Response to Reviewer #2

1. Singh et al. compare estimates of the plant-accessible root-zone water storage capacity (Sr) to the expected amount of water needed to supply ET during a 20-year return drought length across the Amazon and Congo rainforests. They classify forests with Sr smaller than the amount of storage needed to withstand a drought of this magnitude as water-stressed and compare the current extent of water-stressed forests to the projected extent based on simulated future ET and P used to generate future Sr estimates. By using thresholds of water limitation associated with the transition of ecosystems from forest to savanna from a previous publication, they identify areas that might experience forest-savanna transition.
   This work is important because of our limited understanding of climate change-induced ecosystem transition.
   The figures are well made and clear, with excellent explanations both in the figures themselves and in the captions. I also appreciate the attention to subsurface moisture availability as a driving factor of landcover transition and water stress.
   ***Response*:** We appreciate the reviewer's positive feedback on the significance of our work and the clarity of our visualizations.

2. However, I had difficulty following the methods in this paper. I am also concerned with the interpretation of the root-zone water storage capacity metric.
   I am confused by the authors' method of calculating Sr as well as their conversion of Sr to an indication of water stress. Figuring out what they were doing took me quite some time and involved reading their previous paper on this topic [1]. I am still unsure if I understand their methods and believe other readers would also have difficulty following. I would recommend improving the clarity of the terminology used in the method (for example, differentiating between 'maximum deficit' and 'Sr') as well as incorporating more of the "Calculating root zone storage capacity" section of the SI into the main text.
   Response: In the revised manuscript, we will enhance the clarity and articulation of our methods section.

   - *First, we will improve the root zone storage capacity definition and the description of the estimation method. In the revised manuscript, we will expand and move the description of S_r estimation method from Supplementary Information to the main text as suggested by the reviewer. In addition, we will add a figure to visualize the S_r estimation method (see further down):*

   Root zone storage capacity (S_r) refers to the maximum amount of soil moisture that can be accessed by vegetation for transpiration during dry periods. Dry periods refer to periods in which evaporation is greater than rainfall, irrespective of the seasons. The method of estimating S_r is based on the mass-balance approach, through which we assume that ecosystems do not invest in expanding their rooting systems beyond the need for maximum accumulated water deficit experienced by the vegetation.

   For estimating S_r, we first obtained the water deficit (D_t) at daily time step from the daily estimates of precipitation (P_t) and evaporation (E_t) using:

$$D_t = E_t - P_t \qquad (1)$$

   Here, t denotes the day count since the start of the simulation, with simulation for each grid starting in the month with maximum precipitation. Second, we calculated the accumulated water deficit integrated at each one-day timestep for one year using:

$$D_{a(t+1)} = \max\{0, D_{a(t)} + D_{t+1}\} \tag{2}$$

Where $D_{a(t+1)}$ is the accumulated water deficit at each time step. Here, an increase in the accumulated deficit will occur when $E_t > P_t$, and a decrease when $E_t < P_t$. However, since this algorithm estimates a running estimate of root zone storage reservoir size, we use a maximum function to calculate the accumulated deficit, which by definition can never be below zero. Not allowing $D_{a(t+1)}$ to be negative also means that excess moisture from precipitation will either contribute to deep drainage or runoff. Lastly, the maximum accumulated annual water deficit ($D_{a,y}$) will represent the maximum storage required by the vegetation to respond to the critical dry periods.

$$D_{a,y} = \max\{D_{a(t+1)}\} \quad t = 1:n-1 \tag{3}$$

This simulation runs for a whole year, with *n* denoting the number of days in year *y*.

Previous studies also acknowledge that different terrestrial ecosystems are adapted to different drought return periods (i.e., recurrence interval) (Wang-Erlandsson et al., 2016). However, to avoid any artificially introduced transitions between different ecosystems (i.e., forest, savanna and grasslands), a uniform 20-year drought return period is used to calculate S_r (Bouaziz et al., 2020). This drought return period is then simulated for the whole time series of $D_{a,y}$ based on the Gumbel extreme value distribution (Gumbel, 1958). Thus, S_r refers to the maximum amount of root zone moisture available to vegetation for transpiration during the largest accumulated water deficit expected every twenty years under static climate conditions. (See the insets ‘a’ and ‘b’ in the figure below.)

Bouaziz, Laurène JE, et al. "Improved understanding of the link between catchment-scale vegetation accessible storage and satellite-derived Soil Water Index." Water Resources Research 56.3 (2020): e2019WR026365.

Gumbel, EJ. Statistics of extremes. Columbia University Press, New York (1958).

Wang-Erlandsson, Lan, et al. "Global root zone storage capacity from satellite-based evaporation." Hydrology and Earth System Sciences 20.4 (2016): 1459-1481.

- *Second, we will replace the term ‘water-stressed’ with ‘water-limited’ in the revised manuscript to prevent confusion.*

We believe that the source of this confusion is probably the use of the term ‘water stress’, which in our context refers to the magnitude and duration of water-deficit such that it inhibits plant growth, as well as the probability of them transitioning to a savanna ecosystem (Singh et al. 2020). However, we acknowledge that the term ‘water stress’ is commonly used in various contexts with different meanings, which could potentially confuse readers.

In this revision, we would therefore like to replace ‘water-stress’ with ‘water-limited’ to more precisely describe the effects of shifting hydroclimatic conditions on forest ecosystems, specifically in terms of inhibiting plant growth and the potential of them approaching the threshold of forest-savanna transition. Essentially, as ecosystems accumulate water deficits—resulting from higher evaporation, reduced precipitation, or extended dry spells—they adapt by enhancing their S_r, extending their roots to tap into deeper soil moisture for transpiration in dry periods. However, there is a limit to how much S_r can compensate for, beyond which further hydroclimatic shifts may lead to ecosystem tipping to savanna. See the inset ‘c-f’ in the figure below.

We will adapt the manuscript to this ‘water-limited’ term accordingly.

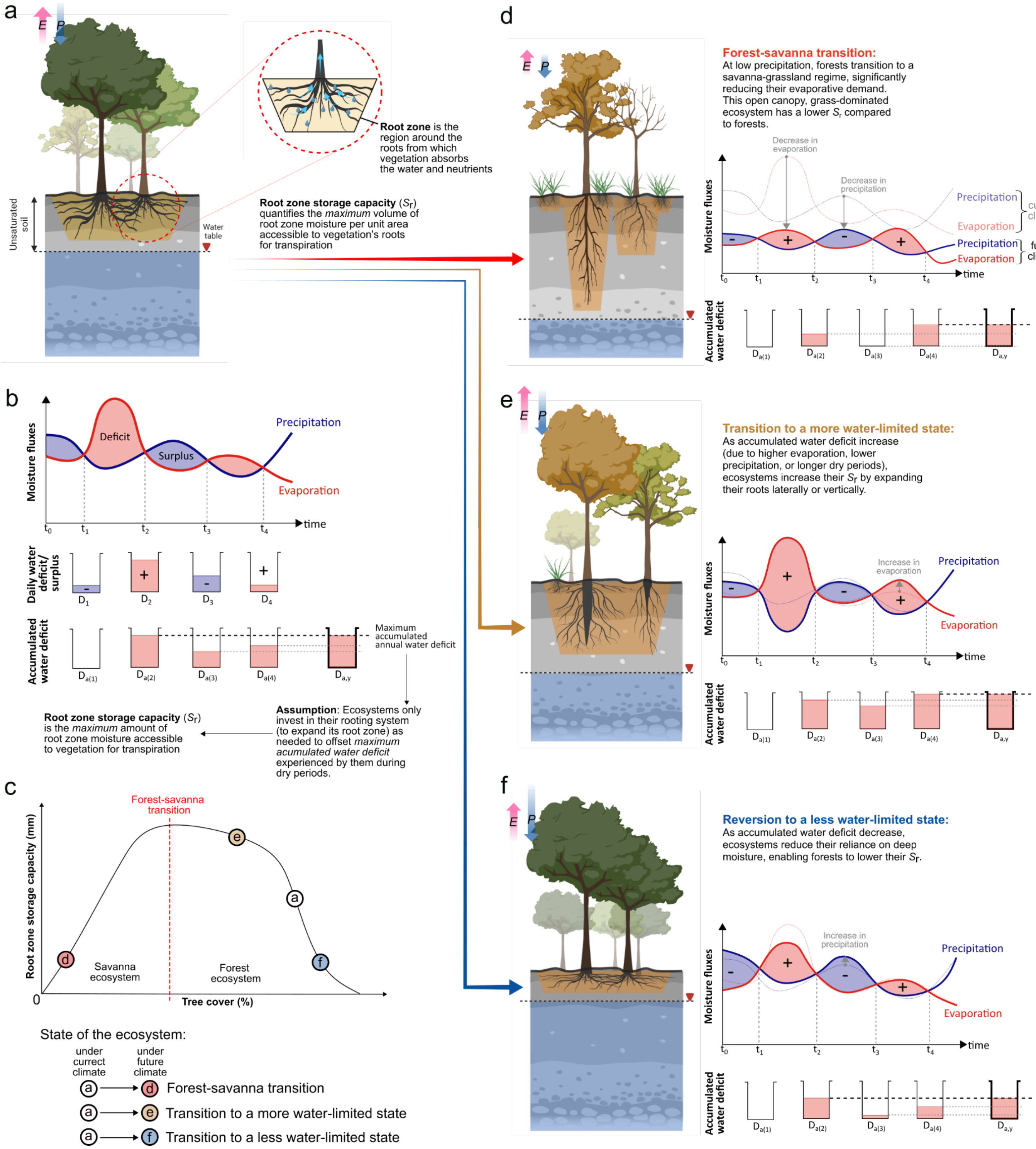


Fig. Conceptual framework to assess forest transitions using root zone storage capacity (S_r). (a) We illustrate the ecosystem's root zone and associated water storage, and (b) explain how we employ a mass-balance method, utilizing precipitation and evaporation data, to compute the accumulated water deficit and its relation to S_r. (c) Here, we outline how variations in S_r lead to forest transitions, with subsequent panels (d-f) offering detailed insights into the associated changes in the ecosystem's above-ground structure and below-ground root zone storage capacity. This figure in panel (b) is adapted from Singh et al. 2023.

3. If I am understanding the authors' calculation of Sr correctly, then I am skeptical about their interpretation of it. This confusion starts for me in the first sentence of the abstract. Forests themselves don't "store moisture" - the subsurface may store moisture (abiotically) and rainforests can access this moisture via roots. There are many places in the manuscript (for example, line 47) where the authors do not fully articulate the abiotic influence on Sr, and I think this may have large consequences for their interpretation of Sr as an indication of water stress.

   Response: This first sentence will be rephrased as **'Tropical rainforests invest in their root systems to access soil moisture stored in their root zone from water-rich periods for use during water-scarce periods**'. We will address and correct these discrepancies across the manuscript.

   Sentences in Line 47 will be rephrased as 'Since the rooting structure is challenging to measure at the ecosystem scale, previous studies have found that empirical mass balance-derived root zone storage capacity (S_r) correlates well with ecosystems' capacity to access water in its root zone and modify their above-ground structure accordingly; and thus can serve as a proxy for assessing an ecosystem's capacity to utilize subsurface moisture in maintaining its structure and functions under future climate change scenarios'.

   We wish to highlight that, in theory, **the empirical mass-balance-based estimates of S_r should reflect the impact of abiotic factors on vegetation's ability to access subsoil moisture.** This is because these mass-balance-based estimates are based on actual evaporation and precipitation data, reflecting the hydrological capacity of the root zone, albeit without directly accounting for the specific rooting strategies of the ecosystem. Nevertheless, these estimates encompass adjustments to rooting strategies influenced by, for example, soil type and structure, nutrient availability, oxygen levels, and mechanical resistance (such as rocks or dense layers that may impede growth and access to soil moisture). For instance, if a forest ecosystem cannot access sufficient soil moisture from deeper layers (i.e., water is not the limiting factor), it may extend its roots laterally to seek moisture; or will transition to a state that doesn't have high evaporative demand (i.e., ecosystem's investment in expanding their root zone is restricted by local factors). In the revised manuscript, we will expand on these factors in more detail.

4. For example, in my understanding, having a large deficit does not necessarily translate to water stress. Instead, it is a reflection of ET from storage, and therefore, of an ecosystem having a high Sr. Whether this high Sr confers resilience or risk to an ecosystem cannot be known from the Sr estimate itself. For example, "excessive short-term water deficits" (line 53-60) can be rephrased as 'a lot of ET and not a lot of P' which may mean that vegetation has a lot of access to subsurface water, not that it is at risk of mortality, as the authors write. I think this paper may be conflating drought and low subsurface moisture levels with the deficit when in my understanding the deficit and Sr are very difficult to convert directly to mortality or stress metrics (see [2] as an example of how complex using deficit-based methods to understand landcover can be). If my understanding of the methods of this paper is correct, this conflation would be a fundamental misuse of Sr.

   Response: *This response is partially covered in our previous response to comment 2.*

   Indeed, large water-deficits do not automatically imply water stress (as per its traditional definition), but rather indicate a high S_r. **However, our previous studies have shown that, under further episodic changes to their hydroclimate (e.g., decrease in precipitation, increase in evaporation or longer dry periods due to a warmer climate), tropical forest**

ecosystems with a higher S_r tend to be more susceptible to transitioning into savanna ecosystems than those with a lower S_r (Singh et al. 2020; 2022). This is because every ecosystem has evolved to sustain its structure and functions under specific hydroclimatic conditions. When an ecosystem exhibits a root zone storage capacity at the upper limits for its type, additional drying of the hydroclimate could trigger a transition from forest to savanna ecosystems. This shift occurs because savanna ecosystems are inherently more adapted and competitive under drier hydroclimatic conditions. In this study, our goal is to apply and extend these empirical insights to evaluate the resilience of rainforest ecosystems and their tipping risk under future climate change conditions.

Therefore, we would like to replace 'water-stress' with 'water-limited' to more precisely describe the effects of shifting hydroclimatic conditions on forest ecosystems, specifically in terms of inhibiting plant growth and the potential of them approaching the threshold of forest-savanna transition. For more information on how S_r links to forest transition and tipping risk, please check our conceptual figure above, which we will incorporate in our revised manuscript.

We also wish to highlight that Hahm et al. (2019; *study recommended by the reviewer*), discuss how the differences in plant-available water (or root zone available water) primarily depend on the depth and degree of weathering in the bedrock beneath the soils (i.e., part of critical zones), which impacts its water retention capacity. **Our S_r metric is designed to quantify the hydrological storage capacity within the root zone exclusively, without delving into rooting extent (e.g., depth or structure), which is influenced by multiple factors beyond the scope of this metric.** However, we would like to mention that apart from our studies, **the hydrological capacity of the root zone, derived from a mass-balance (or climate-based) approach, has been extensively examined, providing insights that more accurately reflect both hydrological regimes (de Boer-Euser et al. 2016) and vegetation dynamics (Dralle et al. 2020; Gao et al. 2014).** Notably, Dralle et al. (2020) assert that this mass-balance methodology can infer attributes of the critical zone, including characteristics of deeper weathered bedrock beneath superficial soil layers, a concept further investigated by McCormick et al. (2021).

Dralle, David N., et al. "Plants as sensors: vegetation response to rainfall predicts root-zone water storage capacity in Mediterranean-type climates." Environmental Research Letters 15.10 (2020): 104074.

McCormick, Erica L., et al. "Widespread woody plant use of water stored in bedrock." Nature 597.7875 (2021): 225-229.

Gao, Hongkai, et al. "Climate controls how ecosystems size the root zone storage capacity at catchment scale." Geophysical Research Letters 41.22 (2014): 7916-7923.

Hahm, W. Jesse, et al. "Lithologically controlled subsurface critical zone thickness and water storage capacity determine regional plant community composition." Water Resources Research 55.4 (2019): 3028-3055.

Singh, Chandrakant, et al. "Rootzone storage capacity reveals drought coping strategies along rainforest-savanna transitions." Environmental Research Letters 15.12 (2020): 124021.

Singh, Chandrakant, et al. "Hydroclimatic adaptation critical to the resilience of tropical forests." Global Change Biology 28.9 (2022): 2930-2939.

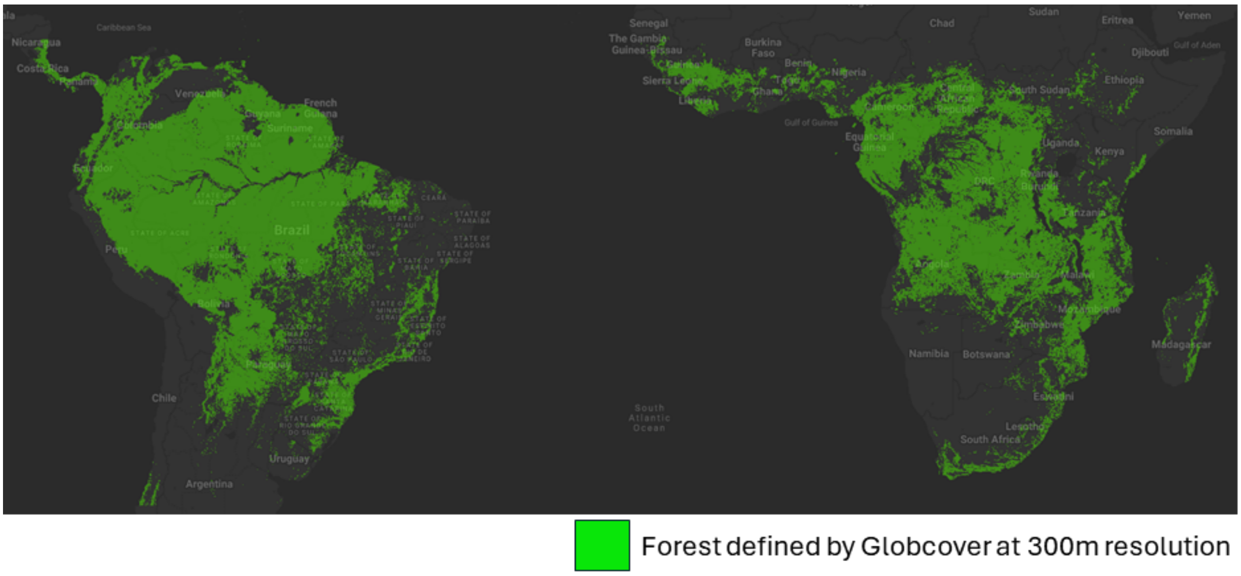
de Boer-Euser, Tanja, et al. "Influence of soil and climate on root zone storage capacity." Water Resources Research 52.3 (2016): 2009-2024.

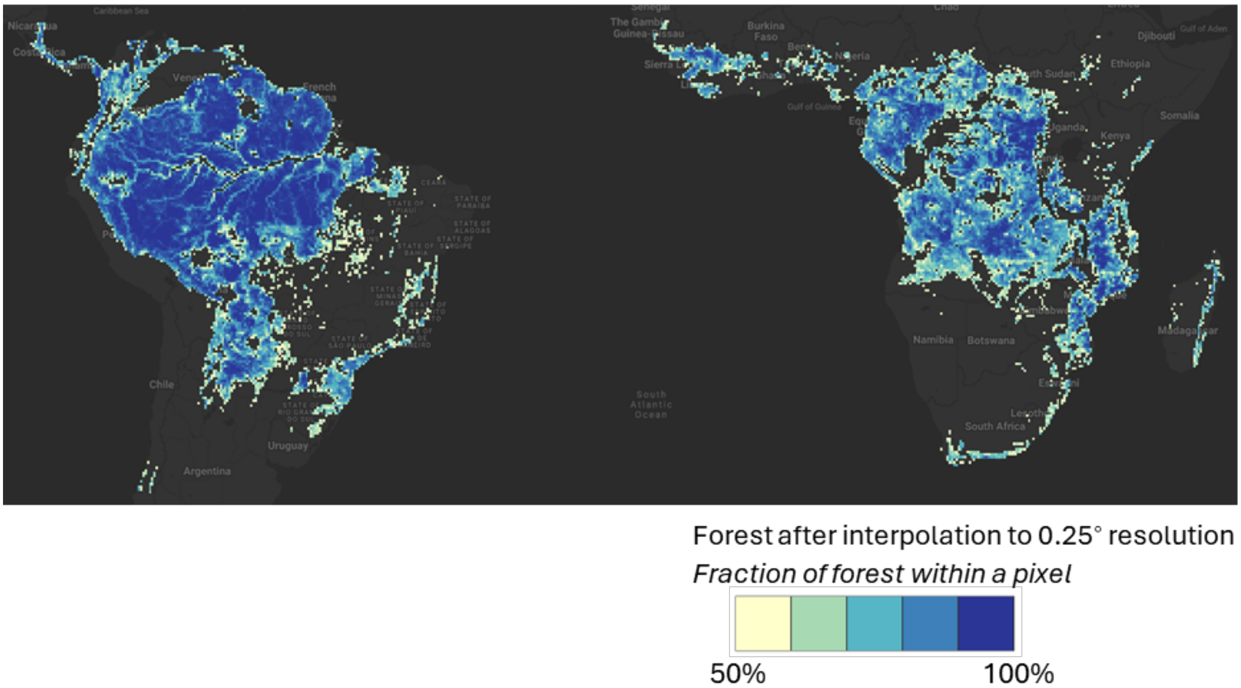
5. At present it is difficult to tell how much Sr is being misinterpreted because it is difficult to follow the methods of the paper. These issues could possibly be improved by (1) improving the clarity of the methods so it is possible for a reader to follow exactly how the metrics are calculated and compared to one another to derive the categories plotted in the figures, (2) more discussion on the abiotic controls of the deficit and how that might conflate interpretations of low vs high Sr as indicative of water stress and landcover transition, including careful examination and explanation of the logic outlined in Figure 2a (describing the relationship between Sr and transition) and (3) more information on the authors' previous thresholds for forest-savanna transition, which are critical to accepting their main results here.
   Response: We agree with the reviewer's suggestions and, as outlined in our previous responses, intend to enhance the clarity of our methods section and its connection to our results. To this end, we will introduce a dedicated sub-section detailing the findings from our prior study and describing how we extend these insights to forecast forest transitions under future climate scenarios.

Other comments:

6. Line 137: Using a threshold of 50% to determine if a pixel should be classified as "forest" seems generous, especially as other ecosystems might be expected to have very different ET (e.g. crops) and would therefore alter estimates of Sr to a large extent. It might be helpful to see the distribution of fractional forest cover present in your "forest" pixels or to otherwise show that the most of the area you are analyzing is more fully forested than 50% coverage.
   Response: It is widely accepted to use a threshold exceeding 50% to differentiate natural forests, characterized by woody vegetation cover greater than 50%, from savannas, where woody vegetation cover is 50% or less (Staal et al. 2018; Zemp et al. 2017). However, we acknowledge that in some instances, evaporation from non-forest land use could affect the overall evaporative trends of a pixel, especially as we aggregate the dataset to a coarser resolution.

   Following the reviewer's suggestion, we present data on the fraction of forest cover within a pixel (*figure below*). Our analysis indicates that instances of forest pixels containing land uses typically associated with non-forest areas frequently arise at the interface of natural and human-influenced regions. However, a visual comparison of these forested areas with the transition zones identified in our study (Fig. 3) reveals that they do not appear to significantly influence the overall findings.





Staal, Arie, et al. "Forest-rainfall cascades buffer against drought across the Amazon." Nature Climate Change 8.6 (2018): 539-543.

Zemp, Delphine Clara, et al. "Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks." Nature communications 8.1 (2017): 14681.

7. The model agreement threshold of 20% seems too low for gaining a robust understanding of likely future transitions. This is especially concerning as the area with >50% model agreement is so small (for example in Figure 2, the forest-savanna transition in Africa).

   Response: While a threshold of >20% may seem low based on the total number of ESMs analyzed, it's important to recognize the varying and often limited capabilities of these models, particularly in simulating biophysical interaction and emerging properties due to our limited understanding of the Earth system (Arora et al. 2023; Reyer et al. 2015). **Opting for a majority-based consensus in ESMs could overlook critical tipping risks identified by a subset of models, which may be as likely to reveal the actual state of such risks as their counterparts.**

Therefore, recognizing these challenges in accurately modeling land surface interactions and transitions within ESM, our study showcases model agreement levels of both >20% and >50% (Fig. 2). Contrary to previous studies that either relied on a single model or used an ensemble of hydroclimate estimates from (6 to 7) ESMs for projecting tipping risks (Supplementary Table 3), which could introduce a selective bias, our approach seeks to address this concern. By integrating a broad spectrum of transitions projected by different ESMs, our model enhances transparency and offers a more comprehensive understanding of rainforest tipping risk. Through this, we aim to illuminate both the discrepancies and alignments among the projected transitions, offering a foundation for future research into the causes behind these potential variances.

Arora, Vivek K., et al. "Towards an ensemble-based evaluation of land surface models in light of uncertain forcings and observations." Biogeosciences 20.7 (2023): 1313-1355.

Reyer, Christopher PO, et al. "Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges." Journal of Ecology 103.1 (2015): 5-15.

8. Line 48: The '-' is a typo? This sentence doesn't make sense.
   Response: Yes, this is a typo. We appreciate your attention in highlighting this. The corrected sentence can be found in our response to the reviewer's comment 3.

9. Typo in Figure 2 panel a, under 'transition to a more water-stressed state" (hydraulic failures).
   Response: Thank you for bringing this to our attention. This will be corrected in the revised manuscript.