rain event (t=0) and subsequent drying period (t_{dry}), as well as its potential micrometeorological drivers. Tropical species are shown as filled shapes and savanna species as open shapes. Graphs are divided into hypostomatous species (stomata on lower surface, left) and amphistomatous leaves (stomata on both surfaces, right).

Performance of CLM under Wet Leaf and Mountainous Conditions

We found that both CLM4.5 and CLM5 overestimated transpiration from and carbon flux to the rainforest at the Soltis Center, a failure likely stemming from both leaf wetness and hillslope factors. Diurnal plots of measured albedo and PAR show that they are skewed toward the morning, consistent with the east-facing slope (Figure 9a and b). However, these are not captured in either version of CLM, leading to the over-prediction of gross primary production (GPP) during the afternoon (Figure 9c). In contrast to the other variables, we found that transpiration was skewed towards the afternoon (Figure 9d), likely due to the inherent time delay between when very tall trees begin to transpire and when sap flux measurements located near their bases can first sense it. While transpiration is out of phase at the hourly scale, total daily transpiration was predicted fairly well in CLM. Additionally, CLM over-predicted both GPP and total evapotranspiration through much of the day; we suspect this is due to one emergent tree causing extensive amounts of shading, but being out of the flux footprint of the EC system. Appropriately adjusting the incoming solar radiation in CLM provided predictions that more reasonably matched the site values. These findings suggest that a more advanced radiative transfer model, which resolves canopy layers and topographic slope, is necessary to accurately predict fluxes at this and other mountainous sites.

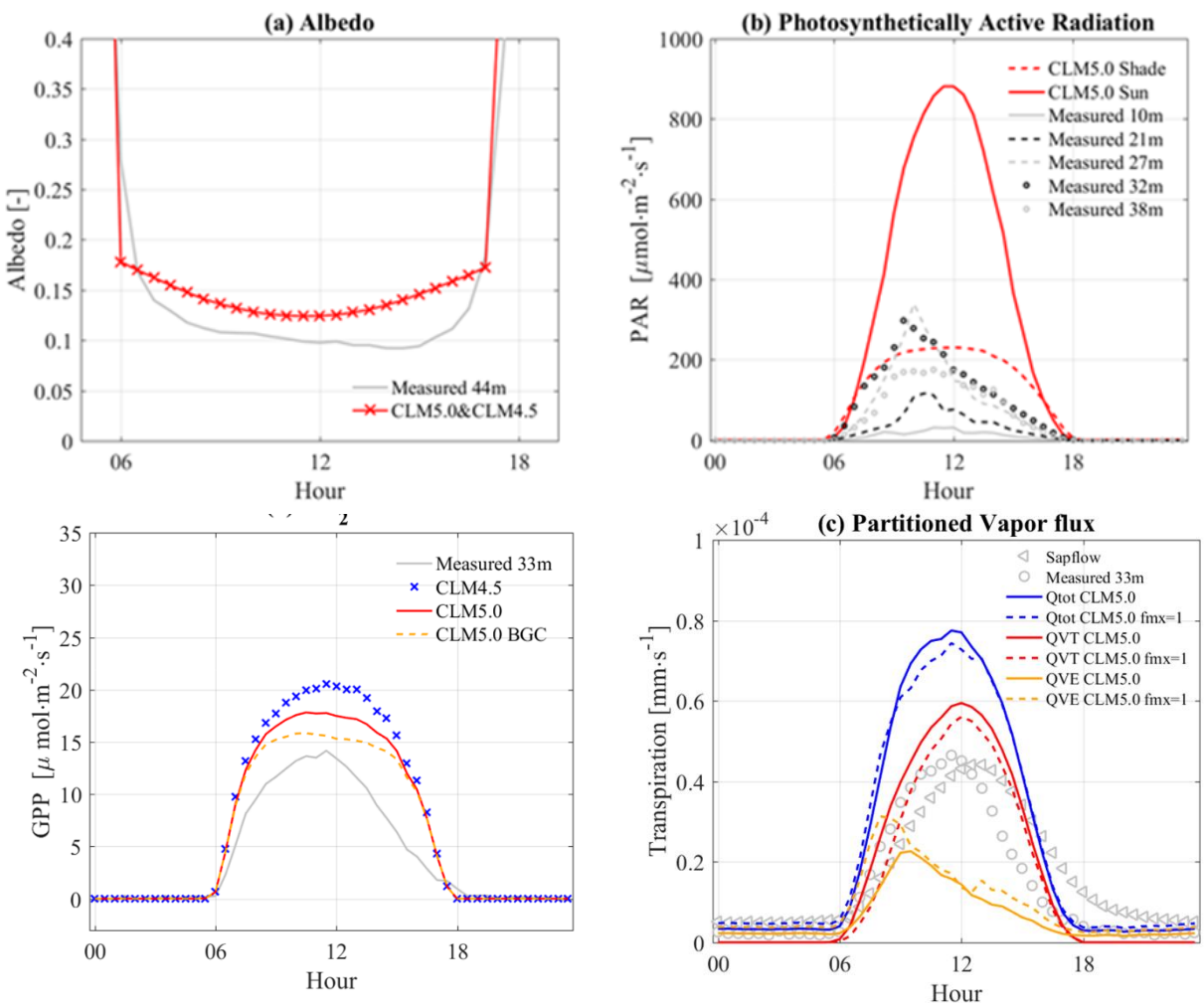

Figure 9: Diurnal variation in albedo (a), photosynthetically active radiation (b), gross primary production (c), and water vapor fluxes (d), as measured and as predicted by CLM.

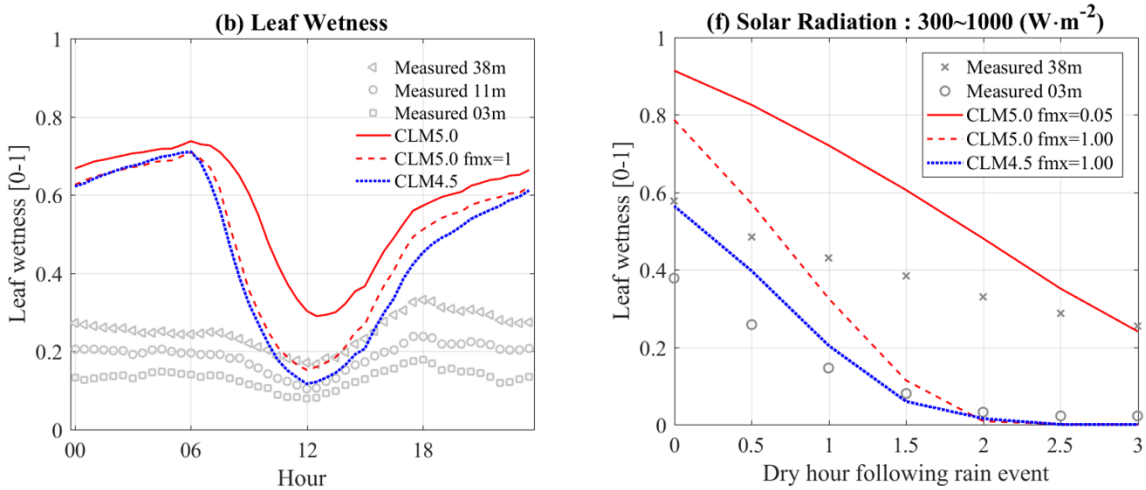

Figure 10: Diurnal patterns of leaf wetness (a) and canopy drying times (b).

CLM is also over-predicting leaf wetness, but under-predicting its consequences. During the mid-day hours, measured and modeled values were similar, but they deviated significantly during the evening hours (Figure 10a). This difference could be attributable to an over-prediction in the amount of water retained on the upper canopy leaves or to differences in the meaning and scale of percent wetness for the model. However, when we compare drying patterns after a rain event, we see that CLM shows a much quicker drying rate. Again, we note that this discrepancy is important for accurate predictions of both GPP and canopy evaporation, and that it could potentially be improved by resolving additional canopy layers.

4. PRODUCTS

Journal Articles – Published

[1] Moore, G.W. and L.M.T. Aparecido (2018 – in press) Sap flux measurements in wet tropical forests: unique challenges and opportunities. *Acta Horticulturae*.

[2] Moore, G., G. Orozco‡, L.M.T. Aparecido†, G.R. Miller (2018). Upscaling transpiration in diverse forests: Insights from a tropical pre-montane site, *Ecohydrology*, 11:e1920, doi: 10.1002/eco.1920.

[3] Aparecido, L.M.T., G.S. Teodoro, G. Mosquera, M. Brum, F.V. Barros, P.V. Pompeu, M. Rodas, P. Lazo, C.S. Muller, M. Mulligan, H. Asbjornsen, G.W. Moore, and R.S. Oliveira (2017a). Ecohydrological drivers of Neotropical vegetation in montane ecosystems, *Ecohydrology*, 11(3), doi: 10.1002/eco.1932.

[4] Aparecido, L.M.T., G.R. Miller, A.T. Cahill, and G.W. Moore (2017b). Photosynthetic responses to leaf surface wetness in tropical and semiarid savanna plants with varying leaf traits, Tree Physiology, doi: 10.1093/treephys/tpx092.

[5] Aparecido, L.M.T., G.R. Miller, A.T. Cahill, and G.W. Moore. (2016). Comparison of Tree Transpiration under Wet and Dry Canopy Conditions in a Costa Rican Premontane Tropical Forest, Hydrological Processes, doi:10.1002/hyp.10960.

Journal Articles – In Progress or Review

[6] Grossiord, C., B. Christoffersen, K. Anderson-Teixeira, L.M.T. Aparecido, C. Berry, C. Baraloto, D. Bonal, I. Borrego, J. Chambers, D. Christianson, M. Detto, B. Faybishenko, C. Fortunel, B. Gimenez, K.J. Jardine, L. Kueppers, G.R. Miller, G.W. Moore, R. Negron-Juarez, C. Stahl, N. Swenson, C. Varadharajan, J. Warren, B. Wolfe, L. Wei, J.S. Wright, C. Xu, and N. McDowell (2018 - In review), Climate and leaf mass per area, not wood density, control tree sap flux across Latin American tropical forests, submitted to *Ecology Letters*.

[7] Aparecido, L.M.T., G.R. Miller, A. Cahill, J. Heilman, R. Andrews, and G.W. Moore (2018 - In preparation). Response of leaf and whole-tree canopy conductance to wet conditions within a mature premontane tropical forest in Costa Rica, for submission to *Agricultural and Forest Meteorology*.

[8] Aparecido, L.M.T., C.E. Cooper, C.F. Miniat, G.R. Miller, and G.W. Moore (2019 - In preparation). Comparison of radial variability of sap flow between tropical and temperate trees with deep sapwood, for submission to *Tree Physiology*.

[9] Andrews, R., G.R. Miller, A.T. Cahill, and G.W. Moore (2018 - In preparation). Vertical profiles of micrometeorological and biophysical variables in a tropical montane forest canopy, for submission to *Agricultural and Forest Meteorology*.

[10] Song, J., G.R. Miller, L.M.T. Aparecido, A.T. Cahill, and G.W. Moore (2018 - In preparation), Modeling land surface processes over a mountainous rainforest in Costa Rica using CLM4.5 and CLM5, for submission to *Hydrological Processes*.

[11] Song, J., G.R. Miller, A.T. Cahill, and G.W. Moore (2019 - In preparation), Modeling subcanopy biometeorlogical processes in a tropical pre-montane rainforest, for submission to *Hydrological Processes*.

Presentations – Completed

[1] Schwandner, F.M., J. B. Fisher, G.Asner, D. Schimel, R. Norby, C. Frankenberg, R. Fisher, C. Deering, A. Braverman, U. Seibt, G. Miller, A. Sanchez-Azofeifa, A. Diaz, E. Duarte, J.M. De Moor, R. Cordero Solorazano, J. Lewicki, G. Matheou, D. Pieri, C. Miller, R. Pavlick. (2018) A Window into the Future of the Earth, Hidden in the Jungles of Costa Rica's Volcanoes, BG05-SE-D2-AM1-304B-008, abstract for oral presentation at the Annual Meeting of the Asia Oceania Geosciences Society, Honolulu, Hawaii.

[2] Varadharajan, C., G. Pasterello, B. Faybishenko, D.S. Christianson, V.C. Hendrix, B.Christoffersen, M.Detto, K. J. Jardine, R. Negron-Juarez, B.O. Gimenez, C.Grossiord, T. L. Powell, L.M. Aparecido†, G. Miller, G. Moore, H. Asbjornsen, C. Berry, D. Bonal, J.M. Warren, B.T. Wolfe, J.Q. Chambers, L.M. Kueppers, N.G. McDowell, D. Agarwal (2018) "NGEE Tropics Data Management and Products," abstract for oral presentation at the DOE ESS PI meeting.

[3] Aparecido, L.M.T., G.R. Miller, A. Cahill, R. Andrews, and G.W.Moore. (2017), Response of leaf and whole-tree canopy conductance to wet conditions within a mature premontane tropical forest in Costa Rica, abstract for presentation at the AGU Fall Meeting, New Orleans, Louisiana.

[4] Song, J., G.R. Miller, A. Cahill, L.M.T. Aparecido, and G.W.Moore. (2017) Earth System Modeling Tested for CLM4.5 in a Costa Rican Tropical Montane Rainforest, abstract for presentation at the AGU Fall Meeting, New Orleans, Louisiana.

[5] Moore, G.W., L.M.T. Aparecido, A. Jaimes. (2017) Reducing uncertainty in transpiration in wet tropical forests and upscaling sap flux measurements in complex heterogeneous systems, invited abstract for presentation at the AGU Fall Meeting, New Orleans, Louisiana.

[6] Fisher, J. B., F.M. Schwandner, G.Asner, D. Schimel, M. Keller, R. Norby, R. Pavlick, A. Braverman, D. Pieri, A. Diaz, M. Gutierrez, E. Duarte, J. Lewicki, C.Manning, C. Deering, U. Seibt, G. Miller, D. Drewry, J. Chambers. (2017) A window into the future of the Earth, hidden in the jungles of Costa Rica's volcanoes, abstract for oral presentation at the AGU Fall Meeting, New Orleans, Louisiana.

[7] Benson, K.; Aparecido, L.M.T.; Moore, G.W. (2017) Variation in tropical tree wood density as related to water use and tree growth. Abstract for poster presentation at the Undergraduate Research Summer Poster Session, College Station, Texas, USA.

[8] Finstad, K., A. Campbell, C. Koven, G. Miller, J. Pett-Ridge, A. Plante, E. Veldkamp, N. Zhang, and K. McFarlane. (2017) "Measurements and modeling of carbon turnover time in tropical forest soils, poster presentation at U.S. Department of Engineering Terrestrial Ecosystem Science PI Meeting, Potomac, MD.

[9] Moore, G.W., and L.M.T. Aparecido, (2017) Sap flux measurements in wet tropical forests: unique challenges and opportunities. Abstract for oral presentation at the 10th International Workshop on Sap flow, Fullerton, California (May 22-26, 2017).

[10] Moore, G.W., and L.M.T. Aparecido, (2016). Sapflow responses to drought across a wide range of species in Costa RicaNGEE-Tropics ENSO Research Meeting, San Francisco, California.

[11] Miller, G.R., and G.W. Moore (2016), Water Cycle of a Transitional Rainforest Hydrology Research at the Texas A&M Soltis Center, oral presentation at the Monteverde-Arenal Bioregion Initiative Conference, Monteverde, Costa Rica.

[12] Moore, G.W., L.M.T. Aparecido, A. Cahill, and G.R. Miller (2016), Ecosystem responses to wet leaf conditions in tropical montane forests of Costa Rica, abstract for poster presentation at the NGEE

Tropics Annual Meeting, Washington, DC.

[13] G.W. Moore, L.M.T. Aparecido, A. Jaimes, G.R. Miller (2016), A review of wet tropical forest transpiration: lessons learned and a path forward, abstract for poster presentation at the AGU Chapman Conference on Tropical Ecohydrology, Cuenca, Ecuador.

[14] L.M.T. Aparecido, G.R. Miller, A.T. Cahill, G.W. Moore (2016), Photosynthetic responses to leaf surface wetness in tropical and semiarid savannah trees with varying leaf traits, abstract for poster presentation at the AGU Chapman Conference on Tropical Ecohydrology, Cuenca, Ecuador.

[15] Cahill, A.T., J. Song, G.R. Miller, and G.W. Moore (2016), Subcanopy modeling of CO_2 and H_2O fluxes in a Costa Rican tropical premontane canopy, abstract for poster presentation at the AGU Chapman Conference on Tropical Ecohydrology, Cuenca, Ecuador.

[16] Miller, G.R., R.A. Andrews, A.T. Cahill, and G.W. Moore, (2016), Data for Next Generation Earth System Models: Profiles of Micrometeorological Variables in a Tropical Montane Rainforest Canopy, abstract for poster presentation at the AGU Chapman Conference on Tropical Ecohydrology, Cuenca, Ecuador.

[17] Aparecido, L.M.T. (2016) Photosynthetic responses to leaf surface wetness in tropical and semiarid savannah trees with varying leaf traits. Abstract for oral presentation at the Texas A&M University Ecological Integration Symposium, College Station, TX, USA.

[18] Andrews, R., G.R. Miller, A.T. Cahill, G.W. Moore, L.M.T. Aparecido, (2015), Water vapor exchange in a Costa Rican lower montane tropical forest, H43B-1498, abstract for poster presentation at the AGU Fall Meeting, San Francisco, California.

[19] Aparecido, L.M.T., (2015) Tree transpiration response to wet and dry canopy conditions in a montane tropical forest. Ecological Integration Symposium, March 26-27, 2015; Texas A&M University – College Station, TX, USA.

[20] Moore, G.W., G.R. Miller, A.T. Cahill, L.M.T. Aparecido, and R. Andrews (2015), Partitioning evaporation and transpiration in wet canopies, abstract for poster presentation at the 5th NACP and AmeriFlux Joint Meeting, Jan. 26 - 29, Washington D.C.

[21] Cahill, A.T., G.R. Miller, G.W. Moore, and C. Merket (2014), The effect of variation of rainfall across different time scales on subcanopy CO2 storage and flux in a Costa Rican rainforest, H21F-0792, abstract for poster presentation at the AGU Fall Meeting, San Francisco, California.

[22] Aparecido, L.M.T., G.W. Moore, G.R. Miller, and A.T. Cahill (2014), Ecohydrological response of trees to leaf wetness gradients under wet and dry canopy conditions in a montane tropical forest, H21F-0796, abstract for poster presentation at the AGU Fall Meeting, San Francisco, California.

[23] Miller, G.R., A.T. Cahill, G.W. Moore, and R. Leung (2014), Improving Land-Surface Modeling of Evapotranspiration Processes in Tropical Forests, abstract for poster presentation at the 2014 Climate Modeling PI Meeting, May 12-15, 2014, Potomac, Maryland.

[24] Cahill, A.T., G.R. Miller, and G.W. Moore (2014), Improving Land-Surface Modeling of Evapotranspiration Processes in Tropical Forests, abstract for poster presentation at the 2014 Joint Terrestrial Ecosystem Science and Subsurface Biogeochemistry PI Meeting, May 6-7, 2014, Potomac, Maryland.

Presentations – Pending

[25] McFarlane, K., K. Finstad, N. Zhang, A. Campbell, J. Pett-Ridge, C. Koven, G. Miller, J. Powers, O. van Straaten, B. Turner, E. Veldkamp, E. Yepez, Q. Zhu (2019 – upcoming), "Neo-tropical forest response to a drier future: a synthesis of measurements and modeling of soil carbon stocks and turnover times," abstract submitted for presentation at Soil Science Society of America Annual Meeting, San Diego, CA.

[26] Prior, B., J. K. Brumbelow, G. Miller, G. Moore, and (2018 - upcoming), "Using UAV Technology to Collect Vertical Temperature and Relative Humidity Profiles over a Tropical Montane Rainforest," abstract submitted for poster presentation at AGU Fall Meeting, Washington DC.

[27] Duffy, A., G. Miller, G. Moore, and K. Brumbelow (2018 - upcoming), "Correlation of Fog/Rain Presence and Plant Functions in a Tropical Montane Rainforest," abstract submitted for poster presentation at AGU Fall Meeting, Washington DC.

[28] Rivera, M. , A. Keebler, A.P. Smith, G. Miller, J. Aitkenhead-Peterson, and G. Moore (2018 - upcoming), "The effect of tropical land use on soil carbon dynamics: Does reforestation mitigate greenhouse gas emissions?" abstract submitted for poster presentation at AGU Fall Meeting, Washington DC.

[29] McFarlane, K., K. Finstad, N. Zhang, A. Campbell, J. Pett-Ridge, C. Koven, G. Miller, J. Powers, O. van Straaten, B. Turner, E. Veldkamp, E. Yepez, Q. Zhu (2018 – upcoming), "Neo-tropical forest response to a drier future: a synthesis of measurements and modeling of soil carbon stocks and turnover times," abstract submitted for presentation at AGU Fall Meeting, Washington DC.

Theses and Dissertations

[1] Aparecido, L.M.T. (2017) Plant-atmosphere responses to wet canopy conditions in a mature tropical forest. PhD dissertation, Texas A&M University.

[2] Andrews, R. (2016). The Temporal Variation of Vertical Micrometeorological Profiles in a Lower Montane Tropical Forest. Master's thesis, Texas A&M University.

Outreach and Media Highlights

[1] txH$_2$O, Texas Water Resources Institute, June 2018, "Compiling a Puzzle: Researchers study water cycle in the tropics to help refine climate model," http://twri.tamu.edu/publications/txh2o/spring-2018/compiling-a-puzzle/

[2] txH$_2$O, Texas Water Resources Institute, June 2018, "Boundless opportunities: Students travel abroad to pursue water resources studies," http://twri.tamu.edu/publications/txh2o/spring-2018/boundless-opportunities/

[3] American Geophysical Union's *EOS*, April 15, 2015, "Postcards from the Field" featured Luiza Aparecido and Soltis Center research site, https://eos.org/wp-content/uploads/2015/04/4.15_Magazine_web.pdf

[4] Texas A&M Spirit Magazine, Fall 2014, "Costa Rican Haven: Aggies thrive at Texas A&M's tropical research hub," quarterly publication of the Former Student Association, http://spiritarchive.txamfoundation.com/Fall2014Spirit/html5/index.html?page.

Networks and Collaborations Developed

- Provided data and co-authored articles in the multi-site NGEE Tropics sapflow synthesis project lead by Bradley Christoffersen (Drs. Moore, Aparecido, and Miller).
- Lead synthesis paper (Drs. Aparecido, Moore) on tropical ecohydrology as a result of AGU Chapman Conference in Ecuador.
- Selected as Cal/Val Lead (Dr. Miller) and site (Soltis Center) on major proposal by NASA-JPL team to the Earth Venture Suborbital program. If funded, the project, ELEVATE, would examine the effects of CO_2 enrichment on tropical forest vegetation, using volcanic emissions as a proxy for climate change.
- Submitted dataset to SAPFLUXNET (http://sapfluxnet.creaf.cat/app).
- Joined the NSF sponsored PHENOCAM Network (https://phenocam.sr.unh.edu/webcam/sites/soltis/).

Other Products

- Comprehensive MySQL database of 5- to 30-minute weather, biometeorological, and flux data spanning 2014-2018, hosted on Amazon Web Service
- Project website: https://soltiscanopy.civil.tamu.edu/.
- Data archived in accordance with the data management plan at:
    - Miller, Gretchen; Moore, Georgianne; Cahill, Anthony; Aparecido, Luiza; Andrews, Ryan; Song, Jaeyoung (2018). Texas A&M Soltis Center Forest Canopy Data, 2014. Available electronically from http://hdl.handle.net/1969.1/169521.2.
    - Miller, Gretchen; Moore, Georgianne; Cahill, Anthony; Aparecido, Luiza; Andrews, Ryan; Song, Jaeyoung (2018). Texas A&M Soltis Center Forest Canopy Data, 2015. Available electronically from http://hdl.handle.net/1969.1/169522.
    - Miller, Gretchen; Moore, Georgianne; Cahill, Anthony; Aparecido, Luiza; Andrews, Ryan; Song, Jaeyoung (2018). Texas A&M Soltis Center Forest Canopy Data, 2016. Available electronically from http://hdl.handle.net/1969.1/169523.
    - Miller, Gretchen; Moore, Georgianne; Cahill, Anthony; Aparecido, Luiza; Song, Jaeyoung (2018). Texas A&M Soltis Center Forest Canopy Data, 2017. Available electronically from http://hdl.handle.net/1969.1/169524.
- All published journal articles have been submitted to DOE STI Management System.

Graduate Students Trained

- Luiza Maria T. Aparecido, PhD in Ecosystem Science
- Jaeyoung Song, PhD Candidate in Civil Engineering
- Ryan Andrews, MS in Civil Engineering