Editor's Comments (Received 07 October 2019)

We thank the editor for her time and summary of the reviewers' comments, which we address in detail in the point-by-point responses below. Additionally, response to the editor's comments are given below (**EC: Editor comment; AR: Author response**), with all line numbers corresponding to the revised manuscript unless otherwise noted.

EC1: As seen in the 2 review reports, both reviewers appreciate your attempt to estimate interception by looking at shallow soil moisture content. However, they also share concerns on:
1) lack of validation data
2) limited throughfall data (in relation to spatial variability)
3) effect of antecedent soil moisture, lateral flow and preferential flow

> **AR1:** We appreciate the editor's summary of the reviewers' concerns and reply in detail about each subject in the responses below. Specifically, we address item #1 in **R1-C4** and **R2-C3**; item #2 in **R1-C7** and **R2-C2**; and item #3 in **R1-C5.** Regarding item #3, we note that the reviewers' comments about antecedent moisture were of support rather than concern, e.g., from **R1-C6:** *"…the new version addresses the problem of antecedent soil water content and its influence on the propagation of the wetting front by use of a soil hydrological model"* and **R1-C9:** "*The paper definitely allows drawing conclusions about how strongly different factors like LAI, %GC and antecedent soil moisture actually affect the top soil moisture response to rainfall*."

EC2: Despite the authors extensive reply, I still think their conclusions remain too strong. I do understand that this study was a 'bi-product' and therefore no validation data is available, however this does not justify limited founded conclusions. Therefore, I highly recommend to downtune your conclusions even more.

> **AR2:** Throughout the manuscript, we have revised the text to better emphasize that our work presents a new promising method for measuring interception, but that future work is needed to further support its application. Note that some revisions are new since our original response to reviewers per the editor's request. Below are examples of text where we have tempered our results and conclusions:
>
> Lines 40-43: "*These results suggest that whole-forest interception can be estimated using near-surface soil moisture time series, though additional direct comparisons would further support this assertion. Additionally, variability in interception across a single forest type underscores the need for expanded empirical measurement.*"
>
> Lines 306-309: "*However, we emphasize that a more robust validation of the method using co-located and contemporaneous measurement using standard techniques is warranted. Below we summarize the assumptions and methodological considerations that affect the potential utility and limitation of the method.*"

Lines 341-343: *"Broad agreement between our results and literature I_a values again supports the potential utility of our method for estimating this difficult-to-measure component of the water budget, though additional direct comparisons would further support this assertion."*

Lines 412-416: "*Additional soil moisture measurements would undoubtedly improve the accuracy of field estimates, and indeed we recommend that more direct methodological comparisons are needed. However, our results support the general applicability of the soil moisture-based approach for developing forest interception estimates across a wide range of hydroclimatic and forest structural settings*."

Lines 424-428: "*We propose that soil moisture-based estimates of β_s have the potential to more easily and appropriately represent combined forest interception relative to existing time- and labor-intensive field methods that fail to account for groundcover and litter interception. However, we emphasize that further experimental work is needed to validate this promising approach."*

Lines 431-435: *Finally, while our comparisons with other empirical measures of forest canopy interception should be treated cautiously, this approach yields values that are broadly consistent with the literature, and provide an estimate of combined canopy and groundcover storage capacity that has the potential to improve the accuracy of water balances models at scales from the soil column to watershed*.

EC3: Plus I would like to see: 1) What is the effect of the uncertainties in Gash plus Hydrus (separately but also together). Are these uncertainties not larger than the variability in soil moisture?

AR3: We used the Gash model to help determine B_s from our observations of P_s, which represents the rainfall amount required to saturate B_s and meet evaporative and infiltration demands. Similarly, other empirical methods (e.g., throughfall collection) estimate the rainfall required to saturate B_s and meet evaporative demands (but not infiltration) and can also use the Gash model to derive B_s by accounting for evaporation. As such, both approaches (i.e., throughfall collectors and our proposed soil moisture-based method) and the subsequent performance of the Gash model are driven by observations; we note that soil moisture measurement errors are likely smaller compared to direct throughfall measurements. However, we agree that use of the Hydrus model to estimate and account for infiltration adds additional uncertainty and have added such text (see our response to **R2-C4**). But, as we note in the manuscript, this issue can be substantially alleviated with shallower sensor placement.

EC4: 2) I appreciate your statement on total interception capacity. However, it's not so straightforward to simply add the two. First of their is a cascading effect of the two storages (first the canopy storage has to be fill, before the litter storage will be filled). This causes a time delay. Secondly, the atmospheric demand (± potential evaporation) is different for the canopy than for the litter. This causes a difference in the emptying time (time scale).

AR4: The approach that we propose does not explicitly include sequential or simultaneous filling of the discrete canopy and litter storages, or any attendant time lags, but rather treats them as one storage (β_s). We disagree with the assertion that discretized storage filling is strictly sequential (canopy storage has low retention efficiency, particularly for intense rain events, such that the litter will receive water even before the canopy is fully saturated), nor would we assert that the drainage of the discretized storages is strictly sequential (litter storage can lose water to evaporation even while the canopy storage is not empty). We do acknowledge that we ultimately assume infiltration occurs only after both storages are full. We maintain that the current practice of neglecting understory and litter interception is incorrect and creates important and unaccounted biases from the use of throughfall collectors to measure vadose zone recharge. Discretization of total interception storage into various finely parsed elements (e.g., top of canopy, mid-story, ground cover, litter) may be theoretically correct, but intractable to measure or model.

Given this, we simply argue that the above-ground storage response can be viewed as a single reservoir that fills and drains with climate variation. The time lags in both filling and draining discrete storage elements are interesting, but are almost certainly non-linear, and well beyond the scope of these or any measurements (including the most intensive field measurements, which assume a single canopy storage when this is clearly not the case) or even state-of-the-art modeling (which assume a single storage). This could be an area for further research for researchers keen to parse the interception storage into increasingly discretized parts, but we warrant that "lumping" is likely advantageous in practical situations and may indeed explain why a small number of measurements per site yielded stable and highly plausible β_s values.

EC5: 3) In your reply about lateral and preferential flow, you only refer to a change in 'arrival time'. However, both also (and maybe more importantly) cause a spatial redistribution. Here again the number of throughfall gauges and soil moisture probes becomes important.

AR5: Our replies to **R1-C5** and **R2-C2** focus on how preferential and lateral flow could affect arrival time due to its specific role in our methodological approach. Specifically, we use the time between rainfall onset and wetting front arrival at the sensor (T) in developing Equations 3-7, and use HYDRUS to simulate the time required for a soil moisture pulse to reach the sensor once infiltration begins (i.e., after β_s has been filled), which is $T- t$ in Eq. 7. We agree that both lateral and preferential flow can cause spatial redistribution of soil moisture, but the relevant outcome of such redistribution (from our methodological approach) is a change in arrival time. In the case of lateral flow, redistribution could cause a delay in first soil moisture response at the sensor as moisture is redistributed laterally in higher soil layers. For preferential flow, redistribution could cause either a delay or hastening of sensor response as moisture is redistributed either quickly to the sensor depth or quickly away from the sensor. In both cases, the specifics of how redistribution occurs may be important, but the outcome (a difference in arrival time) is what is germane to the method. Additionally, as we note in the manuscript, this issue (among others) can be substantially alleviated with shallower sensor placement.

EC6: 4) Please, carefully check your reference list. Some references are missing and many typos exist.

> **AR6:** Our sincere apologies! The reference list has been updated and closely proofread.

Anonymous Referee #1 (Received and published: 18 June 2019)

We thank the reviewer for his or her time and useful comments, which we have attempted to incorporate in manuscript revisions. We have also attempted to clarify and further justify the impact and utility of this work in response to specific reviewer concerns. Below are explanations of our responses to the reviewer's comments (**R1-C: Reviewer 1 comment; AR: Author response**), with all line numbers corresponding to the revised manuscript unless otherwise noted.

Major Comments

R1-C1: Remark: I have been a reviewer of a previous version of this manuscript submitted to Water Resources Research. By chance, the manuscript arrived a second time in my hands, now in HESS. The authors state that the new version is sufficiently different, so this is not a re-submission, but a new manuscript. I find substantial changes reflect a revision, which was expected. I would have appreciated, if the authors would have taken the time to phrase a point by point response, which would have allowed for a much more efficient review round. Please respect the time of the reviewer. Some of my concerns have been addressed, but others not. This review is a mixture of both my previous and new comments.

> **AR1:** We thank the reviewer for the thorough response and appreciate the effort taken in reviewing the manuscript a second time. While we understand that a point-by-point response would have been useful for guiding this second review, we of course had no idea to whom the manuscript would be sent. Thus, submitting a response to reviewers would have been inappropriate in the context of this new submission. For clarity, the WRR decision was to "revise and resubmit", which was our initial intent. However, our assessment of the reviewers' comments led us to believe that the revisions requested, specifically the addition of throughfall and denser soil moisture measurements, were untenable. As such, and because we believed that the findings were defensible without those additional measurements, we sought an alternative venue for the revised manuscript (i.e., this submission to HESS). Again, we thank the reviewer for this second review.

R1-C2: This manuscript proposes that the interception storage can be derived from high temporal resolution top soil moisture measurements. The term "interception storage" here defined broadly as the storage of a surface layer contributing to direct evaporation, and encompasses besides the canopy storage also ground cover, litter and the top soil itself. The proposed method analyses the increase of volumetric soil water content in response to rainfall events. This is done by calculating the interception capacity using the Gash Model with an important alteration. Instead of using the event rainfall depth required to cause canopy drip, the authors use the event rainfall depth required to cause a soil moisture response. Separation between aboveground and soil hydraulic processes is achieved by using simulations with an unsaturated zone model (HYDRUS) to empirically estimate the speed of the propagation of the wetting front as a function of initial soil water content and for typical soil properties in Florida. As a proof of concept the authors apply this method on 33 plots (nested design: 5 sites each with 6 subplots, plus 1 site with three subplots) analyzing soil moisture responses to rainfall events during three years. Direct measurements of canopy, litter interception or soil properties are not available for comparison. They find that their derived interception storage is comparatively high, but plausible. Using multivariate statistics they show that their derived interception storage depends considerably on plot leaf area index, ground cover and antecedent soil moisture. They conclude that their proposed method of deriving "whole forest" interception storage has potential and suggest it as an alternative to other empirical assessments. In a last step, the interception storage is applied to calculate plot interception and the variation between the plots is discussed.

I was very intrigued by the presented idea and also by the dataset, which has a great deal of potential. The paper itself is mostly well written and discusses the case well. The presented data and analysis are of interest for the readers of HESS.

> **AR2:** Thank you for the accurate summary and positive words regarding the potential applicability of this work.

R1-C3: Nevertheless I have some major concerns with the methods and conclusions in this manuscript. My main concern is that the authors claim is too strong, given the substantial uncertainty in the analysis as well as limited data availability:

> **AR3:** We acknowledge the reviewer's specific concerns and answer each point below in detail. We have also worked to generally temper the strength of the conclusions drawn in manuscript revisions; see our response to EC2.

R1-C4: No direct data of canopy or litter interception are available, and those would be necessary to validate the method for good

> **AR4:** We fully acknowledge that this is the case. As noted in the manuscript, these data come from a multi-year study quantifying forest water use under varying silvicultural management, which was measured using diurnal variation in total soil moisture. The analyses we present here were thus performed on a data set that was not directly intended to measure interception. As such, we did not collect any additional empirical interception measurements, nor can we do so retrospectively.
>
> We acknowledge that a lack of "reference" interception measurements is not ideal from a methodological point of view, particularly if our intent was to exactingly quantify the canopy interception of specific sites. However, we believe that these results are useful for illustrating the utility of soil moisture-based interception estimates and is well validated against measurements from previous interception studies in southeastern US and other pine stands. Indeed, Reviewer 2 notes that *"[p]erhaps a full-fledged throughfall monitoring campaign is not necessary in this case," given the availability of "…throughfall and interception field studies…for similar pine stands*." We argue that this is particularly true given the relatively long-term dataset from which our estimates were

derived and their broad numerical and theoretical agreement with both total interception storage capacity and total annual interception losses relative to rainfall estimated in previous studies of similar systems. The reviewer's concern that these results were not directly validated using contemporaneous and co-located data is well taken, however, and we have modified the text to better contextualize the limitations of our comparisons with other studies and stress the potential for this novel method, rather than asserting its quantitative robustness.

Examples of such revisions include (and see response to **EC2** for other examples):

Lines 229-238: *"The scope of the overall project (34 plots spanning 6 sites across Florida) and the emphasis on measuring variation in forest ET and water yield precluded conventional measurements of interception (e.g., throughfall and stemflow collectors). Because model estimates of interception were considered sufficient for water yield predictions across sites, the analyses presented here represent a proposal for additional insights about interception that can be gleaned from time series of soil moisture rather than a meticulous comparison of methods. We assessed results from this new method using comparisons with numerous previous interception studies in pine stands in the southeastern US and elsewhere, and by testing for the expected associations between estimated interception and stand structure (e.g., LAI and groundcover)."*

Lines 304-309: *"Moreover, our estimates of β_s and annual interception corresponded to expected forest structure controls (e.g., LAI and ground cover) on interception, further supporting the feasibility of the soil moisture-based approach. However, we emphasize that a more robust validation of the method using co-located and contemporaneous measurement using standard techniques is warranted. Below we summarize the assumptions and methodological considerations that affect the potential utility and limitation of the method."*

R1-C5: The method assumes only vertical matrix flux takes place between soil surface and measurement depth (the example is 15 cm soil depth), this reduces the applicability of the method to only suitable sites, without lateral flow and without preferential flow. The error is difficult to assess. Similarly, the method assumes that soil properties are comparable between sites and soil moisture measurement points, since the damping of the infiltration front signal should only depend on the differences in interception, not on small scale variation in hydraulic properties.

AR5: We acknowledge that the method assumes only vertical flux through a homogenous soil matrix, with the limitations noted by the reviewer. Regarding lateral flow, we acknowledge that it could delay the wetting front arrival, leading to an overestimation of interception using this method. However, we contend that the shallow placement of the soil moisture sensor would limit this effect to settings where strong vertical layering that leads to lateral flow (i.e., at capillary barriers or differential conductivity layers; Blume et al. 2009) exists very near the surface. Such effects of vertical soil heterogeneity would be further minimized by placing the soil moisture sensor closer to the soil surface (e.g., at 5 cm depth); we now make this specific recommendation. On the other hand, Blume et al. (2008) observed lateral flow within the duff layer (i.e., partially decomposed organic material between the A-horizon and fresh plant litter) during high-intensity precipitation events (Blume et al. 2008). This phenomenon could occur across a broader array of settings. These considerations are now mentioned in the methods and discussion sections:

Lines 172-186: *"This approach assumes no surface runoff or lateral soil-water flow near the top of the soil profile from time t to T. Except for very fine soils under extremely high* $\bar{P}$*, this assumption generally holds during early storm phases, before ponding occurs (Mein and Larsen, 1973). However, where strong layering occurs near the surface, lateral flow above the sensor (i.e., at capillary barriers or differential conductivity layers; Blume et al. 2009) may occur, and wetting front simulations described above would need to account for layered soil structure to avoid potential overestimation of interception. Lateral flow within the duff layer during high-intensity precipitation events as observed by Blume et al. (2008) would be more difficult to correct for, though we note that since our goal is to determine* β_s*, extreme storms can be omitted from the analysis when implementing Eqs. 1-10, without compromising* β_s *estimates. Similarly, not accounting for the presence of preferential flow (e.g., finger flow, funnel flow, or macropore flow; Orozco-Lopez et al. 2018) in wetting front calculations could lead to underestimation of interception, though application in coarser texture soils (as evaluated here) likely minimize this challenge. More generally, these limitations can be minimized by placing the soil moisture sensor close to the soil surface (e.g., within 5 cm)."*

Lines 358-372: *"There are several important methodological considerations and assumptions inherent to estimating interception using near-surface soil moisture data. First is the depth at which soil moisture is measured. Ideally,* θ *would be measured a few centimeters into the soil profile, eliminating the need to account for infiltration when calculating* P_G *in Eqs. (4-6) and thereby alleviating concerns about lateral and preferential flow. Soil moisture data used here were leveraged from a study of forest water yield, with sensor deployment depths selected to efficiently integrate soil moisture patterns through the vadose zone. The extra step of modeling infiltration likely increases uncertainty in* β_s *given field-scale heterogeneity in soil properties and lateral and preferential flow. Specifically, lateral flow would delay wetting-front arrival, leading to overestimation of interception, while preferential flow would do the opposite. Accounting for both processes in wetting front calculations would reduce these errors. Despite these caveats, infiltration in our system was extremely well-described using wetting front simulations of arrival time based on initial soil moisture and rainfall. As such, while we advocate for shallower sensor installation and direct comparison to standard methods in future efforts, the results presented here given the available sensor depth seem tenable for this and other similar data sets."*

Regarding preferential flow (PF), we acknowledge the potential for multiple PF types (e.g., finger flow, funnel flow, and macropore flow) to reduce the time from infiltration to soil moisture response, leading to a potential underestimation of interception. While many authors have highlighted the importance of preferential flow in driving the timing and magnitude of water and pollutant fluxes (e.g., Orozco-López et al. 2018), the characterization, analysis, and simulation of PF remains a fundamental challenge in the hydrological sciences (Jarvis et al. 2012). Orozco-López et al. (2018) synthesize some of the newer laboratory and field-scale attempts (e.g., Jarvis et al. 2016) to address the complex PF challenge, but they note that most current soil-water modeling approaches do not include this process. Given the goal and scope of this work, we have thus modified the methods and discussion as described above to acknowledge this limitation and place the potential errors from neglecting this process in context.

R1-C6: Compared to the last version of the manuscript, the new version addresses the problem of antecedent soil water content and its influence on the propagation of the wetting front by use of a soil hydrological model. I am however still skeptical that the rather idealistic model accounts for confounding soil processes sufficiently. Especially preferential flow occurring specifically in forest sites would strongly affect the wetting front arrival times.

AR6: Please see response to **R1-C5**. We have added several caveats to the discussion to highlight potential differences between an idealized soil profile simulation and a "real-world" forested site.

R1-C7: Research indicates that the correct assessment of interception in the presence of spatial heterogeneity of net precipitation requires a substantial number of sampling locations (i.e. 10 to 100 depending on the forest structure, see Zimmermann et al. 2010, WRR, W01503). Additional spatial variation is introduced by stemflow, which also varies between individuals. Also, soil hydraulic properties vary substantially at very small scales in forests. All this suggests that three sensors are not sufficient to capture the spatial heterogeneity. A larger number of sensors would at the same time imply much more installation effort, which contradicts the claim that this is a comparatively simple method.

AR7: The sampling effort required to characterize interception variability using existing methods has been characterized as ranging from "extreme" (200 funnel-type collectors per hectare for event-based sampling) to "moderate" (25 funnel- or 5 trough-type collectors per hectare for longer-term studies) to maintain mean relative error to 10% (Zimmerman and Zimmerman 2014). We note that this more recent publication updates the recommendation in Zimmerman et al. (2010), which suggested that 1300 funnels or "…150, 100, 75, and 30 troughs of 1, 2, 4, and 10 m length" would be required to meet the same standard. While troughs and soil moisture sensors are not directly comparable in their spatial configuration or methodological approach, given the 5-trough/ha recommendation by Zimmerman et al. (2014), we argue that it is reasonable to at least evaluate the stability of the interception estimates derived from our study using three sensors and assess their agreement with previously measured values.

Specifically, our method yielded interception values that were stable and predictable with only a small number of measurements, indicating that while surface inputs of water may be strongly heterogeneous, the subsurface smooths out some of that variation. In a sense, the soil moisture sensors are in this way acting like troughs, which are intended to sample a larger surface area than funnels, thus capturing more throughfall heterogeneity (i.e., smoothing the surface inputs due to spatial variability in precipitation and canopy structure). Support for the potential of our approach comes both from the fact that our estimates of total interception storage capacity and total annual interception agreed with previous studies and that there were strong and logical associations between forest structure (LAI) and estimated values.

We agree that increasing the number of soil moisture sensors would better characterize spatial heterogeneity, just as adding more trough- or funnel-type collectors would, but we do not think this undercuts the utility of our findings or limits the applicability of the method. Regarding effort, both trough-type collectors and soil moisture sensors can be set up to log automatically, so their installation and data collection efforts are likely comparable. However, trough-type collectors must be consistently maintained to prevent build-up of litterfall, whereas soil moisture sensors require little to no maintenance besides visiting the site to download data. With newer modem-enabled loggers and soil powered sensors, it would be possible to implement long-term interception measurement campaigns with much reduced effort. We have added two new paragraphs to the discussion to contextualize the number of measurements presented here relative to guidance for standard methods:

Lines 389-416: *"Among the many challenges of measuring interception is the spatial heterogeneity of canopy and ground cover layers, with associated heterogeneity in interception rates. Consequently, researchers have suggested that 25 funnel collectors per hectare (or more) are necessary to maintain mean relative error below 10% for long-term monitoring, with as many as 200 collectors needed for similar error rates during event sampling (Zimmerman et al. 2010; Zimmerman and Zimmerman 2014). Spatial averaging using larger trough collectors obviates some of this sampling effort, yielding guidance of 5 trough collectors per hectare (Zimmerman and Zimmerman 2014), but still misses stemflow and groundcover variation. While the spatial integration extent of troughs versus soil moisture sensors remains unknown, the three soil moisture sensors we deployed per plot (with sensor locations selected to span stand spatial heterogeneity) seem likely to capture similar spatial extents. Moreover, the strong correspondence between our measurements and literature reported values for the magnitude of interception storage as well as the forest structure controls (i.e., LAI, ground cover) on that storage volume underscores that soil moisture measurements, at least in this setting, integrate key quantitative aspects of the interception process.*

If soil moisture measurements were subject to the same fine-grained spatial heterogeneity as funnel-type collectors, it seems highly unlikely that our results would comport with literature expectations as closely as they do. One plausible explanation for the consistency of our results is that soil moisture averages across extant spatial heterogeneity in canopy processes, allowing soil moisture measurements to provide comparable spatial integration to throughfall troughs, without the considerable maintenance of litter accumulation associated with those troughs. This finding is concordant with results from Metzger et al. (2017), who found correspondence between throughfall and soil moisture changes across storm events of different sizes, leading these authors to conclude that "net precipitation" can be intuited using soil water dynamics. Additional soil moisture measurements would undoubtedly improve the accuracy of field *estimates, and indeed we recommend that more direct methodological comparisons are needed. However, our results support the general applicability of the soil moisture-based approach for developing forest interception estimates across a wide range of hydroclimatic and forest structural settings."*

R1-C8: Thus, based on the provided evidence I am not convinced that the method allows to estimate interception loss based on soil water content measurements. In the absence of direct measurements, the main claim of the paper is not supported by data. I agree that the derived values are plausible, and the paper can make this claim, but this requires a much more careful formulation of the title, abstract, discussion and conclusion.

AR8: We disagree that the paper's claim is not supported by data but acknowledge that the data supporting the findings come from other studies. We have modified the text in the abstract, methods, discussion and conclusion to stress the potential utility and benefits of the proposed method, along with conceptual caveats, methodological considerations, and suggestions for future work. See examples in our responses above and in our response to **EC2**.

R1-C9: Furthermore, I think the paper contains a great deal of really interesting information, data collected in a thoughtful design as well as a clever analysis. The paper definitely allows drawing conclusions about how strongly different factors like LAI, %GC and antecedent soil moisture actually affect the top soil moisture response to rainfall. I would therefore highly welcome a change of the key message, and instead focusing on the observed soil water response to precipitation. This can be addressed with very similar analysis, but without the need to refer to very indirect evidence as is the case now.

AR9: We appreciate the reviewer's interest in the data, design, and analysis. As noted in AR8, we have modified the text to temper the conclusions and further clarify that we rely on evidence/validation vis-à-vis other studies. We believe that refocusing the paper on observed soil water response to precipitation would reduce its utility, especially given the great quantity of excellent work on that topic over the past many decades. Moreover, the reviewers concern that we have insufficiently sampled a spatially heterogeneous process underscores the promise of this method since the results appear to be both stable and conform with stand structural predictions of interception losses. As such, we view this work, like all scientific efforts, as a contribution to a longer dialog and not the final word on the subject. Throughout the revised manuscript we now make clear that future work should more explicitly consider direct validation rather than literature-based validation as we've done here.

Detailed Comments

Furthermore, some editorial remarks:

R1-C10: The nomenclature in the manuscript is unnecessarily confusing and can be improved easily by homogenizing. For example, abbreviations of P and R are used for variables both referring to precipitation, while P could be used throughout with different indices. The abbreviation f is rather unfortunate choice for “infiltration flow”, etc. Also, “soil moisture content” or “SMC” and Greek letter theta are both used for variables referring to volumetric soil water content. Please note that soil moisture content is rather unspecific and in the entire manuscripts actually “volumetric soil water content” is meant. The latter is a well-defined and established term. The established abbreviation is the Greek letter theta.

> **AR10:** We appreciate the reviewer’s comments and apologize for any unnecessary confusion. We have attempted to better harmonize nomenclature in the revised manuscript. Regarding *P* and *R*, we have modified symbology such that all abbreviations of rainfall use *P*. Regarding the use of “f” for infiltration, this is the standard symbol for infiltration rate (dimensions of length per time) (e.g., in the Green-Ampt and Horton equations) with capital “F” referring to cumulative infiltration (dimensions of Length), so we have left it unchanged. We have modified SMC to θ throughout.

R1-C11: I propose separating the discussion and conclusions section.

> **AR11:** Modified as suggested.

R1-C12: Eq 1: Something is wrong with formatting of the equation. There should be no power to exp.

> **AR12:** Apologies, there was some conversion error during document upload, which we have rectified in the revision.

R1-C13: Eq 3: I find "f" a very unfortunate abbreviation for infiltration rate. The lower case f is so very commonly used to mean “function of” that this "f(..)" is strongly misleading.

> **AR13:** See **AR10**

R1-C14: L 126: change “E and f are infiltration and evaporation rates” to “E and f are evaporation and infiltration rates”

> **AR14:** Modified as suggested.

R1-C15: L 134: Something went wrong with formatting. It is sometimes bar and sometimes prime to demark the average.

> **AR15:** See **AR12**

R1-C16: Eq. 7: The sides of the equation are not equal. The logarithm in the middle part should be in the denominator (as in the right hand side).

> **AR16:** Modified as suggested.

R1-C17: L 140: R is now newly introduced as the rainfall rate – why not P with a different index? The many abbreviations are confusing.

AR17: Modified as suggested; see **AR10**.

R1-C18: L 215: What is meant with banks? Vertical profiles? I tried a search engine and it appears this is a very uncommon formulation. Please rephrase.

AR18: We have changed this term to “sets”.

R1-C19: L 216: “soil moisture content” or “SMC” is rather unspecific. The entire analysis assumes that the “volumetric soil water content” is meant. The established abbreviation is the Greek letter theta. I strongly suggest adjusting the nomenclature to the established scientific literature.

AR19: Modified as suggested; see **AR10**.

R1-C20: L 261: The ANOVA should be introduced in the Methods section.

AR20: Description of the ANOVA has been added to the Methods section

R1-C21: Table 2: From the methods section, it appears as if more model versions were tested: four potential predictors and their interactions. Could you confirm or specify and also state how were the presented models selected? How about a case without LAI and only site and %GC?

AR21: As we stated in the methods, we ran a variety of permutations of model predictors. All models without LAI were markedly worse and were omitted from comparison. We have updated the methods and results to make this clearer.

R1-C22: Figure 2: I have commented on this before: The equation in all panels are repetitions of Eq. 1, where y=P (Rainfall), and x= Δ SMC. However, the x-axis in the Figure is Rainfall (and not Δ SMC). In other words, the equation in the Figure is wrong, given that x and y are swapped in the figure as compared to the original equation. This should be harmonized.

AR22: Modified as suggested. The figures now have rainfall on the y-axis to appropriately represent the relationship in equation 1.

References:

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John Van Stan, Referee 2 (Received and published: 13 August 2019)

We thank the reviewer for his time and useful comments, which we have attempted to incorporate in manuscript revisions. We have also attempted to clarify and further justify the impact and utility of this work in response to specific reviewer concerns. Below are explanations of our responses to the reviewer's comments (**R2-C: Reviewer comment; AR: Author response**), with all line numbers corresponding to the revised manuscript unless otherwise noted. We note that several of the reviewer's comments were also noted by Reviewer 1 (R1), and in the responses below, we refer to those responses to avoid repetition.

Major Comments

R2-C1: The discussion paper by Acharya et al. estimates total forest rainfall interception (canopy, understory, litter and topsoil) from shallow soil moisture sensor data using a modified Gash model (that replaces the 'precip required for throughfall drip' with the 'precip required for soil moisture response'). HYDRUS model-based estimates of the topsoil component were removed from the total forest rainfall interception (hereafter "total interception"). This was done for a large number of pine plots (n=34), then total interception estimates were compared with literature values and other site data (density, LAI, groundcover, age, etc.). The methods are clearly described (the manuscript is very well written), it provides an interesting alternative to deploying throughfall and stemflow gauges, and it would no doubt interest HESS readers. There are, however, some shortcomings that I believe should be addressed before publication.

> **AR1:** We thank the reviewer and appreciate the kind words. We note that several of the reviewer's comments were also noted by Reviewer 1 (R1), and in the responses below, we refer to those responses to avoid repetition.

R2-C2: 1) There are very few soil moisture sensors per plot (n=3?). To estimate rainfall interception, throughfall sampling (using gauges roughly the same-to-larger size as the soil moisture sensor areas) would require 30-50 roving gauges, and 100s of stationary gauges (see publications by Zimmermann, 10.1029/2009WR007776 and Voss, 10.1016/j.jhydrol.2016.06.042). Stemflow monitoring would also be required, although stemflow from the pine species studied is generally negligible. The dense throughfall (and stemflow) sampling is to account for wet and dry points due to canopy rainwater redistribution; yet, for soil moisture sensors, lateral flow is another issue. Preferential flow of net rainfall fluxes laterally is possible and has been reported by the few studies searching for it (e.g., Spencer and van Meervel, 10.1002/hyp.10936). I would like to see these issues discussed; i.e., the total interception estimates are highly localized (sub-plot) estimates that do not account for lateral soil moisture flow.

> **AR2:** Regarding number of sensors, we refer to our response to Reviewer 1 (**R1-AR7)**, where we note that Zimmerman and Zimmerman (2014) suggest only 5 trough-type collectors/ha for longer-term studies such as ours to maintain errors within 10%. We also propose that smoothing of rainfall inputs in the subsurface appears to yield stable and reasonable results with relatively few measurement locations. Regarding stemflow, we acknowledge in the text that "…estimation of β_s using Eqs. 1-7 cannot directly account for stemflow, which can be an important component of rainfall partitioning in forests (e.g., Bryant et al., 2005)", but as noted by the reviewer, stemflow in pine species is generally small. Regarding lateral flow, we refer to **R1-AR5**, where we discuss lateral and preferential flow in detail, leading to new text in the methods and discussion sections. Finally, regarding the suggestion that we refer to our measurements as localized, sub-plot estimates, we agree and have added that description to the methods section:
>
> Lines 241-246: "*Soil-moisture sensors were located to capture representative variation in stand geometry and structure (i.e., within and between tree rows) to capture variation in surface soil moisture response to rainfall events. While this spatial layout was intended to characterize the range of plot-scale forest canopy and groundcover heterogeneity, the three measurements locations were within a 10-m radius and thus represent localized (sub-plot) interception estimates.*"

R2-C3: 2) There are no data from the study sites for evaluation (only comparison with other studies' data). Perhaps a full-fledged throughfall monitoring campaign is not necessary in this case (throughfall and interception field studies are available for similar pine stands already). Instead, the authors could estimate canopy, groundcover, and litter water storage components and, subsequently, evaporation. This could be done by sampling leaves, bark, litter and performing water storage tests in the lab.

> **AR3:** Regarding the lack of data for evaluation, we refer to our response to **EC2** and to Reviewer 1 (**R1-AR4)**, where we acknowledge the concern that results were not validated using contemporaneous and co-located data. In those responses, we also refer to new text that better contextualizes the limitations of our comparisons with other studies and to stress the potential for this novel application, rather than suggesting its quantitative robustness. Regarding the suggestion to estimate canopy, groundcover, and litter water storage components and, subsequently, evaporation, we contend that this was exactly our approach (i.e., we estimated the total storage of those components (β_s) and how that storage capacity interacted with rainfall and evaporation to yield interception), though we did this analytically rather than sampling and measuring materials in the lab.

R2-C4: 3) The proposed method is not quite a "simple" method, especially when applied at the stand scale as this would require a greater number of soil moisture sensors. Additionally, it involves HYDRUS modelling and the issue of lateral soil water transport is, at present, unaddressed.

> **AR4:** Regarding simplicity, we agree that the method only remains simple and tractable if the number of sensors required to adequately estimate interception remains relatively small. We refer to our responses to Reviewer 1 (**R1-AR7**) in this regard, where we contextualize the number of sensors used in this study and discuss the simplicity of effort required and potential benefits. Regarding the need for HYDRUS modeling, we acknowledge that the extra step of modeling infiltration reduces the simplicity of the approach and also likely increases uncertainty in our estimates of β_s; however, this limitation may be avoidable with sensor placement closer to the surface (we used 15 cm, we recommend 5 cm). This methodological improvement was recommended in the original manuscript and is now further stressed in the methods and discussion of the revision (see **R1-AR5**). Regarding lateral transport, we also refer to **R1-AR5**. The general contention that we have under-sampled a spatially heterogeneous process is certainly reasonable, though it seems equally fair to point out that our estimates of interception capacity are stable and robust across sites in spite of this, and that they align remarkably well with literature values and expectations of stand-structural attributes. While further validation is clearly needed, it seems equally valid to note the promise of the method based on the small number of samples. In our response to Reviewer 1 (**R1-AR7**), we describe new text at the end of discussion that explores reasons that our results are both stable and consistent with stand structure. One plausible explanation is that soil moisture measurements may integrate over larger areas than a single point, making their spatial extent closer to a trough than a funnel collector, and thereby implying reduced sampling intensity.

Detailed Comments

R2-C5: a) I don't think the term "loss" in "interception loss" is necessary. As "rainfall interception" is a process that returns rainwater to the atmosphere, it is a "gain" to the atmosphere. Would the authors consider simply using the term "interception" or "rainfall interception" throughout?

> **AR5:** Modified as suggested.

R2-C6: b) The discussion paragraph beginning on lines 298 focuses on the spatiotemporal variability of interception. All the literature discussed is concerned with canopy interception; however, field studies exist which show that variability in seasonal canopy materials can influence litter interception, particularly seed pods: eg:
Levia et al., 2004, doi: 10.1623/hysj.49.5.843.55133
Van Stan et al., 2017, doi: 10.1002/hyp.11292 <-Please note that I am the corresponding author on this publication and only share it as it is directly related to the topic being discussed – a topic little researched.

> **AR6:** The seasonality of canopy materials and this citation have been added to the discussion of spatiotemporal interception variation.

Estimating Interception from Near-Surface Soil Moisture Response

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Abstract

Interception is the storage and subsequent evaporation of rainfall by above-ground structures, including canopy and groundcover vegetation and surface litter. Accurately quantifying interception is critical for understanding how ecosystems partition incoming precipitation, but it is difficult and costly to measure, leading most studies to rely on modeled interception estimates. Moreover, forest interception estimates typically focus only on canopy storage, despite the potential for substantial interception by groundcover vegetation and surface litter. In this study, we developed an approach to quantify "total" interception (i.e., including forest canopy, understory, and surface litter layers) using measurements of shallow soil moisture dynamics during rainfall events. Across 34 pine and mixed forest stands in Florida (USA), we used soil moisture and precipitation (P) data to estimate interception storage capacity (β_s), a parameter required to estimate total annual interception (I_a) relative to P. Estimated values for β_s (mean β_s = 0.30 cm; 0.01 ≤ β_s ≤ 0.62 cm) and I_a/P (mean I_a/P = 0.14; 0.06 ≤ I_a/P ≤ 0.21) were broadly consistent with reported literature values for these ecosystems and were significantly predicted by forest structural attributes (leaf area index and percent groundcover), as well as other site variables (e.g., water table depth). The best-fit model was dominated by LAI and explained nearly 80% of observed β_s variation. These results suggest that whole-forest interception can be estimated using near-surface soil moisture time series, though additional direct comparisons would further support this assertion. Additionally, variability in interception across a single forest type underscores the need for expanded empirical measurement. Potential cost savings and logistical advantages of this method relative to conventional, labor-intensive interception measurements may improve empirical estimation of this critical water budget element.

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Introduction

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Rainfall interception (I) is the fraction of incident rainfall stored by above-ground ecosystem structures (i.e., vegetation and litter layers) and subsequently returned to the atmosphere via evaporation (E), never reaching the soil surface and thus never directly supporting transpiration (T) [*Savenije*, 2004]. Interception depends on climate and vegetation characteristics and can be as high as 50% of gross rainfall [*Gerrits et al.,* 2007; 2010; *Calder*, 1990]. Despite being critical for accurate water budget enumeration [*David et al*., 2006], interception is often disregarded or lumped with evapotranspiration (ET) in hydrological models [*Savenije*, 2004]. Recent work suggests interception uncertainty constrains efforts to partition ET into T and E, impairing representation of water use and yield in terrestrial ecosystems [*Wei et al.,* 2017].

When interception is explicitly considered, it is typically empirically estimated or modeled solely for the tree canopy. For example, direct measurements are often obtained from differences between total rainfall and water that passes through the canopy to elevated above-ground collectors (throughfall) plus water that runs down tree trunks (stemflow) during natural [e.g., *Bryant et al.,* 2005, *Ghimire et al.,* 2012, 2016] or simulated [e.g., *Guevara-Escobar et al.,* 2007; *Putuhena and Cordery,* 1996] rainfall events. This method yields the rainfall fraction held by and subsequently evaporated from the canopy but ignores interception by understory vegetation and litter. Alternatively, numerous empirical [e.g., *Merriam,* 1960], process-based [e.g., *Rutter et al.,* 1971, 1975; *Gash,* 1979, 1995, *Liu*, 1998], and stochastic [*Calder,* 1986] models are available for estimating interception. As with direct measurements, most model applications consider only canopy storage despite groundcover (both understory vegetation and litter layers) interception that can exceed canopy values in some settings [*Gerrits and Savenije*, 2011; *Putuhena and Cordery,* 1996]. As such, it seems likely that conventional measures and typical model applications underestimate actual (i.e., "total") interception.

New field approaches are needed to improve quantification of total interception and refine the calibration and application of available models. A detailed review of available interception models [*Muzylo et al.,* 2009] stresses the need for direct interception measurements across forest types and hydroclimatic regions, but meeting this need will require substantial methodological advances. Throughfall measurements yield direct and site-specific interception estimates [e.g., *Ghimire et al.,* 2017; *Bryant et al.,* 2005], but they are difficult and costly to implement even at the stand scale because of high spatial and temporal variability in vegetation structure [*Zimmerman et al.*, 2010; *Zimmerman and Zimmerman*, 2014]. Moreover, comprehensive measurements also require enumeration of spatially heterogeneous stemflow, as well as interception storage by the understory and litter layers, greatly exacerbating sampling complexity and cost [*Lundberg et al.,*1997]. Empirical techniques that estimate total interception, integrate across local spatial and temporal variation, and minimize field installation complexity are clearly desirable.

Here we present a novel approach for estimating total (i.e., canopy, understory and litter) interception using continuously logged, near-surface soil moisture. Prior to runoff generation, infiltration is equivalent to rainfall minus total interception, and the response of near-surface soil moisture during and directly following rain events can be used to inform interception parameters and thus interception. Since soil moisture is relatively easy and economical to measure continuously for extended periods, successful inference of interception from soil moisture time series may greatly expand the temporal and spatial domains of empirical interception measurements. As a proof-of-concept, we tested this simple interception estimation method in 34

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forest plots spanning a wide range of conditions (e.g., tree density, composition, groundcover, understory management, age, and hydrogeologic setting) across Florida (USA).

Methods

Estimating Interception Storage Capacity from Soil Moisture Data

During every rainfall event, a portion of the total precipitation (P) is temporarily stored in the forest canopy and groundcover (hereafter referring to both live understory vegetation and forest floor litter). We assume that infiltration (and thus any increase in soil moisture) begins only after total interception storage, defined as the sum of canopy and groundcover storage, is full. We further assume this stored water subsequently evaporates to meet atmospheric demand. Calculating dynamic interception storage requires first determining the total storage capacity (β_s), which is comprised of the storage capacities for the forest canopy (β_c) and groundcover (β_g) (Fig. 1a).

To estimate β_s, we consider a population of individual rainfall events of varying depth over a forest for which high frequency (i.e., 4 hr^{-1}) soil-moisture measurements are available from near the soil surface. To ensure that canopy and groundcover layers are dry, and thus interception storage is zero prior to rainfall onset (i.e., antecedent interception storage capacity = β_s), we further filter the rainfall data to only include the events that are separated by at least 72 hours. Volumetric soil water content (θ) at the sensor changes only after rainfall fills β_s, evaporative demands since rainfall onset are met, and there is sufficient infiltration for the wetting-front to arrive at the sensor. Rainfall events large enough to induce a soil moisture change ($\Delta\theta$) are evident as a rainfall threshold in the relationship between P and $\Delta\theta$. An example time series of P and θ (Fig. 1b) yields a P versus $\Delta\theta$ relationship (Fig. 1c) with clear threshold

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behavior. There are multiple equations whose functional forms allow for extraction of this threshold; here we express this relationship as:

$$P = \frac{a}{(1 + b * exp^{(-c * \Delta\theta)})} \quad (1)$$

where P is the total rainfall event depth, $\Delta\theta$ is the corresponding soil moisture change, and a, b, and c are fitted parameters. Figure 2 illustrates this relationship and model fitting for observed $\Delta\theta$ data from six plots at one of our study sites described below. The y-intercept of Eq. 1 (i.e., where $\Delta\theta$ departs from zero) is given by:

$$P_s = \frac{a}{(1 + b)} \quad (2)$$

where P_s represents the total rainfall required to saturate β_s, meet evaporative demands between storm onset and observed $\Delta\theta$, and supply any infiltration required to induce soil moisture response once β_s has been saturated. This equality can be expressed as:

$$P_s = \beta_s + \int_0^T E dt + \int_t^T f dt = \beta_s + \int_0^t E dt + \int_t^T E dt + \int_t^T f dt \quad (3)$$

where T is the total time from rainfall onset until observed change in θ (i.e., the wetting front arrival), t is the time when β_s is satisfied, and E and f are the evaporation and infiltration rates, respectively. To connect this empirical observation to existing analytical frameworks [e.g., *Gash* 1979], we adopt the term P_G, defined as the rainfall depth needed to saturate β_s and supply evaporative losses between rainfall onset ($time = 0$) and β_s saturation ($time = t$):

$$P_G = \beta_s + \int_0^t E dt \quad (4)$$

Solving for β_s in Eq. 3 and substituting into Eq. 4 yields:

$$P_G = P_s - \int_t^T E dt - \int_t^T f dt \quad (5)$$

Equation 5 may be simplified by assuming that average infiltration and evaporation rates apply during the relatively short period between t and T, such that:

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$$P_G = P_s - \bar{f}(T - t) - \bar{E}(T - t) \quad (6)$$

where $\bar{f}$ is the average soil infiltration rate and $\bar{E}$ is the average rate of evaporation from the forest surface (i.e., canopy, groundcover, and soil) during the time from t to T [see *Gash*, 1979]. The storage capacity β_s can now be calculated following Gash [1979] as:

$$\beta_s = -\frac{\bar{E}}{\bar{P}} \frac{P_G}{ln\left(1-\frac{\bar{E}}{\bar{P}}\right)} = -\frac{\bar{E}}{\bar{P}} \frac{[P_s-(T-t)(\bar{f}+\bar{E})]}{ln\left(1-\frac{\bar{E}}{\bar{P}}\right)} \quad (7)$$

where $\bar{P}$ is the average rainfall rate and all other variables are as previously defined. In Eq. 5, $\bar{E}$ is usually estimated using the Penman-Monteith equation [*Monteith,* 1965], setting canopy resistance to zero (e.g., *Ghimire et al.*, 2017).

A key challenge in applying Eq. 5, and thus for the overall approach, is quantifying infiltration, since the time, t, when β_s is satisfied is unknown. Moreover, the infiltration rate embedded in P_s is controlled by $\bar{P}$ and initial soil moisture content (θ_i). It is worth noting that shallower sensor depth placement would likely eliminate the need for this step (see Discussion). However, to overcome this limitation in our study (where our soil moisture sensor was 15 cm below the ground surface), we used the 1-D unsaturated flow model HYDRUS-1D [*Simunek et al.,* 1995] to simulate the required time for the wetting front to arrive (T_w) at the sensor under bare soil conditions across many combinations of $\bar{P}$ and θ_i. As such, T_w represents the time required for a soil moisture pulse to reach the sensor once infiltration begins (i.e., after β_s has been filled), which is T- t in Eq. 7. For each simulation, T_w (signaled by the first change in θ at sensor depth) was recorded and used to develop a statistical model of T_w as a function of $\bar{P}$ and θ_i. We used plot-specific soil moisture retention parameters from Florida Soil Characterization Retrieval System (https://soils.ifas.ufl.edu/flsoils/) to develop these curves for our sites, but simulations can be applied for any soil with known or estimated parameters.

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Simulations revealed that T_w at a specific depth declined exponentially with increasing θ_i:

$$T_w = ae^{-b\theta_i} \quad (8)$$

where a and b are fitting parameters. Moreover, the parameters a and b in Eq. (6) are well fitted by a power function of $\bar{P}$:

$$a = a_1\bar{P}^{a_2}, b = b_1\bar{P}^{b_2} \quad (9)$$

where a_1 and b_1 are fitting parameters. These relationships are illustrated in Fig. 3 for a loamy sand across a range of $\bar{P}$ and θ_i at 15 cm depth. The relationship between θ_i and T_w is very strong for small to moderate $\bar{P}$ (< 3.0 cm/hr). At higher values of $\bar{P}$, T_w is smaller than the 15-minute sampling resolution, and these events were excluded from our analysis (see below).

Assuming that $\bar{f}$ equals $\bar{P}$ over the initial infiltration period from t to T (robust for most soils, see below), Eq. 7 can be modified to:

$$\beta_s = \frac{-E}{\bar{P}}\left[\frac{P_s - T_w(\bar{P}+E)}{ln\left(1-\frac{E}{\bar{P}}\right)}\right] \quad (10)$$

This approach assumes no surface runoff or lateral soil-water flow near the top of the soil profile from time t to T. Except for very fine soils under extremely high $\bar{P}$, this assumption generally holds during early storm phases, before ponding occurs [*Mein and Larsen*, 1973]. However, where strong layering occurs near the surface, lateral flow above the sensor (i.e., at capillary barriers or differential conductivity layers; *Blume et al.*, 2009) may occur, and wetting front simulations described above would need to account for layered soil structure to avoid potential overestimation of interception. Lateral flow within the duff layer during high-intensity precipitation events as observed by Blume et al. (2008) would be more difficult to correct for, though we note that since our goal is to determine β_s, extreme storms can be omitted from the analysis when implementing Eqs. 1-10, without compromising β_s estimates. Similarly, not accounting for the presence of preferential flow (e.g., finger flow, funnel flow, or macropore

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flow; *Orozco-Lopez et al.*, 2018) in wetting front calculations could lead to underestimation of interception, though application in coarser texture soils (as evaluated here) likely minimize this challenge. More generally, these limitations can be minimized by placing the soil moisture sensor close to the soil surface (e.g., within 5 cm). Finally, we note that values of β_s from Eq. 10 represent combined interception from canopy and groundcover, but the method does not allow for disaggregation of these two components.

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Calculating Interception

Interception storage and subsequent evaporation (sometimes referred to as interception loss) for a given rain event are driven by both antecedent rain (which fills storage) and evaporation (which depletes it). Instantaneous available storage ranges from zero (saturated) to the maximum capacity (i.e., β_s which occurs when the storage is empty). While discrete, event-based interception models [*Gash,* 1979, 1995; *Liu*, 1998] have been widely applied to estimate interception, continuous models more accurately represent time-varying dynamics in interception storage and losses. We adopted the continuous, physically based interception modeling framework of *Liu* [1998, 2001]:

$$I = \beta_s(D_0 - D) + \int_0^t (1 - D)E\,dt \qquad (11)$$

where *I* is interception, D_0 is the forest dryness index at the beginning of the time step *t*, *D* is the forest dryness index at time the end of *t*, and *E* is the evaporation rate from wetted surfaces. The dryness index at each time-step is calculated as:

$$D = 1 - \frac{C}{\beta_s} \qquad (12)$$

where *C* is "adherent storage" (i.e., water that does not drip to the ground) and is given by:

$$C = \beta_s\left(1 - D_0 exp\left(\frac{-(1-\tau)}{\beta_s}P\right)\right) \qquad (13)$$

where τ is the free throughfall coefficient. Because our formulation of β_s in Eq. 10 incorporates both canopy and groundcover components (i.e., negligible true throughfall), we approximated τ in Eq. 13 as zero. Between rainfall events, water in interception storage evaporates to meet atmospheric demand, until the dryness index, D reaches unity [*Liu* 1997]. The rate of evaporation from wetted surfaces between rainfall events (E_s) is:

$$E_s = E(1 - D)exp\left(\frac{E}{\beta_s}\right) \quad (14)$$

A numerical version of Eq. 11 to calculate interception at each time step, *t*, is expressed as:

$$I = \beta_s(D_{t-1} - D_t) + \frac{1}{2}[E_{t-1}(1 - D_{t-1}) + E_t(1 - D_t)] \quad (15)$$

Eq. 15 quantifies continuous and cumulative interception using precipitation and other climate data (for *E*) along with β_s derived from soil moisture measurements and corresponding meteorological data.

Study Area and Data Collection

As part of a multi-year study quantifying forest water use under varying silvicultural management, we instrumented six sites across Florida, each with six 2-ha plots spanning a wide range of forest structural characteristics. Data from two of the plots at one site were not used here due to consistent surface water inundation, yielding a total of 34 experimental forest plots. Sites varied in hydroclimatic forcing (annual precipitation range: 131 to 154 cm/yr and potential *ET* range: 127 to 158 cm/yr) and hydrogeologic setting (shallow vs. deep groundwater table). Experimental plots within sites varied in tree species, age, density, leaf area index (LAI), groundcover vegetation density (%GC), soil type, and management history (Table 1). Each site contained a recent clear-cut plot, a mature pine plantation plot, and a restored longleaf pine (*Pinus palustris*) plot; the three remaining plots at each site included stands of slash pine (*Pinus elliottii*), sand pine (*Pinus clausa*), or loblolly pine (*Pinus taeda*) subjected to varying silvicultural treatments (understory management, canopy thinning, prescribed burning) and hardwood encroachment. The scope of the overall project (34 plots spanning 6 sites across Florida) and the emphasis on measuring variation in forest ET and water yield precluded conventional measurements of interception (e.g., throughfall and stemflow collectors). Because model estimates of interception were considered sufficient for water yield predictions across sites, the analyses presented here represent a proposal for additional insights about interception that can be gleaned from time series of soil moisture rather than a meticulous comparison of methods. We assessed results from this new method using comparisons with numerous previous interception studies in pine stands in the southeastern US and elsewhere, and by testing for the expected associations between estimated interception and stand structure (e.g., LAI and groundcover).

Within each plot, three sets of TDR sensors (CS655, Campbell Scientific, Logan, UT, USA) were installed to measure soil moisture at multiple soil depths (Fig. 1a). Only data from the top-most sensor (15 cm below the ground surface) were used in this study. Soil-moisture sensors were located to capture representative variation in stand geometry and structure (i.e., within and between tree rows) to capture variation in surface soil moisture response to rainfall events. While this spatial layout was intended to characterize the range of plot-scale forest canopy and groundcover heterogeneity, the three measurements locations were within a 10-m radius and thus represent localized (sub-plot) interception estimates. Within each clear-cut plot at each site, meteorological data (rainfall, air temperature, relative humidity, solar insolation, wind speed and direction) were measured using a weather station (GRSW100, Campbell Scientific, Logan, UT; Fig. 4c) every 3 seconds and used to calculate hourly *E* by setting the canopy resistance to zero [*Ghimire et al.,* 2017; *Gash,* 1995; *Monteith,* 1965]. Growing season forest

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canopy LAI (m^2 m^{-2}) and groundcover (%) were measured at every 5-m node within a 50 m x 50 m grid surrounding soil moisture measurement banks. LAI was measured at a height of 1 m using a LI-COR LAI-2200 plant canopy analyzer, and %GC was measured using a 1 m^2 quadrat.

To estimate β_s, mean $\Delta\theta$ values from the three surface sensors were calculated for all rainfall events separated by at least 72 hours. Storm separation was necessary to ensure the canopy and groundcover surfaces were mostly dry (and thus antecedent storage capacity = β_s) at the onset of each included rainfall event. Rainfall events were binned into discrete classes by depth and plotted against mean $\Delta\theta$ to empirically estimate P_s (e.g., Fig. 2). For each rainfall bin, mean θ_i, $\bar{P}$ and $\bar{E}$ were also calculated to use in Eq. 10, which was then applied to calculate β_s. Subsequently, we developed generalized linear models (GLMs) using forest canopy structure (site-mean LAI), mean groundcover (% GC), hydrogeologic setting (shallow vs. deep groundwater table), and site as potential predictors, along with their interactions, to statistically assess predictors of β_s estimates. Because models differed in fitted parameter number, the best model was selected using the Akaike Information Criteria (AIC; *Akaike,* 1974). Finally, we calculated cumulative annual interception (I_a) and its proportion of total precipitation (I_a/P) for each study plot using the mean β_s for each plot (across the 3 sensor banks), climate data from 2014 to 2016, and Eq. 15. Differences in I_a/P across sites and among plots within sites were assessed using ANOVAs. All analyses were performed using R [*R Core Team,* 2017].

Results

Total Storage Capacity (β_s)

The exponential function used to describe the P-$\Delta\theta$ relationship (Eq. 1) showed strong agreement with observations at all sites and plots (overall R^2 = 0.80; 0.47 ≤ R^2 ≤ 0.97; Table 1)

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as illustrated for a single site in Fig. 2. This consistency across plots and sites suggests that Eq. 1 is capable of adequately describing observed P-$\Delta\theta$ relationships, enabling estimates of β_s across diverse hydroclimatic settings and forest structural variation. Estimates of β_s ranged from 0.01 to 0.62 cm, with a mean of 0.30 cm (Table 1). Plot-scale LAI was moderately correlated with plot-mean β_s, describing roughly 32% of observed variation across plots (Fig. 4a). This relatively weak association may arise because LAI measurements only characterize canopy cover, while β_s combines canopy and groundcover storage. The best GLM of β_s (Fig. 4b) used %GC and an interaction term between site and LAI (R^2 = 0.84 and AIC = 253.7, Table 2). The best GLM without site used LAI and hydrogeologic setting (shallow vs. deep water table) but had reduced performance (R^2 = 0.55 and AIC = 338.3; Table 2). All models excluding LAI as a predictor performed poorly, so we report model comparisons only for those including LAI.

Annual Interception (I_a)

Despite having similar rainfall regimes (mean annual precipitation ranging from 131 to 154 cm yr^{-1} across sites), mean annual interception (I_a) differed significantly both across sites (one-way ANOVA $p < 0.001$) and among plots within sites (one-way ANOVA $p < 0.001$). Estimates of I_a/P across all plots and sites ranged from 6 to 21% of annual rainfall (Table 1) and were moderately, but significantly, correlated with mean LAI, explaining approximately 30% of variation in I_a/P (Fig. 5a). Correlations among I_a/P and LAI were stronger for individual sites than the global relationship ($0.51 \leq R^2 \leq 0.84$), except for site EF, where I_a was small and similar across plots regardless of LAI (Fig. 5b; Table 1). This suggests that additional site-level differences (e.g., hydroclimate, soils, geology) play a role in driving I_a, as expected following from their effects on β_s described above.

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Discussion

When combined with local rainfall data, near-surface soil moisture dynamics inherently contain information about rainfall interception by above-ground structures. Using soil moisture data, we developed and tested an analytical approach for estimating total interception storage capacity (β_s) that includes canopy, understory, and groundcover vegetation, as well as any litter on the forest floor. The range of β_s given by our analysis (mean β_s = 0.30 cm; 0.01 ≤ β_s ≤ 0.62 cm) is close to, but generally higher than previously reported canopy-only storage capacity values for similar pine forests (e.g., 0.17 to 0.20 cm for mature southeastern USA pine forests; *Bryant et al*. 2005). Moreover, our estimates of β_s and annual interception corresponded to expected forest structure controls (e.g., LAI and ground cover) on interception, further supporting the feasibility of the soil moisture-based approach. However, we emphasize that a more robust validation of the method using co-located and contemporaneous measurement using standard techniques is warranted. Below we summarize the assumptions and methodological considerations that affect the potential utility and limitation of the method.

An important distinction between our method and previous interception measurement approaches is that the soil moisture-based method estimates composite rainfall interception of not only the canopy, but also of the groundcover vegetation and forest floor litter. Rainfall storage and subsequent evaporation from groundcover vegetation and litter layers can be as high, or higher than, canopy storage in many forest landscapes [*Putuhena and Cordery,* 1996; *Gerrits et al.,* 2010]. For example, *Li et al.* [2017] found that the storage capacity of a pine forest floor in China was between 0.3 and 0.5 cm, while maximum canopy storage was < 0.1 cm. *Putuhena and Cordery* [1996] also estimated storage capacity of pine forest litter to be approximately 0.3 cm based on direct field measurements. *Gerrits et al.* [2007] found forest floor interception to be

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34% of measured precipitation in a beech forest, while other studies have shown that interception by litter can range from 8 to 18% of total rainfall [*Gerrits et al.,* 2010; *Tsiko et al.,* 2012; *Miller et al.,* 1990; *Pathak et al.,* 1985; *Kelliher et al.,* 1992]. A recent study using leaf wetness observations [*Acharya et al.*, 2017] found the storage capacity of eastern redcedar (*Juniperus virginiana*) forest litter to range from 0.12 to as high as 1.12 cm, with forest litter intercepting approximately 8% of gross rainfall over a six-month period. Given the composite nature of forest interception storage and the range of storage capacities reported in these studies, the values we report appear to be plausible and consistent with the expected differences between canopy-only and total interception storage.

Interception varies spatially and temporally and is driven by both β_s and climatic variation (i.e., *P* and *E*). Our approach represents storage dynamics by combining empirically derived β_s estimates with climatic data using a previously developed continuous interception model [*Liu* 1998, 2001]. Cumulative I_a estimates in this study ranged considerably (i.e., from 6% to 21% of annual rainfall) across the 34 plots, which were characterized by variation in canopy structure ($0.12 < LAI < 3.70$) and groundcover ($7.9 < \%GC < 86.2$). In comparison, interception by pine forests reported in the literature (all of which report either canopy-only or groundcover-only values, but not their composite) range from 12 to 49% of incoming rainfall [*Bryant et al.,* 2005; *Llorens et al.,* 1997; *Kelliher and Whitehead,* 1992; *Crockford and Richardson,* 1990]. Notably, most of the variation in this range is driven by climate rather than forest structure, with the highest I_a values from more arid regions [e.g., Llorens et al. 1997]. Future work could also consider seasonally disaggregated measurements to explore intra-annual variation in canopy structure and litter composition [Van Stan et al. 2017].

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Broad agreement between our results and literature I_a values again supports the potential utility of our method for estimating this difficult-to-measure component of the water budget, though additional direct comparisons would further support this assertion. Additionally, the magnitude and heterogeneity of our I_a estimates across a single forest type (southeastern US pine) underscores the urgent need for empirical measurements of interception that incorporate information on both canopy and groundcover storage in order to develop accurate water budgets. This conclusion is further bolstered by the persistent importance of site-level statistical effects in predicting β_s (and therefore I_a), even after accounting for forest structural attributes, which suggests there are influential edaphic or structural attributes that we are not currently adequately assessing. For example, while estimated I_a in clear-cut plots was generally smaller than plots with a developed canopy, as expected, one exception was at EF where the clear-cut plot exhibited the highest I_a of the six EF plots (8.4%, Table 1). However, differences among all EF plots were very small (I_a ranged only from 7.9 to 8.4 % of annual rainfall), a rate consistent with or even lower than other clear cuts across the study. This site is extremely well drained with nutrient-poor sandy soils and differs from other sites in that it has dense litter dominated by mosses, highlighting the need for additional local measurements to better understand how forest structure controls observed interception.

There are several important methodological considerations and assumptions inherent to estimating interception using near-surface soil moisture data. First is the depth at which soil moisture is measured. Ideally, θ would be measured a few centimeters into the soil profile, eliminating the need to account for infiltration when calculating P_G in Eqs. (4-6) and thereby alleviating concerns about lateral and preferential flow. Soil moisture data used here were leveraged from a study of forest water yield, with sensor deployment depths selected to

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efficiently integrate soil moisture patterns through the vadose zone. The extra step of modeling infiltration likely increases uncertainty in β_s given field-scale heterogeneity in soil properties and potential lateral and preferential flow. Specifically, lateral flow would delay wetting-front arrival, leading to overestimation of interception, while preferential flow would do the opposite. Despite these caveats, infiltration in our system was extremely well-described using wetting front simulations of arrival time based on initial soil moisture and rainfall. As such, while we advocate for shallower sensor installation and direct comparison to standard methods in future efforts, the results presented here given the available sensor depth seem tenable for this and other similar data sets.

Another methodological consideration is that, in contrast to the original Gash (1979) formulation, Eq. 5 does not explicitly include throughfall. While throughfall has been a critical consideration for rainfall partitioning by the forest canopy, our approach considers total interception by aboveground forest structures (canopy, groundcover, and litter). A portion of canopy throughfall is captured by non-canopy storage and thus intercepted. Constraining this fraction is not possible with the data available, and indeed our soil moisture response reflects the "throughfall" passing the canopy, understory and litter. Similarly, estimation of β_s using Eqs. 1-7 cannot directly account for stemflow, which can be an important component of rainfall partitioning in forests [e.g., *Bryant et al.,* 2005]. We used the mean soil moisture response across three sensor locations (close to a tree, away from the tree but below the canopy, and within inter-canopy rows), which lessens the impact of this assumption on our estimates of β_s. Finally, Eqs. (3-10) assume the same evaporation rate, *E*, for intercepted water from the canopy and from the understory. Evaporation rates may vary substantially between the canopy, understory, and forest floor [*Gerrits et al.,* 2007, 2010], especially in more energy-limited environments. Future work

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should consider differential evaporation rates within each interception storage, particularly since the inclusion of litter as a component potentially accentuates these contrasts in *E*.

Among the many challenges of measuring interception is the spatial heterogeneity of canopy and ground cover layers, with associated heterogeneity in interception rates. Consequently, researchers have suggested that 25 funnel collectors per hectare (or more) are necessary to maintain mean relative error below 10% for long-term monitoring, with as many as 200 collectors needed for similar error rates during event sampling [*Zimmerman et al.*, 2010; *Zimmerman and Zimmerman,* 2014]. Spatial averaging using larger trough collectors obviates some of this sampling effort, yielding guidance of 5 trough collectors per hectare [*Zimmerman and Zimmerman,* 2014], but still misses stemflow and groundcover variation. While the spatial integration extent of troughs versus soil moisture sensors remains unknown, the three soil moisture sensors we deployed per plot (with sensor locations selected to span stand spatial heterogeneity) seem likely to capture similar spatial extents. Moreover, the strong correspondence between our measurements and literature reported values for the magnitude of interception storage as well as the forest structure controls (i.e., LAI and ground cover) on that storage volume underscores that soil moisture measurements, at least in this setting, integrate key quantitative aspects of the interception process.

If soil moisture measurements were subject to the same fine-grained spatial heterogeneity as funnel-type collectors, it seems highly unlikely that our results would comport with literature expectations as closely as they do. One plausible explanation for the consistency of our results is that soil moisture averages across extant spatial heterogeneity in canopy processes, allowing soil moisture measurements to provide comparable spatial integration to throughfall troughs, without the considerable maintenance of litter accumulation associated with those troughs. This finding

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is concordant with results from Metzger et al. (2017), who found correspondence between throughfall and soil moisture changes across storm events of different sizes, leading these authors to conclude that "net precipitation" can be intuited using soil water dynamics. Additional soil moisture measurements would undoubtedly improve the accuracy of field estimates, and indeed we recommend that more direct methodological comparisons are needed. However, our results support the general applicability of the soil moisture-based approach for developing forest interception estimates across a wide range of hydroclimatic and forest structural settings.

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Conclusions

Rainfall interception by forests is a dynamic process that is strongly influenced by rainfall patterns (e.g., frequency, intensity), along with various forest structural attributes such as interception storage capacity (β_s) [*Gerrits et al.,* 2010]. In this work, we coupled estimation of a total (or "whole-forest") β_s parameter with a continuous water balance model [*Liu,* 1997, 2001; *Rutter et al.,* 1975], providing an integrative approach for quantifying time-varying and cumulative interception. We propose that soil moisture-based estimates of β_s have the potential to more easily and appropriately represent combined forest interception relative to existing time- and labor-intensive field methods that fail to account for groundcover and litter interception. However, we emphasize that further experimental work is needed to validate this promising approach. Soil moisture can be measured relatively inexpensively and easily using continuous logging sensors that require little field maintenance, facilitating application of the presented approach across large spatial and temporal extents and reducing the time and resources that are needed for other empirical measures [e.g., *Lundberg et al.,* 1997]. Finally, while our comparisons with other empirical measures of forest canopy interception should be treated cautiously, this approach yields values that are broadly consistent with the literature, and provide an estimate of combined canopy and groundcover storage capacity that has the potential to improve the accuracy of water balances models at scales from the soil column to watershed.

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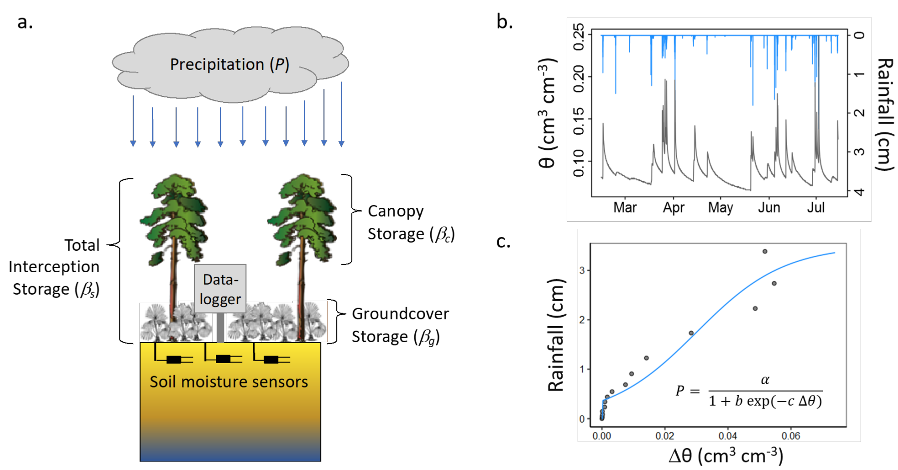

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Figure 1. (a) Schematic illustration of experimental setup and interception water storages, where total interception storage (β_s) is the sum of canopy storage (β_c) and groundcover (understory and litter) storage (β_g). (b) Example time series of rainfall (blue lines) and corresponding near-surface soil moisture content (θ, black line; observed at 15 cm in this study). (c) Resultant relationship between rainfall and change in soil moisture $\Delta\theta$ during rainfall, along with fitted model to extract the y-intercept (i.e., P_s).

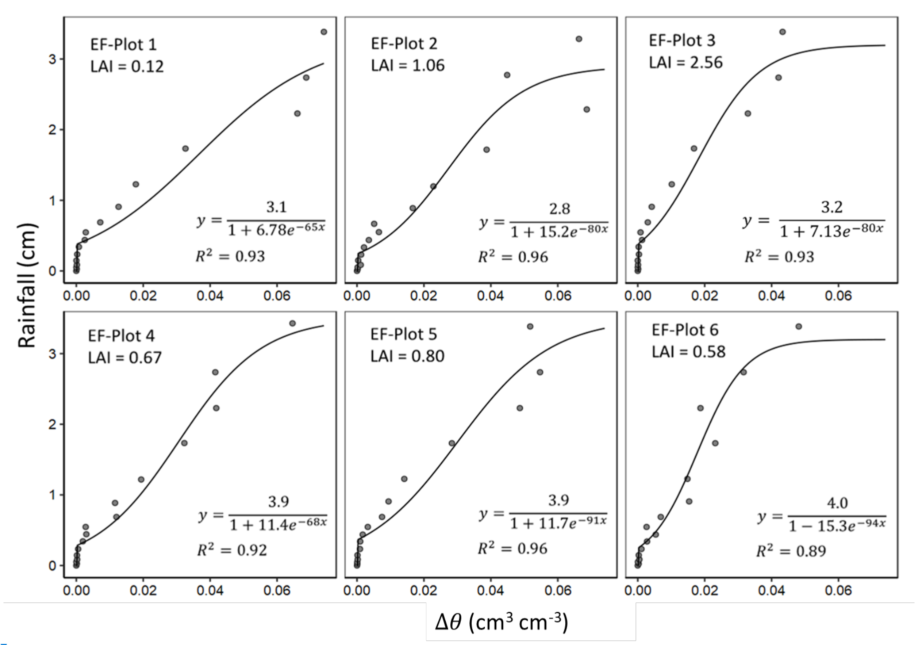

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Figure 2: Binned rainfall depths vs change in soil moisture content (*Δθ*) for six plots at one of the study sites used in the study (Econfina; EF). The y-intercept of the fitted relationships were used to derive P_s in Eq. 2. Note different y-axis scale for EF-Plot 3.

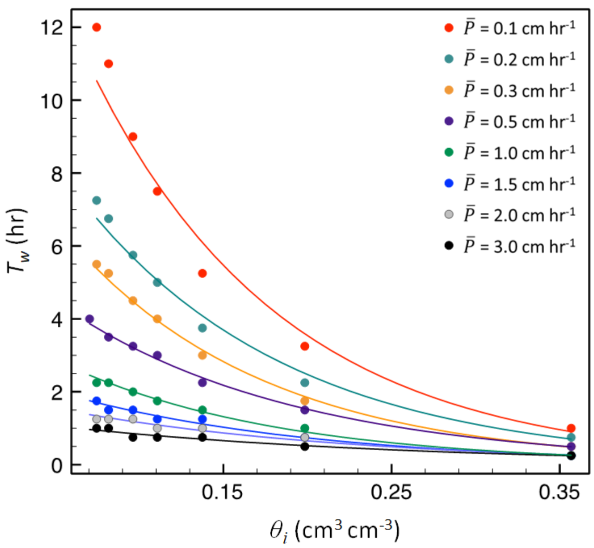

Figure 3: Initial soil moisture content (θ_i) versus time of wetting front arrival (T_w) at 15 cm depth for a loamy sand soil. Dots are simulated results from HYDUS-1D simulation, and lines are the exponential model given in Eq. 8, fitted for each rainfall rate, $\bar{P}$.

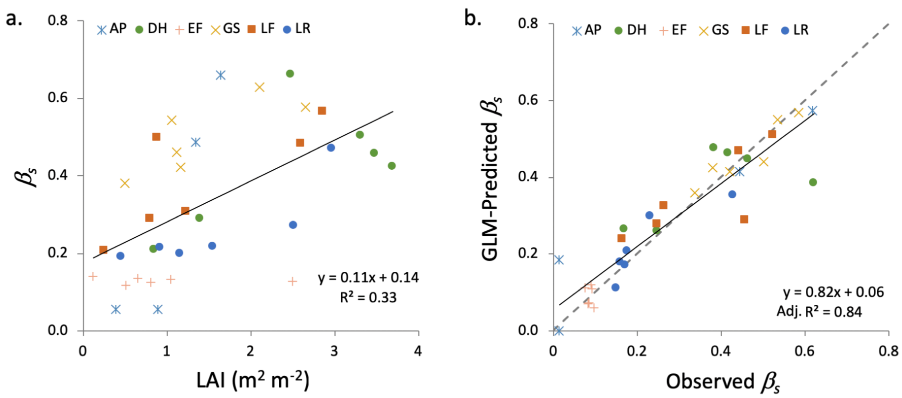

Figure 4. (a) Interception storage capacity (β_s) versus leaf area index (LAI) for all sites and plots. (b) Modeled versus observed β_s using the best GLM, which included % groundcover vegetation and an interaction term between site and LAI. The dashed line is the 1:1 line.

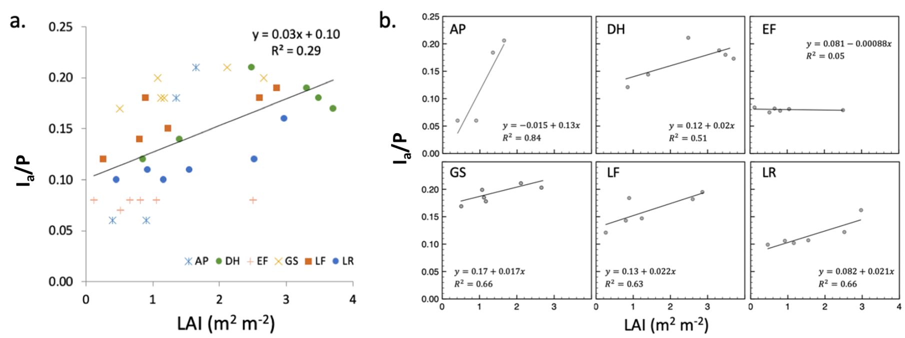

Figure 5. (a) Annual proportion of rainfall that is intercepted (I_a/P) intercepted versus LAI for all sites and plots. (b) Site-specific I_a/P versus LAI relationships. The relationship is generally strong except for the EF site, where the overall storage capacity is small across all values of LAI.

Table 1. Summary of storage capacity (β_s) and annual interception losses (I_a) for all sites and plots, along with plot characteristics (mean annual precipitation, P; leaf area index, LAI; percent groundcover, %GC; and species). Note that the AP site only had four plots with the data required for the analysis.

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Site	Plot	LAI	%GC	Species	β_s (cm)	R^2 ($\Delta\theta$-P)	P (cm)	I_a/P
AP	2	1.65	47.6	SF Slash	0.620	0.31	145.0	0.206
AP	3	0.90	62.8	SF Slash	0.014	0.78	145.0	0.06
AP	4	1.35	49.1	SF Slash	0.445	0.67	145.0	0.184
AP	6	0.40	73.4	Longleaf	0.014	0.57	145.0	0.06
DH	1	0.85	86.2	Loblolly	0.170	0.90	131.5	0.121
DH	2	2.48	51.2	Slash	0.621	0.68	131.5	0.211
DH	3	1.40	39.2	Slash	0.249	0.49	131.5	0.144
DH	4	3.31	35.8	Slash	0.464	0.71	131.5	0.188
DH	5	3.70	27.1	Loblolly	0.383	0.69	131.5	0.173
DH	6	3.48	32.9	Slash	0.418	0.40	131.5	0.18
EF	1	0.12	13.6	Clearcut	0.099	0.93	153.8	0.084
EF	2	1.05	56.9	Slash	0.092	0.96	153.8	0.081
EF	3	2.50	11.8	Sand	0.086	0.93	153.8	0.079
EF	4	0.66	50.9	Slash	0.094	0.92	153.8	0.082
EF	5	0.81	17.9	Sand	0.085	0.96	153.8	0.078
EF	6	0.52	52.0	Longleaf	0.076	0.89	153.8	0.075
GS	1	1.07	67.9	Clearcut	0.502	0.84	132.4	0.199
GS	2	2.66	7.9	Slash	0.535	0.88	132.4	0.203
GS	3	2.11	71.5	Slash	0.587	0.82	132.4	0.211
GS	4	1.12	42.4	Slash	0.421	0.90	132.4	0.185
GS	5	1.17	45.6	Slash	0.382	0.76	132.4	0.178
GS	6	0.51	55.2	Longleaf	0.339	0.78	132.4	0.169
LF	1	0.26	43.5	None	0.166	0.85	136.3	0.121
LF	2	2.86	23.1	Slash	0.525	0.64	136.3	0.195
LF	3	1.23	24.9	Slash	0.266	0.72	136.3	0.147
LF	4	0.80	25.7	Slash	0.248	0.64	136.3	0.143
LF	5	2.60	12.3	Slash	0.443	0.63	136.3	0.182
LF	6	0.89	25.9	Longleaf	0.458	0.69	136.3	0.184
LR	1	0.46	34.0	Clearcut	0.151	0.96	144.5	0.099
LR	2	2.97	38.1	Slash	0.429	0.84	144.5	0.162
LR	3	0.92	47.0	Slash	0.173	0.95	144.5	0.106
LR	4	2.52	26.7	Slash	0.232	0.92	144.5	0.122
LR	5	1.55	28.1	Slash	0.177	0.96	144.5	0.107
LR	6	1.16	35.5	Longleaf	0.160	0.96	144.5	0.102

Table 2. Summary of generalized linear model (GLM) results for interception storage capacity (β_s). LAI is leaf area index, GC is groundcover, and WT is water table (shallow vs. deep). The best model (by AIC) is shown in bold.

Model #	Variable(s)	AIC	R^2
1	LAI	378.1	0.32
2	LAI + site	318.5	0.66
3	LAI * site	255.9	0.83
4	**LAI * site + GC**	**253.1**	**0.84**
5	LAI + WT	338.3	0.55
6	LAI * WT	339.8	0.55
7	LAI * WT + GC	341.8	0.55
8	LAI + WT + GC	340.3	0.55