

## ***Interactive comment on “Scaling properties reveal regulation of river flows in the Amazon through a “forest reservoir”” by Juan F. Salazar et al.***

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Comment:

This work by Salazar et al. is an interesting study and presents original ideas. The authors study scaling properties of river flows of the Amazon basin and its subbasins. Identifying whether a basin attenuates or amplifies extremes in the flow regime, they propose that (Amazonian) river basins can go through tipping points of river flow regulation if forest loss exceeds a critical level.

Despite the interesting features of this study, I have a number of concerns that leave me yet unconvinced of some of the interpretations and conclusions drawn from them. These issues need to be addressed in a major revision before I can recommend publi-

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cation of this manuscript.

Response:

We thank the reviewer for his/her comments. Specific answers to each comment are provided below.

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Comment:

The authors hypothesize that, generally, river flows in Amazonian basins are regulated by the forests, meaning that extreme lows and highs in flows are attenuated by the forest. Mainly forest-induced precipitation recycling would be responsible for this attenuation. Indeed, this provides a positive feedback between the land/biosphere and rainfall, and such positive feedbacks are necessary for tipping points to occur (Van Nes et al. 2016, Trends in Ecology & Evolution 31:902-904). It should, however, be made more clear how land-atmosphere interactions cause both higher minima and lower maxima in river flows. Moisture recycling also has a typical spatial scale and direction. How does this affect the regulation of river flows and could the finding that the Tapajos is unregulated be an artefact of its size (and possibly shape)?

Response:

The proposed land-atmosphere mechanisms that lead to potential loss of streamflow regulation with forest loss in the Amazon are highlighted in Figure 6. In this figure, we indicate how forest loss reduces both infiltration and evapotranspiration fluxes, which result in decreased soil and atmospheric water storage. These reductions in infiltration and evapotranspiration are compensated by increases in direct runoff, which in turn result in increased floods (Figure 6a). As soil water storage is decreased in response to forest loss, base flow (occurring in the dry season) that depends on sub-surface runoff and surface-groundwater interactions is likely decreased (Figure 6b). In addition, reduced evapotranspiration can lead to a reduction of precipitation, and lengthen-

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ing of the dry season, particularly in the Amazon basin, where precipitation recycling is a dominant climatic feature. These land-atmosphere mechanisms effects combined, potentially amplify the difference between low flows and floods, leading to loss of hydrologic regulation. To improve clarity, we propose a revised description for Figure 6 (which can be read in the response to next comment in this document).

In this paper we propose an approach for assessing hydrologic regulation based on the scaling properties of river flows. When applied to the Amazon tributaries, this approach allows the identification of different levels of regulation, including an unregulated basin such as the Tapajos. Our approach for assessing hydrologic regulation depends solely on the basin's scaling properties and, therefore, depends on river flow observations (as explained in Section 2 of the paper). However, the processes that result in specific scaling properties of each basin can be manifold and are related, generally, to the basin's biophysical attributes. We propose that forest-loss in the Amazon can affect river flow regimes in ways that lead to loss of regulation, which is then indicated by the basin's scaling properties (Section 3), such as in the Tapajos basin.

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Comment:

Key for understanding the feedbacks in the system should be figure 6. However, it rather confused me, for the signs of the arrows do not seem to represent the sign of individual interactions: for example, evapotranspiration does not decrease (as is indicated now), but increase atmospheric water storage. And how could atmospheric water storage increase direct runoff? Both the figure and the text should be revised to guide the reader more to understand the core of the idea that is proposed.

Response:

Signs in Figure 6 should not be interpreted independently, but rather as part of a story that begins with forest loss. For instance, to clarify the reviewer's example: the decrease in atmospheric water storage results from a decrease in evapotranspiration

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produced by the loss of forest. To avoid potential confusion, we will describe Figure 6 in the text as follows:

"Increased forest loss results in decreased Evapotranspiration (ET), related to loss of leaf area and root depth. As a consequence of decreased land-atmosphere water flux (ET), atmospheric water storage and precipitation recycling are reduced. Following general mass conservation principles in the long-term water balance for a basin ( $P=ET+R$ ), when ET is reduced, R (direct runoff) increases. Increased forest loss can also reduce infiltration, both through changes in soil properties, as well as a consequence of increased runoff. Lower infiltration leads to decreased soil water storage, which feedbacks into a further reduction of ET. Overall, the combined effects of reductions in ET, soil water storage and increased runoff result in increased floods (Figure 6a).

Decreased water storage resulting from increased direct runoff in the wet season, results in decreased baseflow in the dry season, which corresponds, generally to lower low flows. In addition, forest loss can also lead to reduced base flow through a lengthening of the dry season, and a reduction of precipitation (Figure 6b). Both of these effects have been previously related to deforestation in the Amazon."

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Comment:

Furthermore, I am not convinced of the threshold of 60% tree cover below which river basins shift from regulated to unregulated. The evidence for this threshold is that the Tapajos, inferred to be the only unregulated subbasin in the Amazon, is also the only one with an average tree cover of below 60%. This correlation is too weak to draw the conclusion that this threshold exists, let alone that deforestation has caused the Tapajos to pass a tipping point.

Response:

C4

We thank this comment as it allows us to distinguish between what we can conclude from our proposed approach and what we propose as a hypothetical explanation of our result. We can conclude that the river flow regime in the Tapajos is unregulated, based on the behavior of its scaling exponents for low flows and floods ( $B_L < B_F$ ), following the theoretical framework developed in Section 2. This conclusion, based on river flow observations for multiple gauges within the basin, does not address the causes of such unregulation. We propose the Forest reservoir hypothesis (Section 4) as a potential explanation linking forest cover and river flow regulation, and provide a conceptual framework highlighting the mechanisms that could lead to such linkage (Figure 6).

Previous studies have highlighted the potential effects of losing approximately 40% of forest cover in the Amazon, particularly on atmospheric and other hydrologic processes. We highlight this forest cover threshold, as it coincides with the amount of forest cover that separates regulated from unregulated basins in our study. However, our results do not allow us to conclude that this amount of forest cover is a critical threshold in the Amazon basin.

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Comment:

The authors also relate the 60% threshold to its correspondence to the threshold that can separate forests and savannas as alternative stable states. However, the latter threshold applies at local scales instead of at basin scale. A basin-scale average tree cover does not provide information about how far from such a threshold a forest is in any particular location; having a larger extent of grasslands in a basin does not necessarily mean that the forests in the basin are closer to a threshold. Indeed, the southern subbasins have more naturally occurring savannas and therefore lower average (subbasin-scale) tree cover. The presence of these savannas is a result of rainfall seasonality (Staver et al. 2011, *Science* 334:230-232), which, as pointed out by referee 1, itself affects the regulation of river flows.

C5

Response:

Based on this and the previous comment, we have modified the last paragraph in the discussion to exclude the sentences that indicate the existence of forest-savanna alternative stable states, as our results do not refer to alternative ecosystem states but rather to river flow regulation states. The modified paragraph reads as follows:

“A critical implication of our forest reservoir concept is that forest loss can induce a transition from the regulated state to the unregulated state in the Amazonian river basins. The value of the forest cover fraction where the inequality reverses from  $\beta_L > \beta_M > \beta_F$  (regulated state) to  $\beta_L < \beta_M < \beta_F$  (unregulated state) is  $\sim 0.60$  (Fig. 5a), equivalent to  $\sim 40\%$  deforested area in a river basin. This value coincides with previous studies suggesting that forest loss beyond  $\sim 30\text{--}50\%$  constitute a critical threshold in the Amazon beyond which rainfall is substantially reduced and a shift in the biosphere-atmosphere equilibrium can occur (Boers et al., 2017; Lawrence and Vandecar, 2015; Hirota et al., 2011; Sampaio et al., 2007). Our empirical findings, as well as the forest reservoir concept, indicate that presence and absence of tropical forest cover is concurrent with the regulated and unregulated states, respectively: the Tapajos and Madeira are the less regulated basins and also the ones with the lowest forest cover in the region.”

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Comment:

If the hypothesis that river flow regulation can pass tipping points holds, what would be the concrete consequences of such transitions? Obviously the limit case of infinitely high and low river flows will not be reached, so how do the authors see the future of the Tapajos and other basins if land use change continues? The paper lacks explicitness in this sense, which will leave readers like myself to question the validity of the forest reservoir concept.

Response:

C6

We agree with the reviewer that the case of infinitely high and low flows will not be reached, as this is a mathematical solution for our proposed theoretical framework. We propose that the physically-feasible limits for low flows and for floods are, respectively, zero and the value of precipitation. In the case of low flows, when the “forest reservoir” is empty (i.e. no water storage in the soil) and there is no precipitation, base flow tends to zero. This kind of behavior is common in water-limited basins. In the case of floods, when the forest reservoir is limited in its storage capacity, almost all precipitation becomes instant runoff. Both extremes have important ecological, economic and social implications.

It is not the purpose of this paper to produce future scenarios in the basins, as we have only used historic records to test our regulation hypothesis. However, if forest loss advances in any of the basins (but particularly in the Tapajos which is currently in the unregulated state), extreme river flows will likely become more extreme, and this can be exacerbated as the regulation capacity of the basin is further reduced. We recognize that forest loss is a factor affecting river flow regulation, but acknowledge that it is not the only factor potentially affecting regulation. For example, changes in precipitation associated with large scale changes in atmospheric circulation linked to climate change, will affect river flow regimes independent of the basin’s regulatory capacity.

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Comment:

Minor points:

In figure 5 the bar charts for tree cover are presented relative to a baseline of 60%, suggesting independent evidence for such a baseline, whereas the results in the figure itself are the evidence for a threshold of 60%. Please change to bar charts for tree cover starting at 0.

Response:

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Agree, we will revise the figure as suggested.

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Comment:

In figure 3e, the dots indicate that the exponents are significantly different. Yet, it is also said that it cannot be rejected that the exponents differ from 1. One of these statements must be wrong.

Response:

Agree, points will be removed in the revised version of Figure 3e.

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