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YSSP Report
Young Scientists Summer Program

Self-influencing feedback of deforestation on the actors responsible

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Approved by

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Program: Biodiversity and Natural Resources Program
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Abstract

Deforestation due to increasing global food demand has driven massive agricultural and pasture expansions in South America, which threatens both natural and human-managed land use. These serious threats pose challenges for future local and global water and food security. However, to circumvent such a future and implement sustainable land management practices, the extent of the deforestation-impact relationship needs to be studied critically. Here we propose two experiments to quantify the precipitation loss due to deforestation over the downwind region using the Lagrangian moisture tracking model. Our results reveal a strong north-south gradient of deforestation to moisture loss across the continent. This is because the northern regions are primarily dependent on oceanic moisture sources, and therefore, are unaffected by deforestation. In contrast, southern regions are dependent on transpiration from Amazon and are, therefore, influenced more considerably by deforestation. The dependence of northern ecosystems on oceanic moisture sources also increases their potential for recovery post-deforestation than those in the south. Comparing the suitability of crops under both these deforestation experiments revealed that precipitation is considerably reduced if deforestation happens in the south, so much so that even the moderate water-demanding crops were unsuitable for growth. Comparing our results with landowner demographics suggests that the large-scale landowners' have much more leverage over moisture flows than small-scale landowners. This report emphasizes the need for stringent forest policies to factor in the influence of deforestation on downwind actors and the need for more effective ecosystem stewardship.

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About the authors

Chandrakant Singh is a PhD student in Sustainability Science at Stockholm Resilience Centre, Stockholm University in Sweden. His PhD focuses on exploring the eco-hydrological patterns in the tropical terrestrial ecosystems of South America and Africa due to climate and land-use change. His overarching research interest lies in analyzing and identifying pathways/trajectories that lead to responsible ecosystem stewardship and effective transboundary governance.
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Introduction

Transpiration from the forests influences the precipitation over the vegetation (Staal et al., 2018). A portion of this transpired moisture gets transported to the downwind region of the source region (van der Ent et al., 2014). For Amazon, a major portion of moisture originates from its own basin; part of which is transported to the downwind cropland and pasturelands outside the basin through atmospheric teleconnection (Staal et al., 2018). Studies suggest that rainforests maintain regional and global water cycle by regulating this moisture flow through the atmosphere (Keys et al., 2016). However, this delicate moisture flow is threatened by deforestation, leading to profound negative impacts on the precipitation across the continents (Oliveira et al., 2013; Staal, Flores, et al., 2020; Zemp et al., 2017). Other than influencing forest stability (Hirota et al., 2011; Singh et al., 2020), this decrease in precipitation has negatively impacted crop production downwind to the Amazon (Oliveira et al., 2013). Therefore, a better understanding of the deforestation-impact relationship is important to circumvent any undesirable future, such as water scarcity or food insecurity.

The history of deforestation in South America suggests a serious threat to the stability of the rainforest ecosystems and ecosystem services associated with them (Amigo, 2020). Approximately 20% of the Amazon rainforests have been lost to deforestation and fires over the last fifty years, and this forest loss is projected to reach as high as 40% by 2050 (Feng et al., 2021). Studies also suggest that the future forest loss in the rainforests can be even severe than what is already predicted under the combined influence of climate change and land-use change (LUC) (Amigo, 2020; Davidson et al., 2012). This report, however, is only focused on the LUC impacts.

Fig. 1: Spatial extent of forest cover (>50% tree cover) and deforestation in South America [Source: Amigo (2020)]. Deforestation for other regions (including tree cover ≤ 50%) are shown in Annexure-1.

The current deforestation trends across the Amazon are majorly accredited to massive croplands and pasturelands expansions driven by increasing global food demand (Fig. 1) (Grau & Aide, 2008; Song et al., 2021). In recent years, along with increasing food demand, studies speculate that the current political regime's relaxed enforcement of stringent forest-related policies has further aggravated these deforestation trends (Feng et al., 2021). Nevertheless, to study the impact of deforestation and associated moisture loss, we need a flexible tool to quantify this relationship spatially.

With advancements in empirically derived moisture tracking models using remote sensing datasets, it is now possible to explore the remote influence of deforestation on other remote land use (Tuinenburg et al., 2020). These empirical models are much more flexible than the climate models. Thus, it can be used to visualize and quantify moisture trends both spatially and temporally (Tuinenburg et al., 2020).

The overarching objective of this report is to evaluate the deforestation-impact relationship within South America. Through this, we contribute to the (i) overall understanding of the influence of deforestation on precipitation over remote land use, and (ii) evaluate the suitability of the current agricultural regime under future LUC. (iii) We also evaluate the possibility of natural ecosystem recovery post-deforestation under the current climate.

The insights from this report will help us deduce whether the actors responsible for deforestation and reducing precipitation sabotage their own interest or make gains at the expense of other downwind actors. In the former case, knowledge support may be necessary so that actors can better understand driver-impact relationships. In the latter case, however, strong regulation to manage externalities might be critical. Hence, shedding light on this aspect will contribute to more effective governance.

Data and Methods

Projection of future land-use change

Several studies have projected future LUC in the Amazon; however, they are still surrounded by uncertainties, implying a divergence between the observed and projected LUC (Dalla-Nora et al., 2014). This is because the justification behind capturing the complex LUC interaction around the Amazon is different. On the one hand, some studies highlight the LUC projections based on agricultural or pasture expansion (Schielein & Börner, 2018; Wassenaar et al., 2007); others are based on just single commodity-specific deforestation (e.g., soybean-driven LUC) (Sampaio et al., 2007). There are also those models grounded on environmental changes such as climate change and fire (Lapola et al., 2011), all the way to those linking complex drivers such as international markets and regional policies (Pacheco et al., 2011). Since the recent trajectory of LUC in the Amazon has been much different from what was observed in the past (Dalla-Nora et al., 2014), all models predict the perception of a potential future.

In this report, we explore an alternative scenario by projecting the future LUC on the hydroclimate of South America. We devised two experiments where: (1) future LUC occurs only in the least resilient (i.e., prone to perturbations) part of the forest ecosystems (will be referred to as Experiment-1), and (2) LUC occurs in proximity to the current agricultural land cover (will be referred to as Experiment-2).

For Experiment-1: we derived the least resilient forest (i.e., forest resilience < 80th percentile) using the methodology by Singh et al. (2021) (Fig. 2). This method estimated the resilience of the forest ecosystems using mean annual precipitation (MAP; mm) and root zone storage capacity (S_r ; i.e., the subsoil buffer capacity of the ecosystem during dry periods) (Fig. 4 in Singh et al. (2021)). The detailed methodology is provided in Appendix-2. To estimate forest resilience, we used precipitation, evaporation and tree cover datasets. The precipitation estimates were acquired from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for 2000-2019 (Funk et al., 2015). We derived an equally-weighted ensemble of three evaporation products for the year 2000-2012: Breathing Earth System Simulator (BESS), Penman-Monteith-Leuning (PML) and FLUXCOM-RS (Jiang & Ryu, 2016; Jung et al., 2019; Zhang et al., 2015). These evaporation datasets chosen for resilience estimation were free from any prior biome dependent parametrization. Lastly, the tree cover dataset was acquired from the remotely-sensed MOD44B (version 6) for 2000-2019 (Dimiceli et al., 2017).

For Experiment-2: we estimated the upwind regions that contributed > 50% to the MAP on the current croplands (Fig. 2). These upwind source moisture regions are commonly referred to as precipitationsheds, and the sink regions (e.g., croplands in the present case) are referred to as evaporationsheds. The moisture contribution from the source to the sink is estimated using the 'Utrack moisture recycling model' (see 'Utrack: Lagrangian moisture recycling model' in the Data and Methods). The cropland dataset was acquired from Foley et al. (2005) (Appendix-3). Globcover land cover dataset was used for classifying the landcover into 'permanently deforested', 'projected land-use change' and 'natural vegetation' for both Experiment-1 and -2. Ultimately, all the datasets mentioned above were spatially interpolated from their native resolution to 1° grid resolution to match the Utrack moisture recycling model.

We assumed that the projected future LUC regions would be utilized for agriculture in both of these experiments. Therefore, we substituted the evaporation post-deforestation (i.e., evaporation of Class-1 in Fig. 2) with the average monthly evaporation of South American agricultural lands.

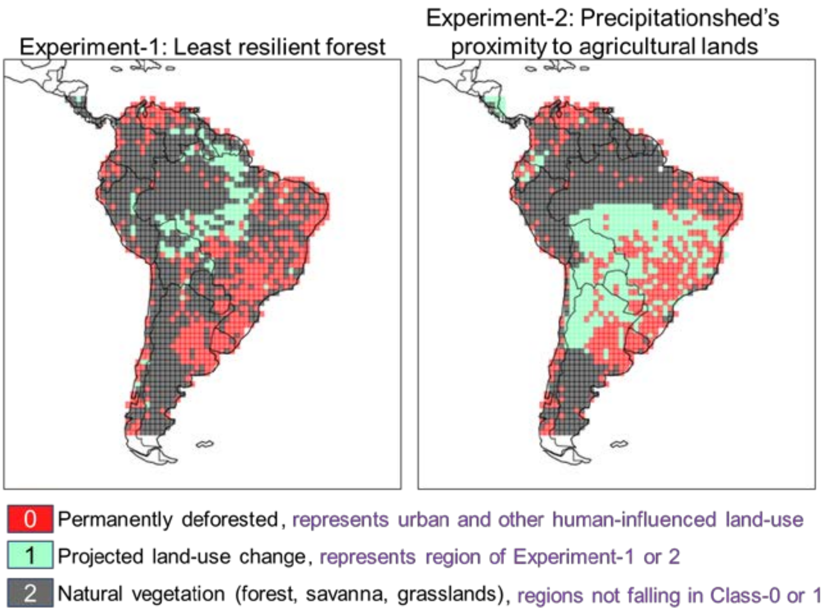

Fig. 2: Projections of future land-use change.

Utrack: Lagrangian moisture tracking model

The water cycle is a key component of the Earth system processes that regulate atmospheric moisture flows all over the globe. Studies suggest that 36% of the total global precipitation originates from the land (Tuinenburg et al., 2020; van der Ent et al., 2014). This evaporated moisture is transported through the atmosphere from a few meters to several thousands of kilomteres before precipitating. Utrack lagrangian moisture tracking model by Tuinenburg et al. (2020) tracks these moisture flows through the atmosphere and quantifies the evaporated moisture from a source precipitating over the sink region.

Using the Utrack moisture recycling model, we quantify the change in precipitation due to the projected land-use change over the other land use. The Utrack model quantifies the evaporation from source to sink as the fraction of source evaporation at a monthly timescale. This has to be multiplied by monthly evaporation estimates to get the absolute value of total precipitation from the source on the sink (mm/month) (Fig. 3). Also, since the Utrack model is based on Era5 forcings (2008-2017), we directly used Era5 evaporation to estimate total precipitation from source-to-sink to maintain the water balance (rather than using the ensemble evaporation as mentioned in 'Projection of future land-use change' in Data and Methods).

Cascading moisture recycling

The evaporated moisture from a particular upwind land cover can precipitate and evaporate repeatedly (Fig. 3), and thus promotes vegetation growth over remote downwind land cover's (Staal et al., 2018; Zemp et al., 2014). However, this cascading moisture flow (i.e., re-evaporation of precipitated moisture) is rarely considered due to the challenges in quantifying the atmoispheric pathway of moisture transport and the number of re-evaporation cycles. A study suggests that out of the total moisture transpired by the forests in the Amazon, 49% of the moisture can re-evaporate multiple times (i.e., re-evaporation cycle ≥ 1) (Staal et al., 2018). Therefore, other than directly tracking the moisture from the source, we also include the influence from the cascading effect of the transported moisture.

The atmospheric moisture pathways were tracked using the Utrack model. The re-evaporation was based on the evaporation by precipitation ratio of the grid. We only included up to three re-evaporation cycles to avoid considering moisture transport between the months. This is because the residence time of moisture in the atmosphere can be up to 10 days (Gimeno et al., 2021). These re-evaporation cycles were tracked up until either the monthly moisture reduced to ≤ 1mm/month (regardless of the re-evaporation cycles) or the re-evaporated moisture flows to the ocean. Lastly, the sum from direct and cascading runs was corrected to never exceed the total actual precipitation of the sink grid.

A conceptual flow diagram that explains the mentioned direct and cascading moisture flow is mentioned in Fig. 3. Furthermore, an example of direct and individual CMR runs in South America for Class-0 is shown in Appendix-4.

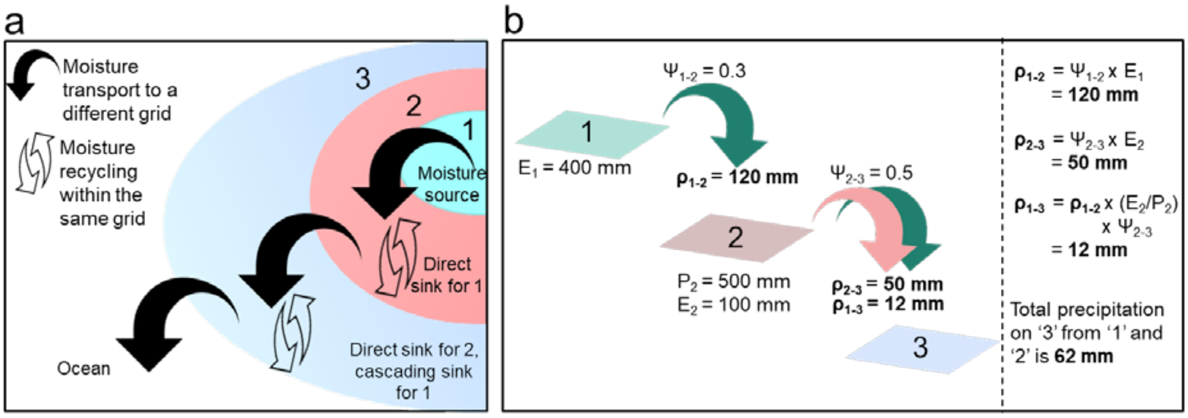

Fig. 3: (a) Conceptualization of direct and cascading moisture flows. (b) Example: quantification of the direct and cascading moisture flows using precipitation (P), evaporation (E), and the fraction of source evaporation to sink (Ψ) estimates from the Utrack model. Here, both ρ_{1-2} and ρ_{2-3} are direct moisture flows from source '1' and '2', respectively, whereas ρ_{1-3} is the cascading moisture flow on '3' (sink) from '1' (source).

Potential of recovery post-deforestation

The recovery of deforested ecosystems has received considerable attention in recent years, not only from a biodiversity perspective (Wright & Muller-Landau, 2006), but also from the prospect of future food security (Meyfroidt, 2018). Several studies have outlined the crucial efforts necessary for ecosystem recovery (Castro et al., 2021; Espírito-Santo et al., 2020; Hérault & Piponiot, 2018). However, due to the longer time scale of natural regeneration, whether the regenerated ecosystems from these recovery efforts will provide the equivalent level of ecosystem services as the native ecosystems is still uncertain (Poorter et al., 2016).

One standard theory among several studies is 'alternative stable states' (Hirota et al., 2011). According to it, there exists a threshold beyond which the tropical forest ecosystems will collapse to a savanna-grassland or a treeless state (Fig. 4). However, this threshold is not the same for ecosystem recovery (i.e., savanna to forest). Therefore, another threshold needs to be crossed beyond which the climate conditions will naturally facilitate forest recovery (Fig. 4), given enough time (Hirota et al., 2011). This is because the stabilizing feedbacks of the respective ecosystems help them retain their structural and functional characteristic under change (Singh et al., 2021). We use the same concept to spatially highlight the potential of climate in assisting the natural recovery of the deforested ecosystems.

We determined the thresholds for ecosystem recovery (i.e., natural transition of the deforested land cover back to forest) using the empirical bifurcation diagram (Fig. 4). This bifurcation diagram relates MAP with tree cover to determine the stable and unstable ecosystems by constructing the potential stability landscape (Hirota et al., 2011). We directly used the thresholds from Staal et al. (2020) for our analysis (Fig. 4). It should be noted that this concept does not quantify the time for recovery, and only provides the conditions that will facilitate the ecosystem regeneration. Example: deforested ecosystems (i.e., ecosystems below the white dot in Fig. 4) crossing the 2050 mm/year threshold will naturally transition to forests, given enough time.

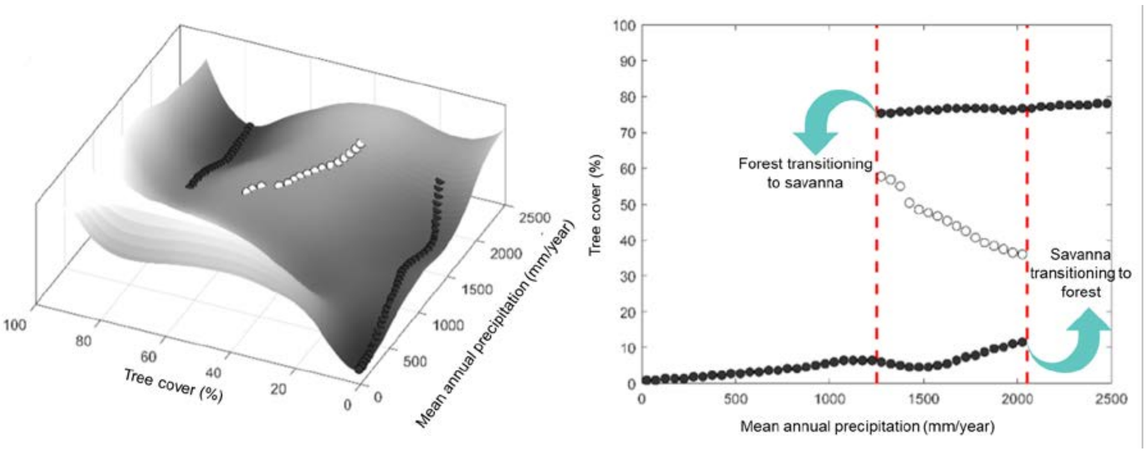

Fig. 4: Empirical bifurcation diagram for South America. The black dots (valleys in Fig. 4a) represent the stable state of the forest (> 50% tree cover) and savanna (≤ 50% tree cover)) ecosystems, whereas white dots (hilltop in Fig. 4a) represent the unstable state. The dashed red line (in Fig. 4b) represents the bifurcation threshold for forest-to-savanna and savanna-to-forest transition. In the present case, deforested ecosystems can be categorized as savanna since they have a tree cover <50%. To put it into perspective, a forest ecosystem in South America will naturally transition to a savanna if the MAP needs to decrease below 1250 mm/year (dashed red line on the left in Fig. 4b). Whereas for the savanna ecosystem to naturally transition to a forest, the 2050 mm/year threshold needs to be exceeded. [Source: Staal et al. (2020)].

Results

Moisture contribution to the current land use

Our results reveal that Class-0, i.e., the human-influenced land use (including croplands), directly contributes to the moisture falling over Brazil's eastern and southern parts; Paraguay, Bolivia and northern Argentina (Fig. 5a). This moisture contribution increases further when the CMR effect is considered (Fig. 5b). The most considerable increase is observed near the eastern flank of the Andes adjacent to the western part of Paraguay, Argentina, and southern Bolivia. Therefore, we also observe an increase in moisture contribution to south-eastern Brazil, Uruguay, and Argentina. Quantification of these observed spatial patterns suggests that the current human-influenced land use contributes to about (median) 27% and 76% to the current croplands directly and also by considering the CMR effect, respectively (Fig. 5c). Furthermore, the human-influenced land use contributes to about 19% and 42% directly and including CMR, respectively, over itself.

We also observe a clear gradient of moisture contribution between the northern and southern parts of South America. This suggests that the atmospheric moisture is transported towards the southern part of the continent, where it channels through the Andes and flows into the ocean by crossing the Río de la Plata basin. This increase of CMR near the eastern Andes is due to the South American low-level jet, which facilitates the moisture channelled through this region and contributes to a considerable increase in precipitation over the Río de la Plata basin (Zemp et al., 2014). This trajectory further suggests that any degrading change (i.e., directly reducing evaporation) to the current upwind human-influenced land use will reduce the moisture falling over the downwind direction (i.e., the southern part of the continent). Since the northern-eastern part of the continent receives moisture from oceanic sources (Staal et al., 2018), they are more resilient to deforestation patterns.

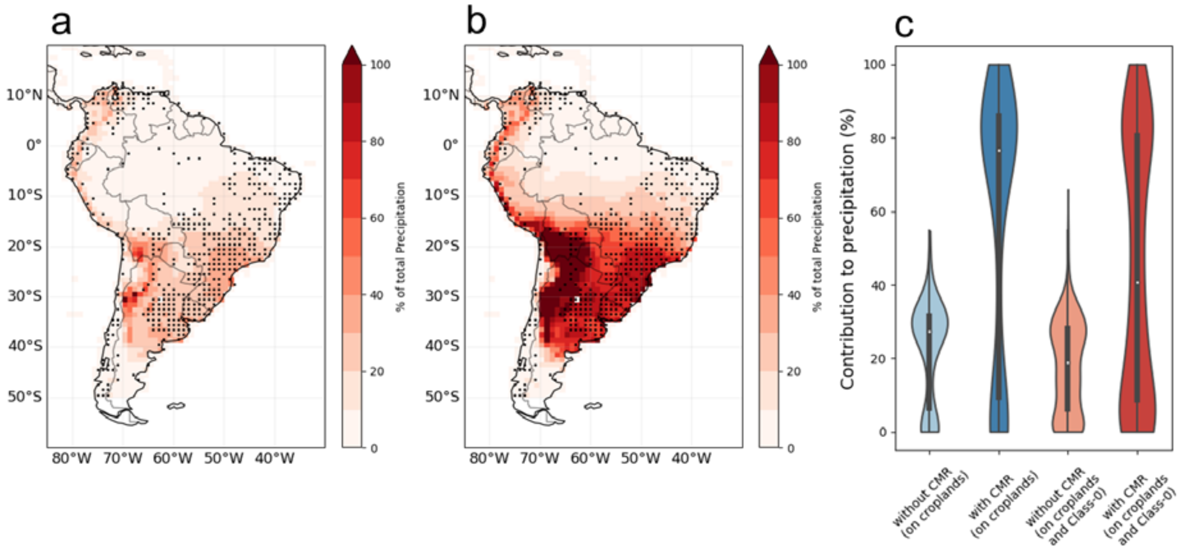

Fig. 5: The contribution of Class-0 (i.e., urban and other human-influence land use, including agricultural regions; represented by the dotted regions) on the total precipitation in South America, where (a) representing the direct contribution, and (b) representing the direct+cascading contribution to the mean annual precipitation. (c) Contribution to the total precipitation on the current croplands (i.e., cropland cover > 20% as defined by Foley et al. (2005)) and other Class-0 grids. The white dots in (c) represent the median, the thick line in the middle representing the 25th and 75th percentile, with

the top and bottom representing the minimum and maximum contribution. The width of the violin plot represents frequency distribution.

Similar results are observed for other experiments as well. For the 'Experiment-1' Class-1, i.e., deforestation of the least resilient part of the forest, the direct contribution of moisture is mostly over the south-western and southern part of Brazil, Bolivia, and Paraguay (Fig. 6a). Similar to the results of Fig. 6, this moisture contribution increases further when the CMR effect is considered (Fig. 6b). Most of the increase is again observed in the south-western (near the Andes) and south-eastern part of the continent. We also observe that comparatively, the moisture contribution from Class-1 (Experiment-1) is less than that of Class-0. This is due to the smaller area of 'Experiment-1' Class-1 and the geographical location of the experimental deforestation (i.e., distributed along north and south). Quantification of the observed spatial patterns suggests that that Class-1 (Experiment-1) contributes to about (median) 3% and 38% to the current croplands directly and also by considering the CMR effect, respectively (Fig. 6c). When considering the extended croplands (since we assume the deforested forests are converted to agricultural lands), the effect of moisture contribution becomes 4% and 20% directly and including CMR, respectively.

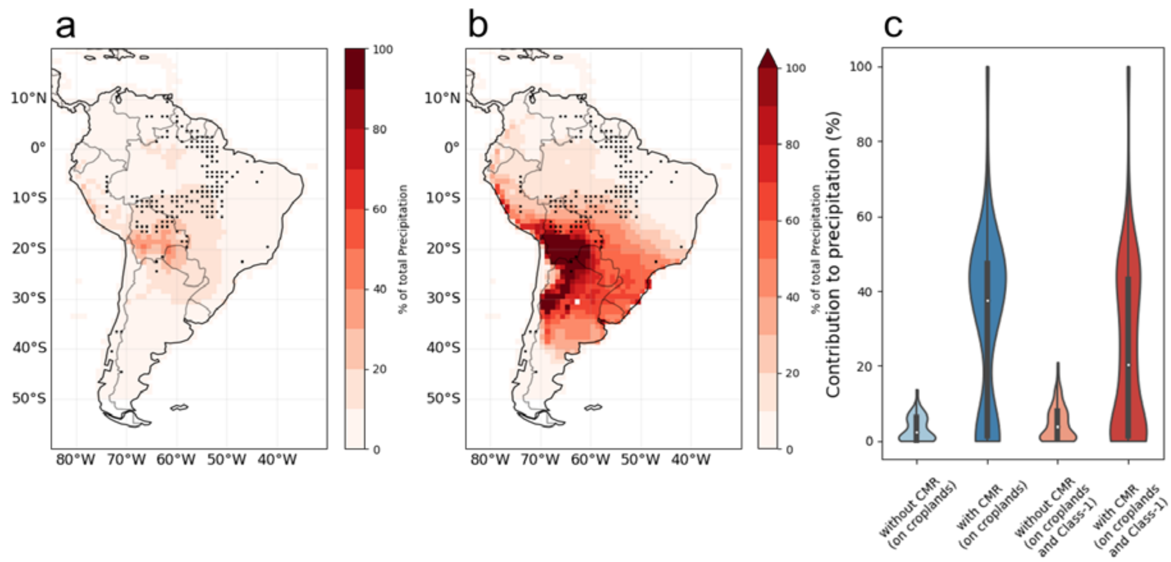

Fig. 6: The contribution of 'Experiment-1' Class-1 (i.e., projected land-use change in the least resilient forest; represented by the dotted regions) on the total precipitation in South America, where (a) representing the direct contribution and (b) representing the direct+cascading contribution to the mean annual precipitation. (c) Contribution to the total precipitation on the current croplands (i.e., cropland cover > 20% as defined by Foley et al. (2005)) and other Class-1 grids (i.e., extended croplands).

As for the 'Experiment-2' Class-1, i.e., deforestation of the precipitationsheds in the proximity of current agricultural lands, both the direct and CMR contribution have increased considerably. We observe that the moisture contribution is high from central Brazil to central Argentina (Fig. 7a). Similar to the results of Fig. 5 and 6, this moisture contribution increases further when the CMR effect is considered (Fig. 7b), with the most considerable increase over the eastern Andes connecting Brazil, Paraguay and the northern part of Argentina. This moisture contribution from Class-1 (Experiment-2) is significantly higher than previous cases due to the distinctive southern gradient of deforestation. Spatial patterns suggest that that the current Class-1 (Experiment-2) contributes to about (median) 22% and 63% to the current croplands directly and also by considering the CMR effect, respectively (Fig. 7c). When considering the extended croplands, the effect of moisture contribution doesn't vary much compared to previous cases; and remains about 23% and 58% directly and including CMR, respectively.

In all the above cases, the channeling of moisture through the eastern flank of Andes highlight their role in the cascading moisture transport over the Río de la Plata basin, which can significantly influence the precipitation falling over the croplands (Zemp et al., 2014).

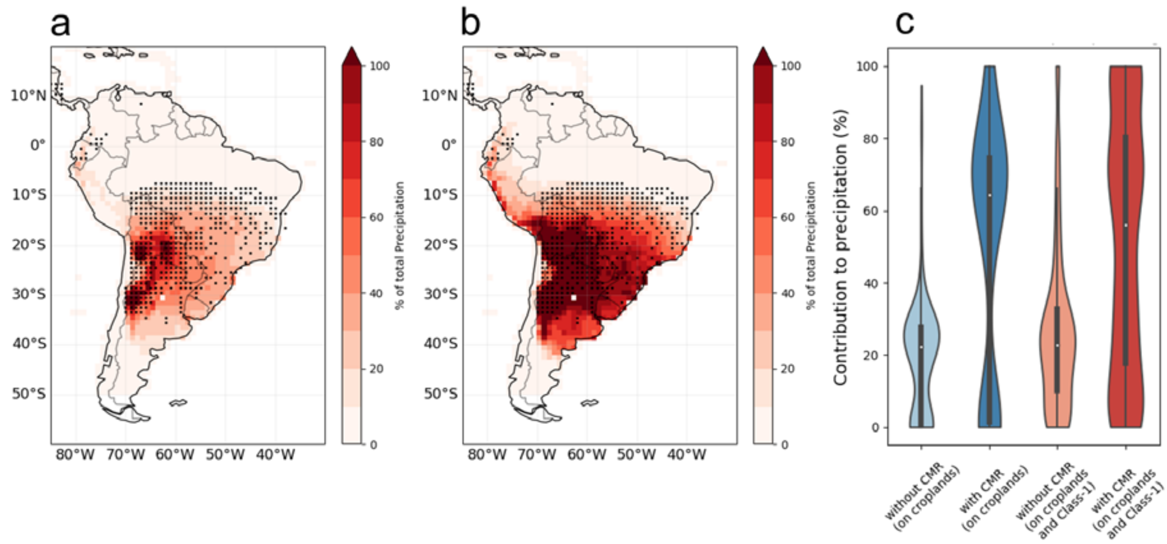

Fig.7: Similar to Fig. 6, the contribution of 'Experiment-2' Class-1 (i.e., projected land-use change near the proximity of croplands; represented by the dotted regions) on the total precipitation in South America.

Water scarcity and suitability for crops under future deforestation

We further assess the suitability of crops under deforestation based on crop water demand (i.e., amount of water a crop needs) during the growing period over the current croplands. The water demand estimated was acquired from the Food and Agriculture Organization of the United Nations (FAO, 1998). Due to the lack of specific water demand for different growth stages of the individual crops, we have distributed the current water demand equally between all the months (Fig. 8).

We observe a noticeable water deficit under future deforestation while comparing the crop water demand for different experiments (Fig. 8). On the one hand, the precipitation simulated from the direct run of Experiment-1 shows a higher water deficit. The precipitation simulated from the direct+CMR run of Experiment-2, on the other hand, suggest a much higher water deficit. In the former case, the direct contribution of forest in the Amazonian arc of deforestation has a higher contribution to the current croplands. However, in the latter case, due to the strong cascading effect (i.e., repeated re-evaporation and precipitation), a much higher amount of moisture will be lost under future LUC in the Río de la Plata basin.

Due to the deforestation in Experiment-1, most crops will face water scarcity, mostly only during the dry seasons (Fig. 8a). However, this water-scarcity trend will also extend to the wet seasons if the deforestation takes place in close proximity to current croplands (i.e., Experiment-2 in Fig. 2; Fig. 8b). This will make even the moderate water-demanding crops (such as maize, soybean and wheat) unsuitable for growth in the current agricultural locations.

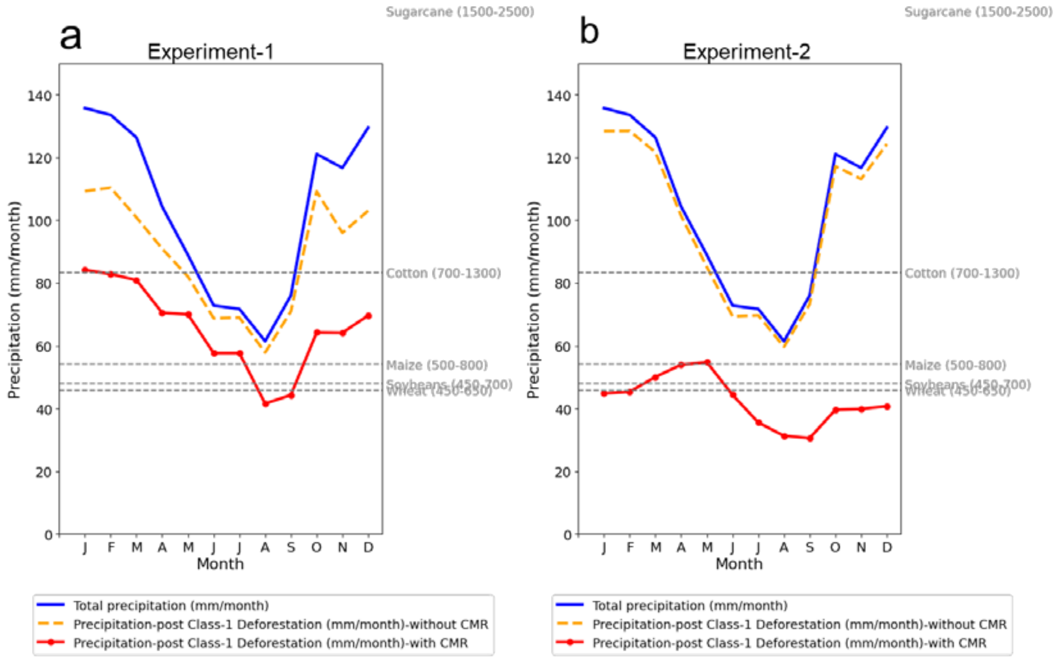

Fig. 8: Suitability of crops under different experimental deforestation. The grey lines represent the water demand of crops during the growing season under current climate. This water demand is distributed equally among the months. The solid blue line represents the current average precipitation over the croplands, with dashed yellow and solid red line representing direct and direct+CMR simulated precipitation, respectively, over the croplands.

Recovery under current climate

Here, we highlight the potential of the experimentally deforested ecosystems to revert to a forest ecosystem based on the theory of 'alternative stable states'. For this, we analyze the precipitation loss due to the Class-1 from Experiment-1 and -2 (Fig. 9a and 10a), and check whether these ecosystems exceed the 2050 mm/year threshold (i.e., the threshold for savanna-to-forest transition (Staal, Fetzer, et al., 2020)). We acknowledge that the modified-local conditions can influence the ecosystem recovery (e.g., human-induced fire drive seedling mortality (Moser et al., 2010)) even if the threshold criteria are met. However, here, we assume that all conditions required for natural ecosystem recovery are fulfilled.

We find that for Experiment-1, 44% of the total deforested region (out of which 83% were forest pre-experimental deforestation) show the potential for recovery under the current climate (i.e., MAP from 2008-2017) (Fig. 9b). Whereas, for Experiment-2, only 16% of the total deforested region (out of which 46% were forest pre-experimental deforestation) shows recovery potential (Fig. 10b). In both cases, only the northmost part of the deforested region show recovery. In the case of Experiment-1, the northern part of the deforested regions is dependent on moisture from the oceanic sources. In contrast, the southern part is dependent on the transpiration from the Amazon (Staal et al., 2018). With the reduction in moisture over the Amazon (Fig. 9a), the subsequent cascading moisture flow over the southern regions is significantly reduced. In Experiment-2, however, the low precipitation condition is due to the dependence of southern forest ecosystems on Amazon transpiration and the strong cascading effect within the Río de la Plata basin (Fig. 8b and 10a).

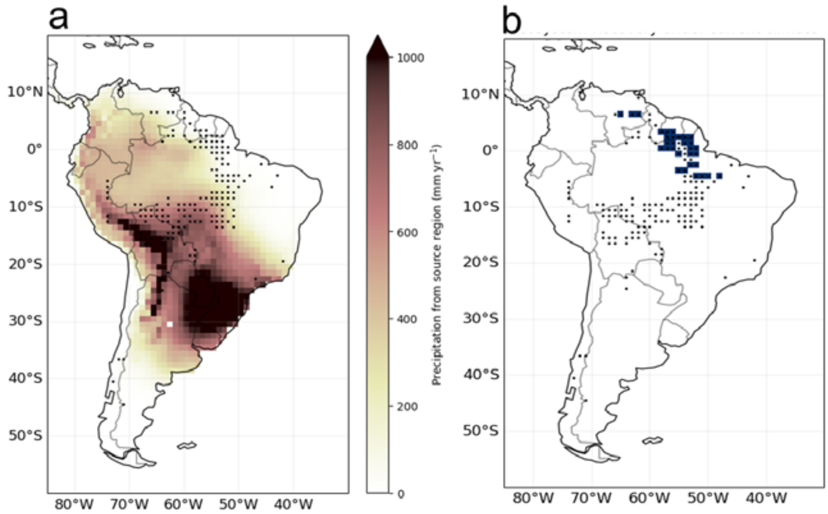

Fig. 9: (a) Absolute precipitation contribution (mm/year; direct+CMR) from 'Experiment-1' Class-1 for South America. (b) The blue regions show the potential for natural recovery under the current climate (i.e., MAP from 2008-2017). Potential for ecosystem recovery based on alternative stable state theory (Fig. 4). Dotted regions show the experimental deforestation.

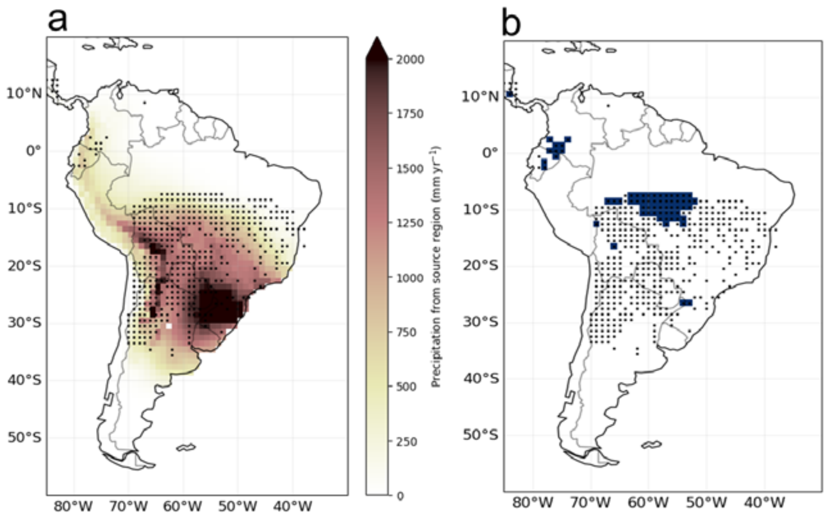

Fig. 10: Similar to Fig. 9, (a) absolute precipitation contribution (mm/year; direct+CMR) from 'Experiment-2' Class-1 for South America. (b) The blue regions show the potential for natural recovery under the current climate (i.e., MAP from 2008-2017).

Discussion

Water and food security

Our results highlight that upwind deforestation actors can significantly reduce the moisture precipitating over the downwind remote locations, and on themselves too, if moisture recycling within the grid is high (e.g., south-eastern region of Brazil in Fig. 9a and 10a). On the one hand, the direct reduction in moisture over the croplands due to upwind deforestation can lead to severe water scarcity and threaten the local and global future food systems (Meyfroidt, 2018; Ritchie et al., 2020). On the other hand, the loss of moisture over the forest ecosystems will reduce the outgoing moisture on the sink region. This can again have profound indirect implications of deforestation if the downwind sink region is cropland.

Furthermore, moisture loss over the forest can lead to loss of resilience (i.e., reduction in the capacity of the forest to offset water-stress conditions), which can even initiate a self-amplified forest loss under strong feedback between the ecosystem and regional climate (Zemp et al., 2017). This loss in the forest can be quite critical, as it signifies a permanent loss of moisture sources. Depending on the geographical location (Fig. 9b and 10b), recovery of these ecosystems might be challenging (as we observed in Fig. 9b and 10b). This challenge might be further aggravated under future climate change, when certain regions all over the globe will face much higher water shortages than those projected under LUC only (Coe et al., 2013; Koutroulis et al., 2019).

Similarly, keeping in mind the influence of LUC, food security will also be threatened under future climate. This is because under a warmer climate, the water demand for crops will increase (i.e., high evaporation under high radiative fluxes), with certain regions over the globe facing extreme (wet and dry) weather conditions, unfavorable for agriculture (Fig. 8) (Brown & Funk, 2008; Lobell et al., 2008). Nevertheless, despite the uncertainties due to the personal perspective of future LUC, this report spatially highlights the deforestation actor's-impact relationship and emphasizes the urgency for exploring sustainable pathways for transforming agricultural food systems against unfavorable LUC events.

Inequality influences the ability to adapt

The stakeholders demographic by Godar et al. (2014) (Appendix-5) for Brazilian Amazon reported that large-scale landowners (property size >500 ha) dominate the south-eastern and much of the southern part of Brazil. At the same time, small-scale landowners (<100 ha) were distributed all over the landscape. Comparing the patterns of moisture contribution (Fig. 9a and 10a) with this demographic of landowners suggests that upwind large-scale landowners (those situated in the south-eastern and southern Brazil) influence downwind landowners to about 40-80%. In comparison, small-scale landowners have <20% of moisture contribution over other landowners. This suggests that upwind large-scale landowners have much higher leverage over other landowners. Therefore, if motivated by only short-term economic gains, their actions can (knowingly or unknowingly) disrupt the moisture source for other downwind actors (Arruda et al., 2019), thereby positioning them in a vulnerable situation.

In recent years, adaptation strategies (refers to implementing strategies to moderate impact under possible unfavorable conditions) have been widely researched as a viable option to mitigate potential impacts of water scarcity (Wilson et al., 2020). However, implementing them has its own set of challenges. These challenges can be either due to financial resources, conflicts between parties, lack of awareness, political regime, support from the local community, among several others (Aylett, 2015; Dodman & Mitlin, 2013). The driving factor for all these challenges stems from inequality (power and economic imbalance) in South America, which facilitated molding environmental laws to economic gains for stakeholders (Ceddia, 2019).

Economic gains also play a significant role in defining the stakeholders' ability to adapt under adverse environmental conditions. On the one hand, large stakeholders have much higher productivity and are better equipped to extract better economic gains for their production (Godar et al., 2014). On the other hand, small stakeholders might not get proportionally the same economic gains for their production. This could imply that in case of adversity, the large stakeholders will be in a much better position – financially – to implement strategies such as developing infrastructure for accessing ground water, storage of water from wet season, among others. In comparison, smallholders might not have such capacity. This inequality among the stakeholders makes small-scale landowners vulnerable to even implementing certain adaptive strategies (Füssel, 2010; Muyeye Chambwera et al., 2014).

Building resilience against future water scarcity

While LUC due to deforestation presents a serious challenge for local-global water and food security, such escalation is primarily due to inefficient stewardship by institutions responsible for managing the natural resources (Gober, 2018). Unlike climate change, which requires national and global partnerships and efforts to mitigate, LUC can be managed at a country scale. Studies have shown that public and political interventions such as restricting supply chains, positive incentives for sustainable practices by stakeholders, enforcing stringent laws regarding conservation and facilitating expansion of protected areas have contributed to slowing deforestation practices in South America (Nepstad et al., 2014). This coupled with active stakeholder engagement to aid learning by building awareness about potential impacts (both local and remote) and adaptable strategies, might motivate such practices that help circumvent an unfavorable future (Wehn et al., 2018). Actionable strategies around these aspects mentioned above will assist in building long-term resilience against water scarcity.

Conclusions

In this report, we contribute to understanding the negative impact of deforestation in reducing precipitation over remote land use in South America. For this, we devised two experiments: one where deforestation takes place in the least resilient part of the forest, and the other where deforestation happens in the proximity to current croplands. By quantifying moisture transport using the Utrack moisture tracking model, we highlight the significance of atmospheric teleconnection in influencing the deforestation-impact relationship over forest and agricultural lands, which otherwise is difficult to visualize in climate models.

We find that by only considering direct moisture transport, different deforestation experiment shows a moisture contribution ranging between 3-33% (25th and 75th percentile) on remote land use. However, when we account for cascading effect, i.e., evaporation of precipitated moisture more than once, this contribution increases to 74% (75th percentile) over the remote land use. Our results also reveal a strong north-south gradient of moisture contribution in South America, where deforesting in the northern gradient primarily reduces the moisture over the rainforests. Whereas deforestation in the southern gradient directly influences precipitation over the croplands (as most of them are in the south-eastern part of the continent) because the southern part of the continent is dependent on the moisture contribution from the Amazon. Eastern flank of Andes plays a major role here in channeling the moisture to the current croplands.

These experiments show a profound negative influence on crop suitability, where water deficit in dry seasons is imminent in both cases. However, if the deforestation takes place more in the southern part of the continent, the water deficit extends to the wet seasons, making even the moderate water-demanding crops unsuitable for growth. We went a step further and evaluated the potential for natural recovery under climate. We find that in both the cases, majority of the forests never recovers. However, the forests ecosystems in the north-eastern part of the continent will recover post-deforestation due to their primary dependence on oceanic moisture sources.

Comparing our results with the census data of stakeholders' demographic in Brazil reveals that upwind large-scale landowners' control much of the moisture falling on other downwind landowners. Furthermore, the inequality in economic gains among landowners puts small-scale landowners in a vulnerable potion to future water scarcity. This report highlights some potential strategies which can be further explored to build long-term resilience against water scarcity.

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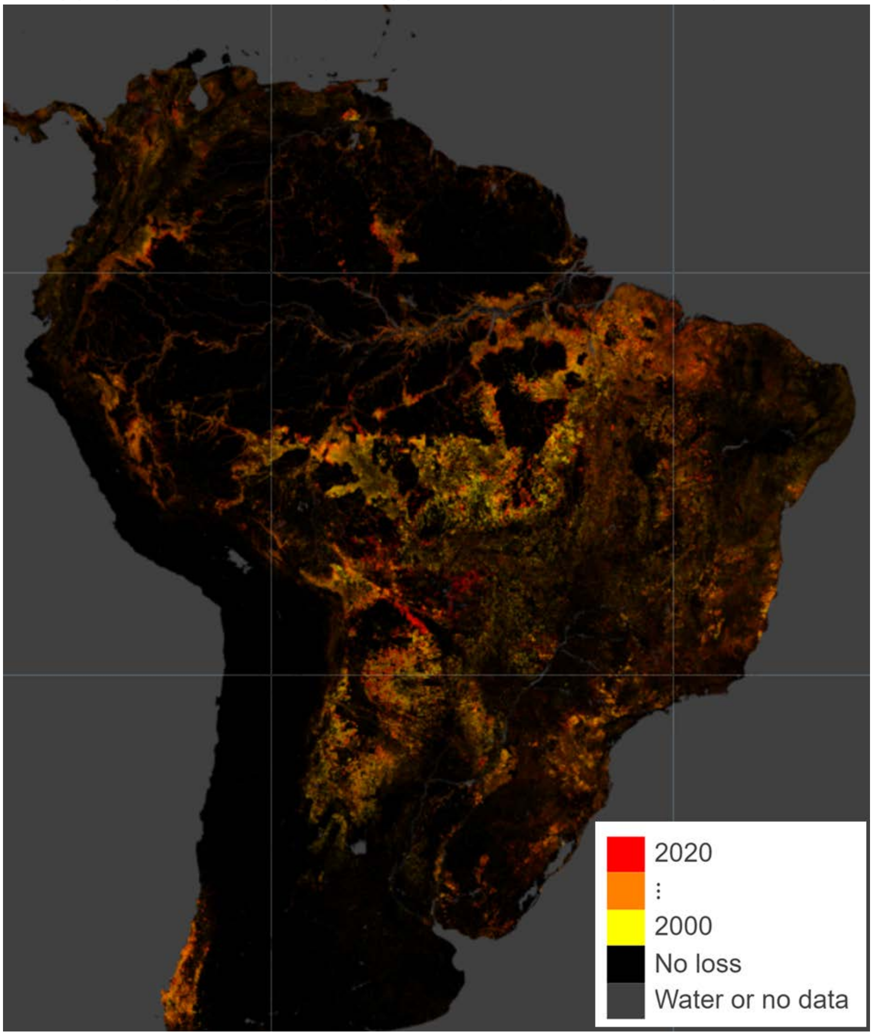
Appendix

Appendix-1: Forest-loss in South America from year 2000-2020 (Hansen et al., 2013)(https://glad.earthengine.app/view/global-forest-change)



Appendix-2: Resilience calculation used in Experiment-1

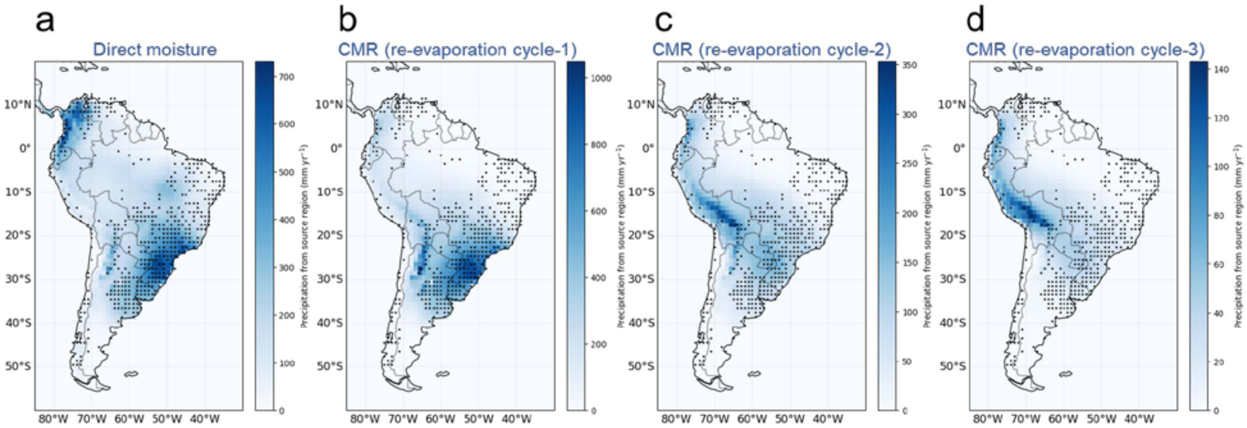
The resilience metric is adapted from Hirota et al. (2011), and defines the resilience of the forest ecosystems (i.e., tree cover > 50%) as a function of MAP and S_r (Singh et al., 2021). This function is given as below:

$$f(z) = \frac{1}{1 + e^{(-z)}}$$

$$z = a + b(\mathrm{MAP}) + c(S_\mathrm{r})$$

Appendix-3: Croplands (>20%) in South America from Foley et al., (2005)

Appendix-4: Example of direct and individual CMR runs for Class-0 in South America



Appendix-5: Stakeholders demographic of actor dominance by Godar et al. (2014) in Brazilian Amazon. *Abbreviations*: AC, Acre; AM, Amazonas; AP, Amapá; MA, Maranhão; MT, Mato Grosso; PA, Pará; RO, Rondônia; RR, Roraima; TO, Tocantins.