Supplementary Information

of

Pinpointing Amazon forest tipping in global warming and deforestation pathways

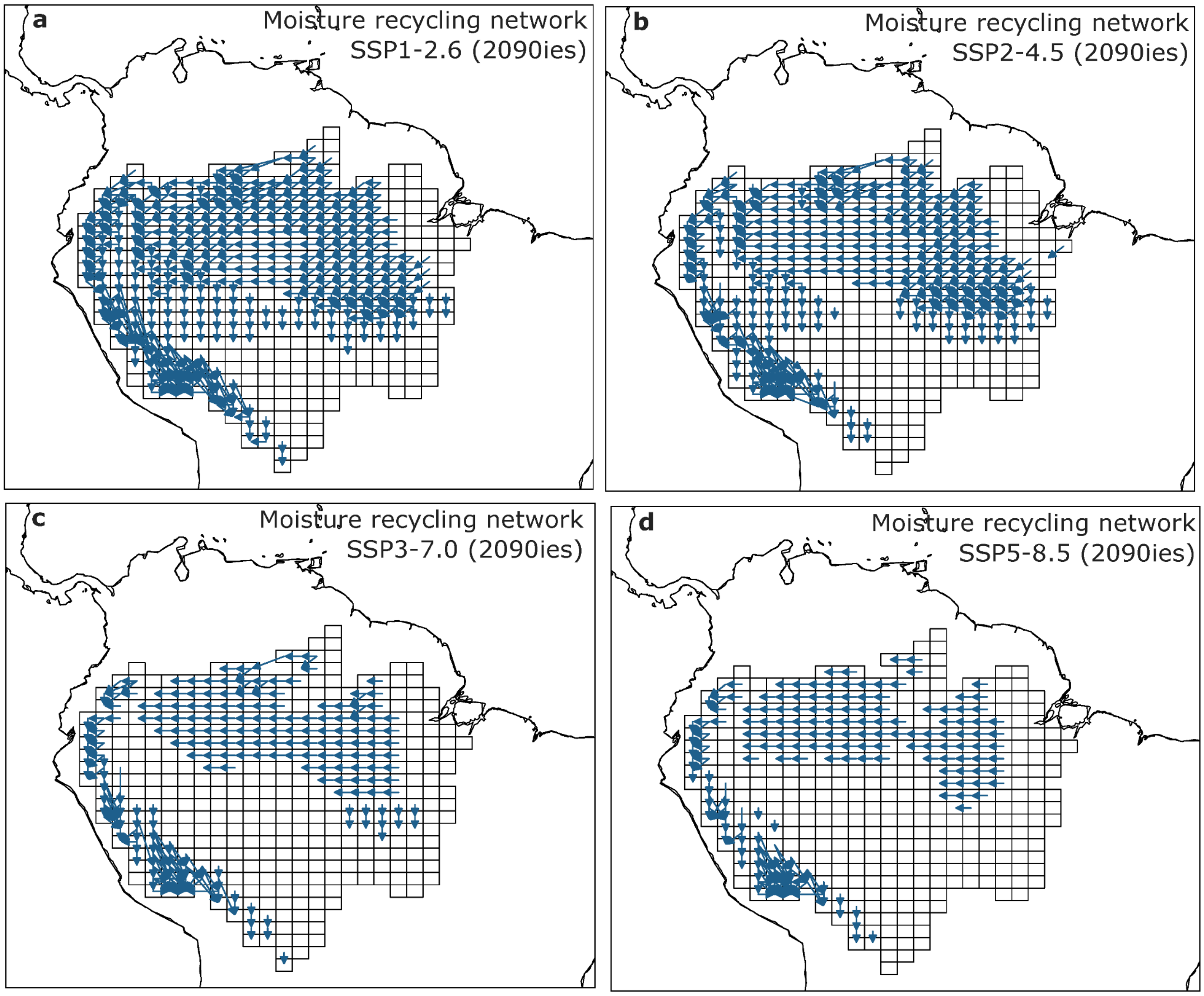

Figure S1 | Atmospheric moisture recycling network. Moisture recycling network for the decade 2090 for the scenarios **a,** SSP1-2.6, **b,** SSP2-4.5, **c,** SSP3-7.0 and **d,** SSP5-8.5. It can be seen that the strength of the moisture recycling network decreases with increasing global warming. This is expected since more global warming also means that precipitation over the Amazon forest region decreases (see also Fig. 2a, S2a). In all the simulations, moisture recycling values of 1 mm/month or more are taken into account but to increase visibility in this figure, only the moisture recycling links of more than 20 mm/month are shown.

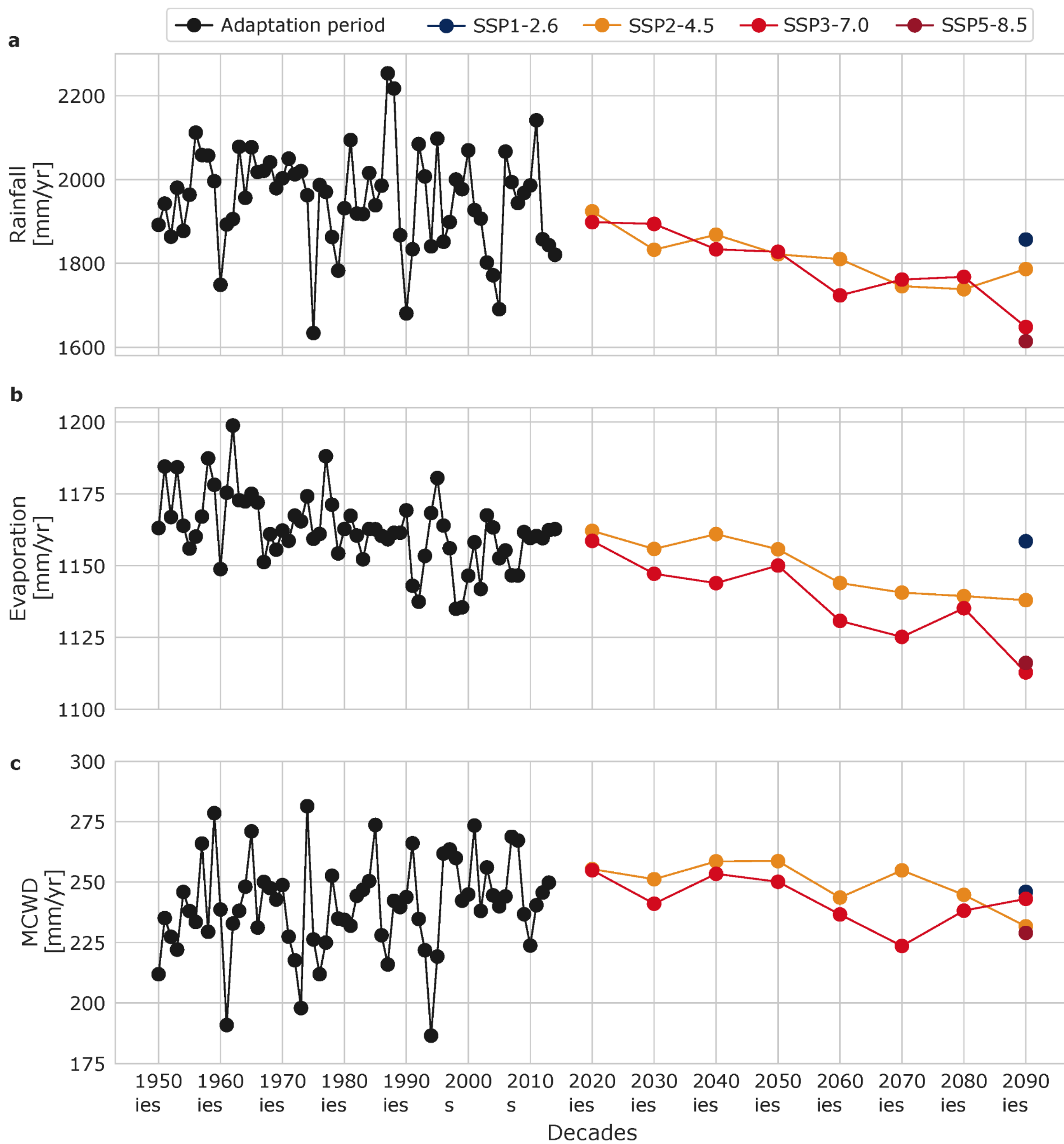

Figure S2 | Time series of environmental variables. Yearly values for **a,** rainfall, **b,** evaporation, and **c,** MCWD (derived from hydrological years starting in October until next year's September) for the adaptation period (1950-2014, see black dots) and for the four different SSP scenarios (averaged for the respective decade). The data is averaged over the entire Amazon basin. There is a clear trend that stronger climate change scenarios lead to lower rainfall and also to less evaporation across the Amazon basin. Following from that, the trend in MCWD does not show a clear trend across the scenarios. A spatial resolution for the average values of MAP and MCWD is shown in Fig. S3.

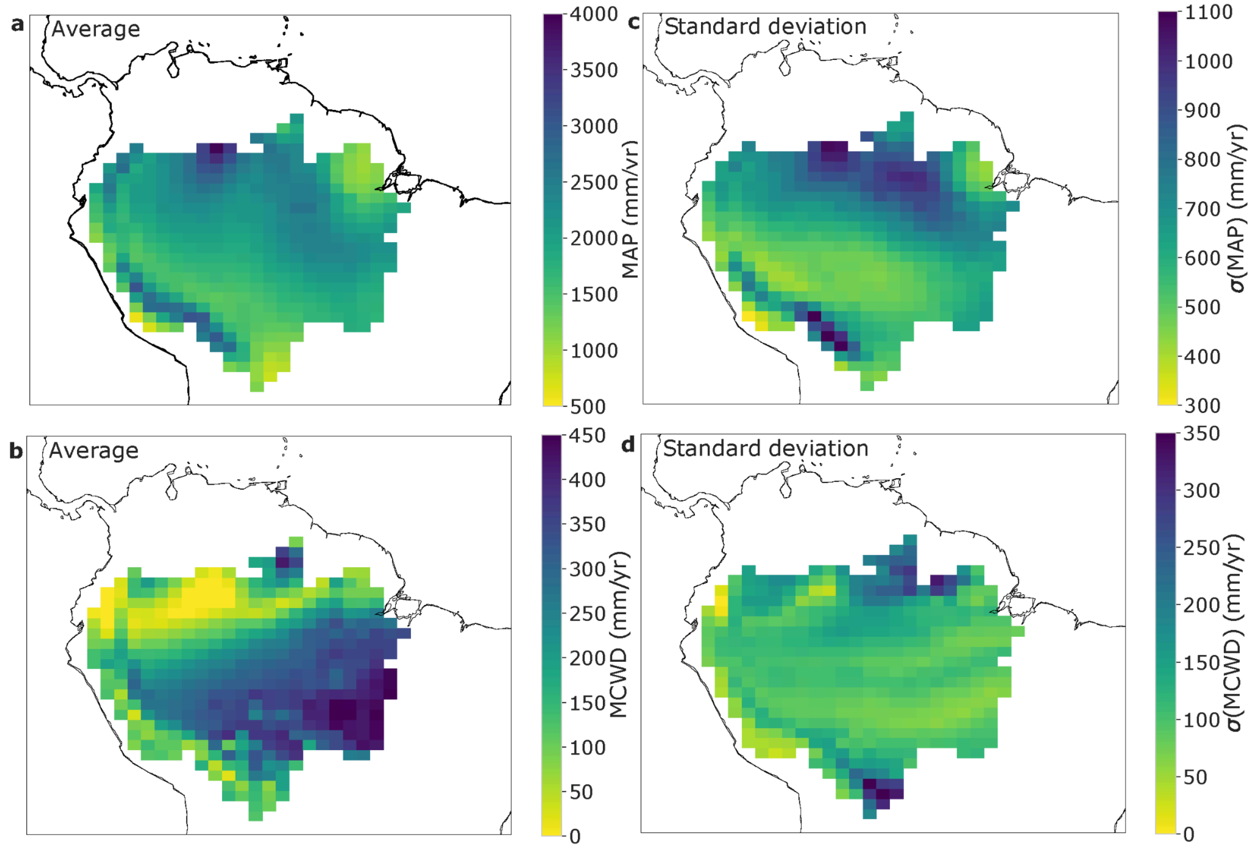

Figure S3 | Moisture supply in the adaptation period over the Amazon basin. a, c, Average and standard deviation for MAP. **b, d,** Same for MCWD.

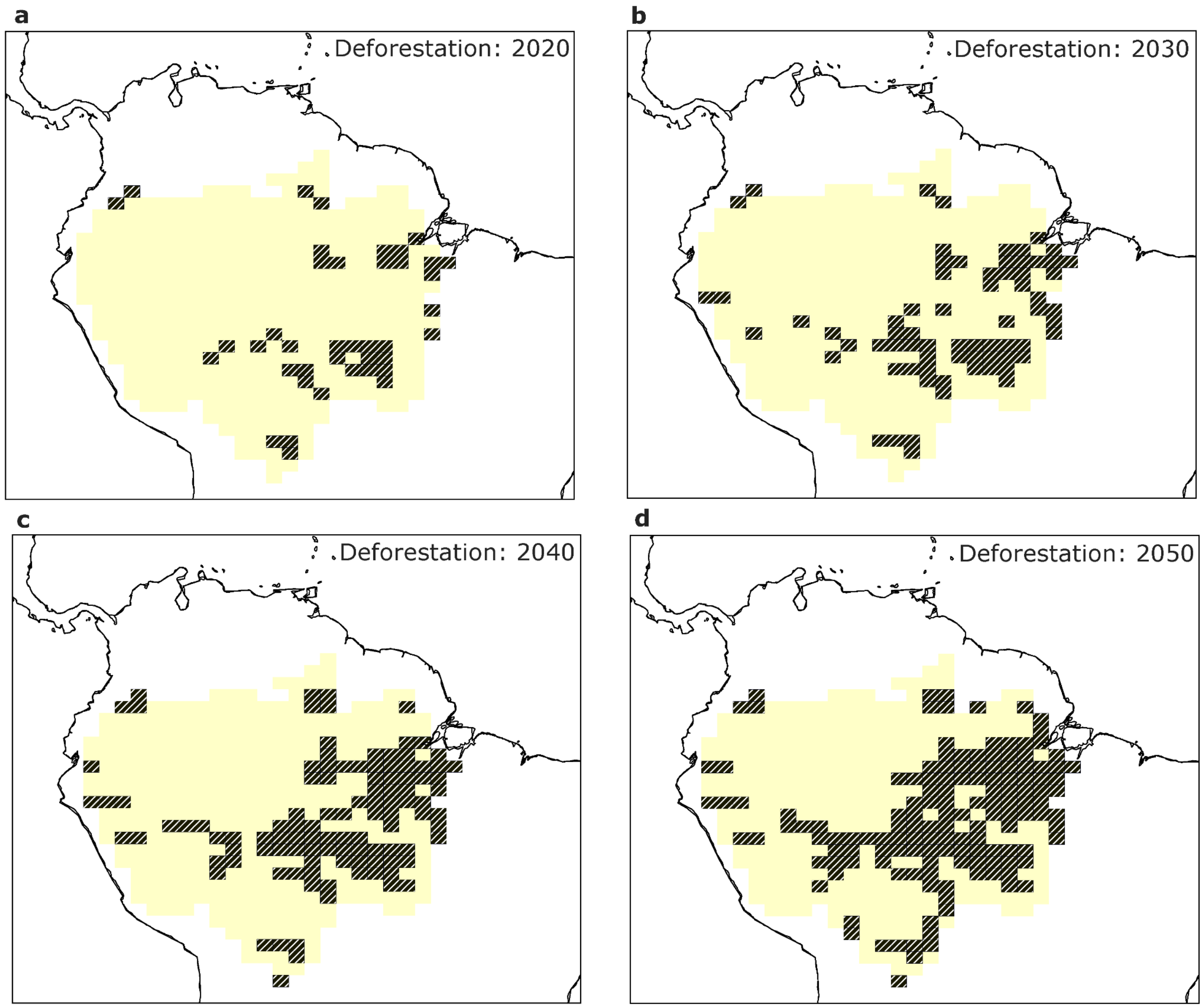

Figure S4 | Regional distribution of Business-as-Usual deforestation scenario. Business-as-Usual deforestation where the deforestation exceeds 50% of the grid cell (black hatched areas) following Soares-Filho et al. (2013)[1] in **a,** the year 2020, **b,** the year 2030, **c,** the year 2040 and **d,** the year 2050. After the year 2050, the deforestation is kept constant until the year 2099. The deforestation strongly increases from around 20% of the Amazon basin (panel **a**) until close to 40% (panel **b**). In all our simulations including deforestation, we use the exact percentage value of deforestation as input value on a 1°x1° grid cell basis.

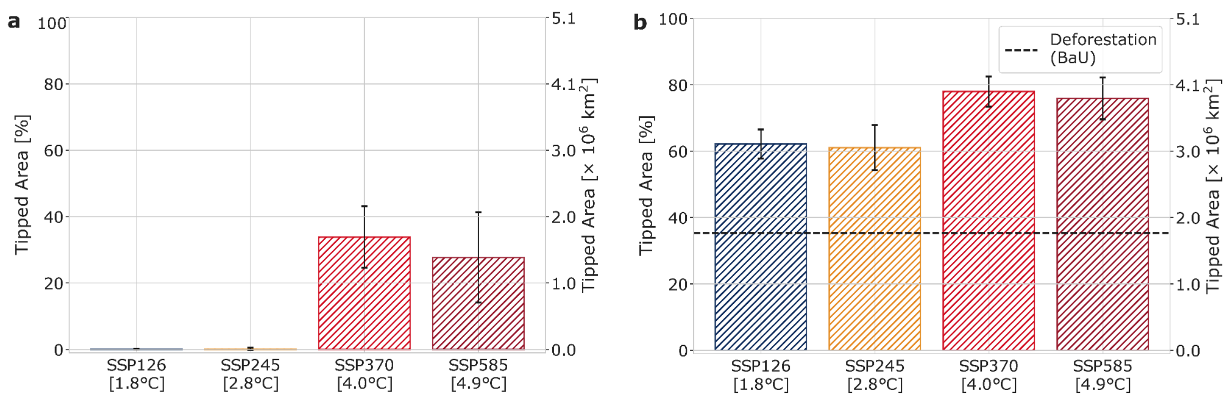

Figure S5 | Tipping responses in the Amazon forest system with respect to global warming and deforestation in the 2090ies. a, Tipped area in percent and km² of the entire Amazon basin in the 2090ies (average from 2090-2099) without deforestation. The tipped area is very low in SSP2-4.5 (representing 2.8°C of global warming) but becomes evident for stronger climate change scenarios SSP3-7.0 (representing 4.0°C of global warming). Error bars denote standard deviations across our large-scale Monte Carlo ensemble. **b,** Same as in panel a but with deforestation. Under the BaU deforestation, all scenarios show large tipping risks.

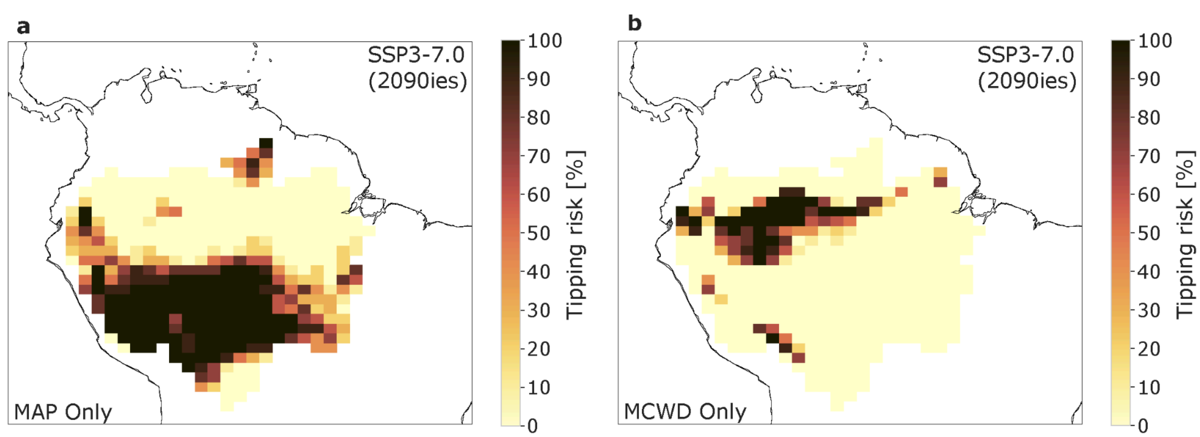

Figure S6 | Tipping risks in the Amazon forest for different SSPs broken down to MAP and MCWD contributions. a,b, Respective contributions from MAP and MCWD as individual critical variables. The corresponding bar charts can be found in Fig. S7a,b. Several sensitivity analyses show robust results for (i) a mixture of adaptive capacities together with fixed critical thresholds following Flores et al.[2] (see Fig. S7c, d) and (ii) for constant evapotranspiration of 100 mm/month (see Fig. S7e, f). More details on robustness checks are denoted in the methods.

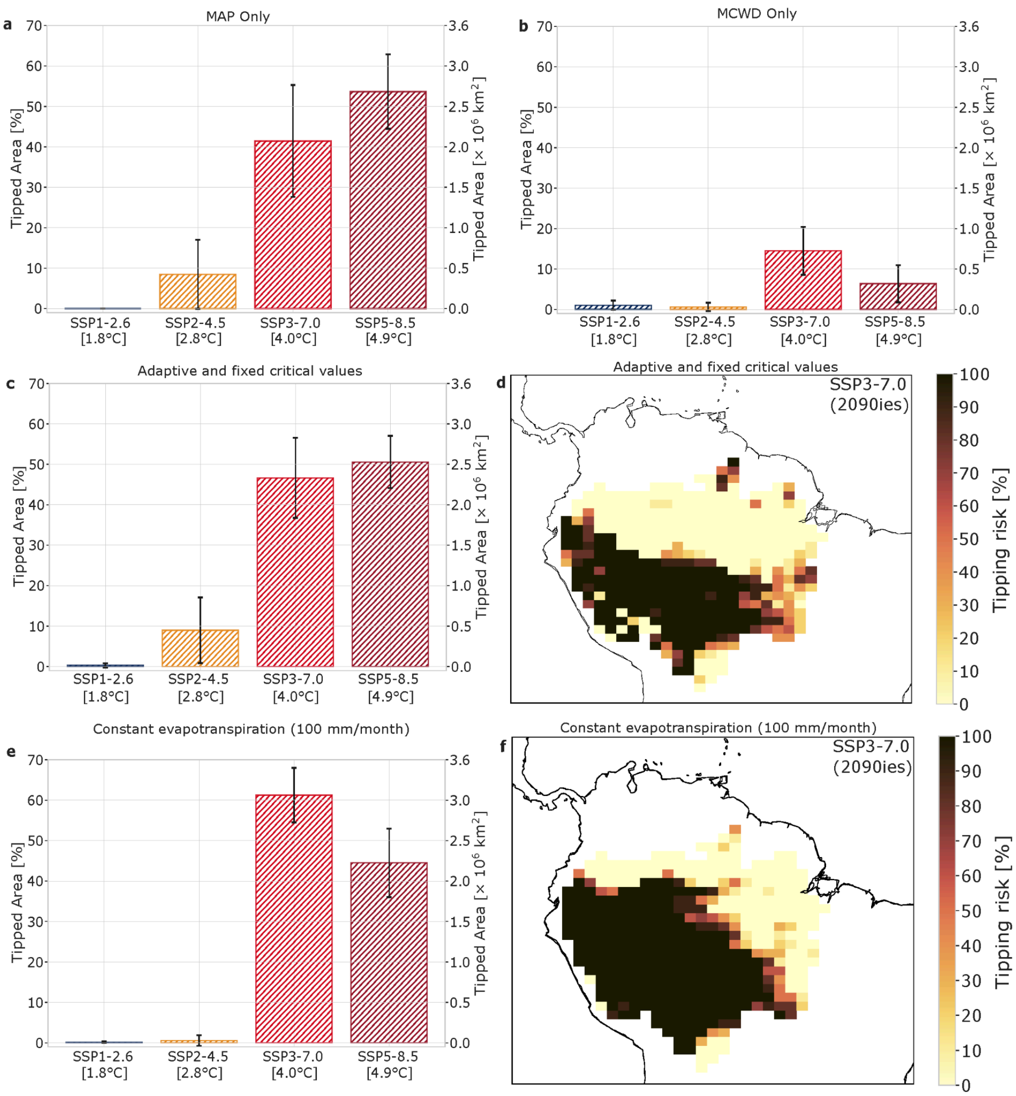

Figure S7 | Crossing critical thresholds in the Amazon forest in response to global warming. Supplementary investigations to Fig. 1 in the main manuscript. **a,** Robustly detected tipping point for MAP as the sole critical threshold (not taking into account MCWD) as tipped area in percent and km² of the entire Amazon basin, again with a sharp increase between an SSP2-4.5 (2.8°C of global warming) and SSP3-7.0 (4.0°C of global warming) scenario at 2090. Error bars denote standard deviations across our large-scale Monte Carlo ensemble. **b,** Same as for panel a for the case that MCWD is the sole critical threshold (not taking into account MAP). Here, the overall increase of tipped area is still significant at SSP3-7.0 but not at the same magnitude as for MAP only. This hints at the fact that the region where MCWD induced tipping events are relevant is smaller than for MAP (see also Fig. S6a,b). **c,** Robustness check of our results for an admixture of adaptive critical thresholds (description in methods: *adaptive threshold approach*) as well as fixed critical thresholds following Flores et al. (2024)[2]. **d,** Regional resolution of tipping risk for an SSP3-7.0 scenario in the 2090ies. **e,f,** Same as in c,d but for constant evapotranspiration values of 100mm/month. For the details of all robustness checks, see methods: *robustness checks*.

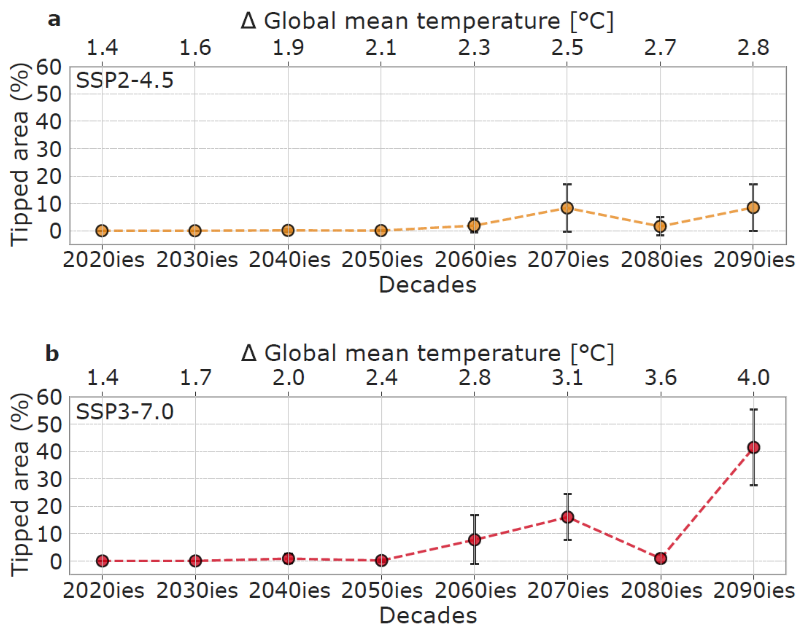

Figure S8 | Tipped area for MAP as sole critical variable. a, Tipped area in percent (with standard deviation as error bars) for each decade starting from the 2020ies up to the 2090ies for SSP2-4.5. **b,** Same for SSP3-7.0.

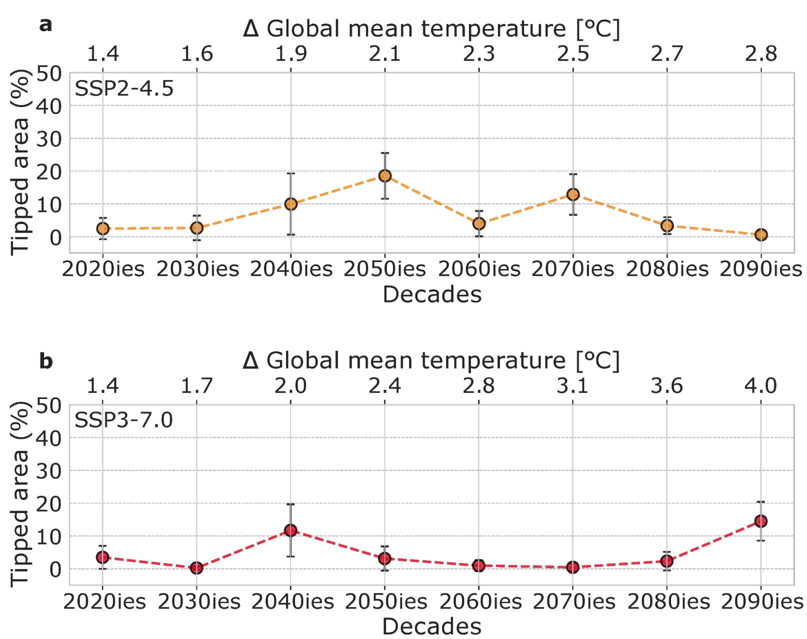

Figure S9 | Tipped area for MCWD as sole critical variable. a, Tipped area in percent (with standard deviation as error bars) for each decade starting from the 2020ies up to the 2090ies for SSP2-4.5. **b,** Same for SSP3-7.0.

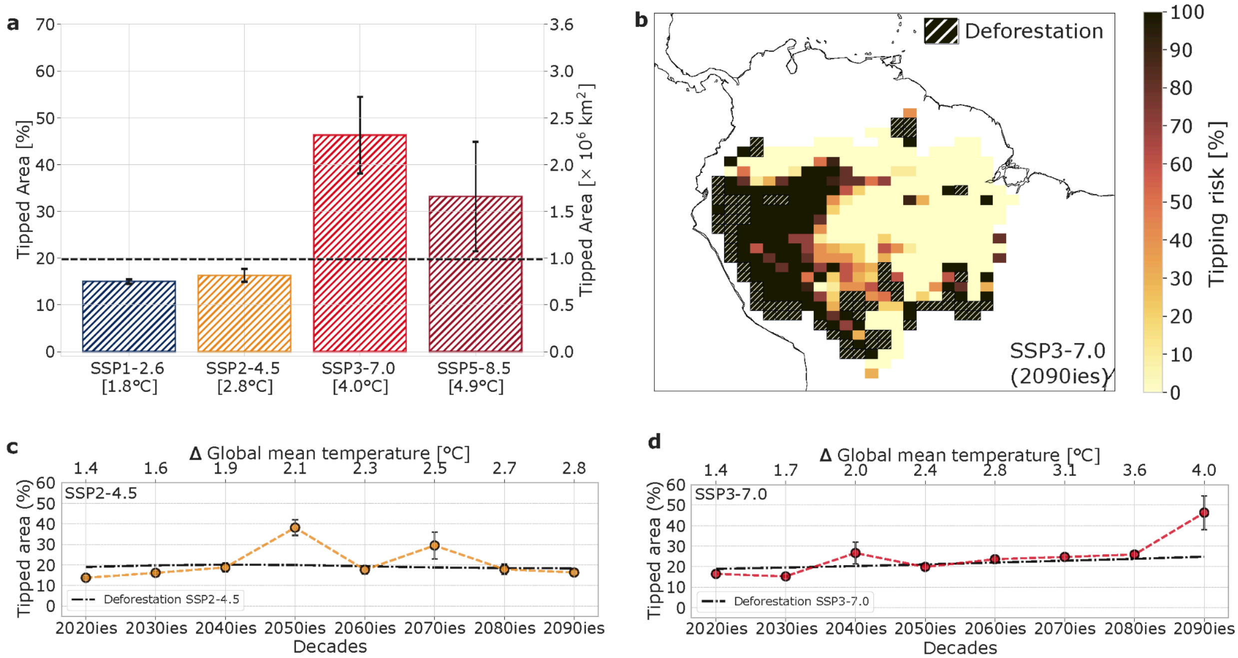

Figure S10 | Effect of SSP-based deforestation scenarios on the tipped area in the Amazon forest. a, Tipped area in percent and km² of the entire Amazon basin with a sharp increase between an SSP2-4.5 (2.8°C of global warming) and SSP3-7.0 (4.0°C of global warming) scenario in the 2090ies. Error bars denote standard deviations across our large-scale Monte Carlo ensemble. **b,** Regions of the Amazon forest most at risk of crossing critical thresholds (west and southwestern part of the Amazon basin) for an SSP3-7.0 scenario at 4.0°C (2090ies decade) of global warming. The hatched region denotes deforested locations. **c,** Tipped area in percent (with standard deviation as error bars) for each decade starting from the 2020ies up to the 2090ies for SSP2-4.5 including deforestation for the respective decade (black dash-dotted line). **d,** Same for SSP3-7.0. Fig. S16 shows the tipped area dependent on the MAP and MCWD, given its respective moisture transport or global warming level.

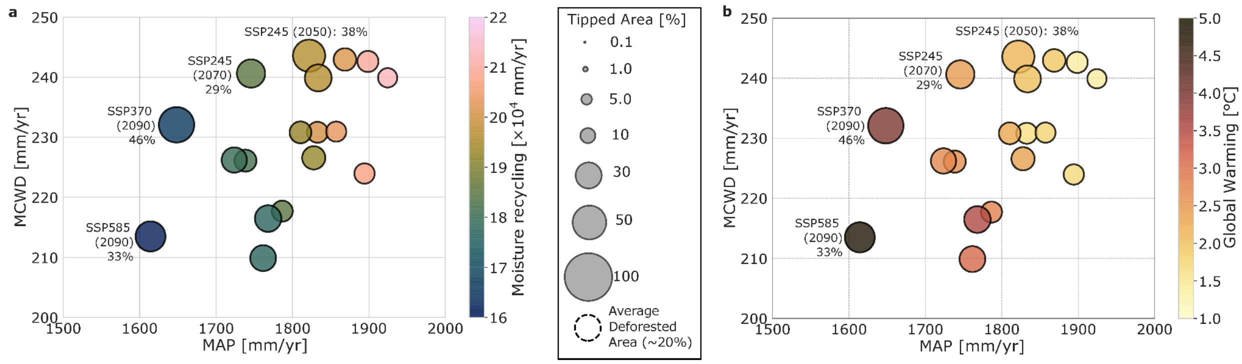

Figure S11 | Critical thresholds in annual water supply (MAP, MCWD) for SSP deforestation scenarios. a, Tipped area (size of the circle; in percent of the entire Amazon basin) dependent on the MAP and MCWD. The color of the circle depicts the moisture recycling strength across the entire Amazon basin. **b,** Same as in panel a but for the respective global warming levels. The circles are larger than without deforestation due to the deforested parts of the Amazon forest (~20%, see size of deforested circle as black dashed circular line).

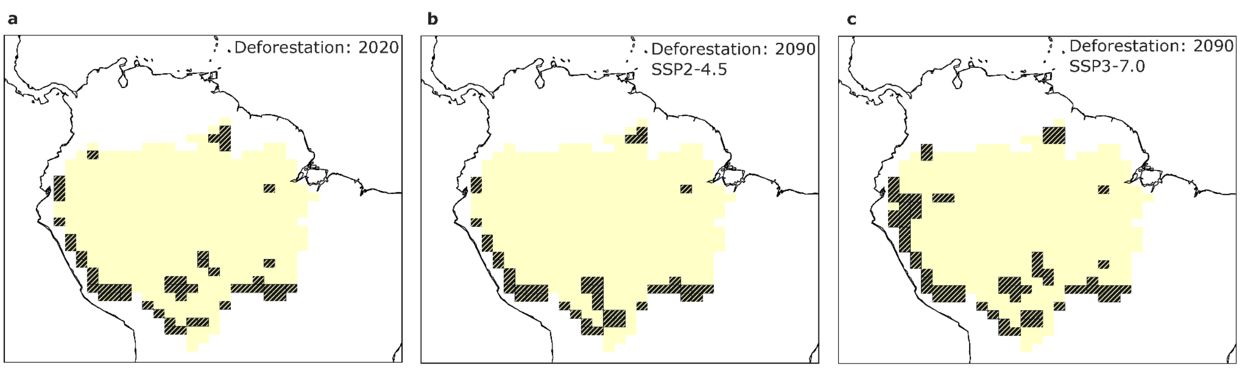

Figure S12 | Regional distribution of SSP-based deforestation scenario. SSP-based land-use changes (i.e. deforestation) where the deforestation exceeds 50% of the grid cell (black hatched areas) in **a,** the year 2020, **b,** the year 2090 for SSP2-4.5, **c,** the year 2090 for SSP3-7.0. In these scenarios, deforestation only weakly increases from around 20% to 25% for SSP3-7.0 of the Amazon basin (panel **c**). For SSP2-4.5, deforestation remains at 20% across the 21st century and is even declining towards the end of the century (panel **b**). Overall, the SSP-based deforestation scenarios are very optimistic.

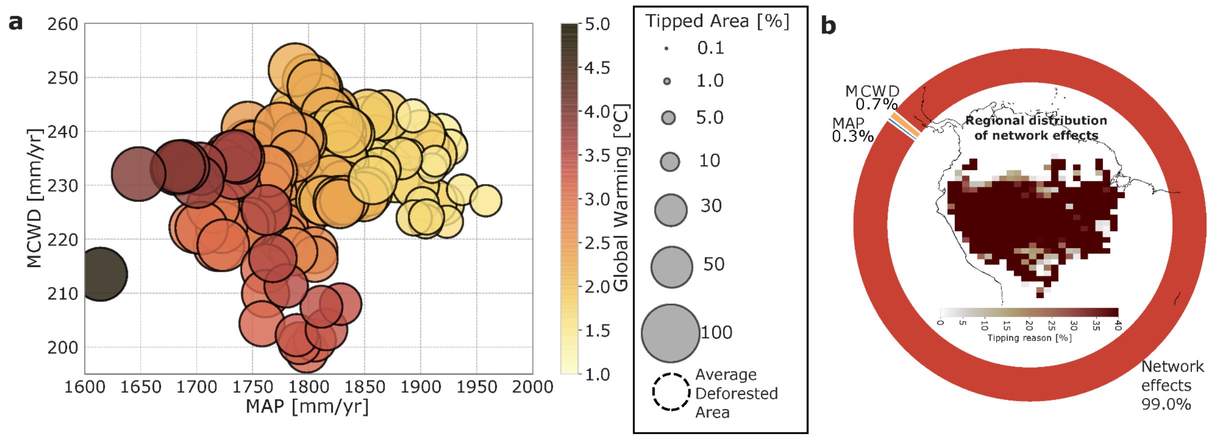

Figure S13 | Tipping reason across all investigated emission scenarios and critical thresholds in annual water supply following a BaU deforestation scenario. a, Tipped area (size of the circle; in percent of the entire Amazon basin) dependent on the MAP and MCWD. The color of the circle depicts global warming in the respective scenario. For comparison, the dashed circle denotes the average deforestation following a Business-as-Usual scenario[1]. **b,** Pie-chart with the three tipping reasons: MAP, MCWD, and network effects (tipping cascades). The inset shows the location of tipping cascades that are the dominant tipping reason caused by deforestation (99.0%).

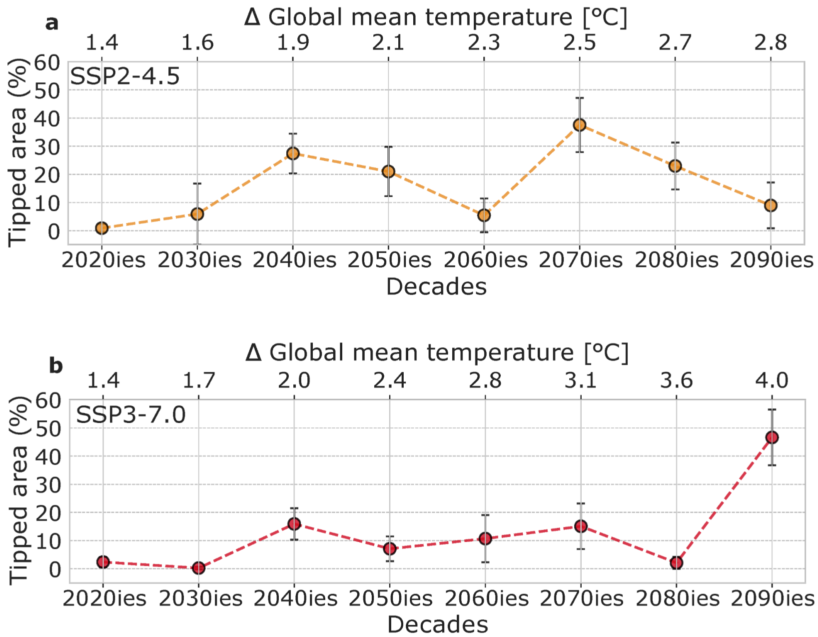

Figure S14 | Tipped area for adaptive and fixed critical thresholds. Following Flores et al., (2024)[2], we quantify the tipped area across the 21st century for **a,** SSP2-4.5 and **b,** SSP3-7.0. This robustness check shows that SSP3-7.0 tipping risks, again, strongly increase for the decade 2090. More details on the setup of this robustness check, see methods: *robustness checks*.

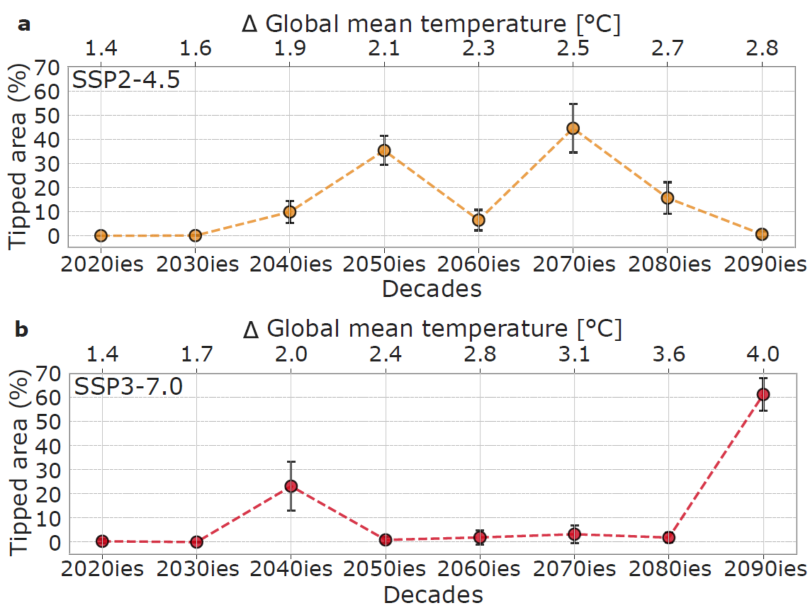

Figure S15 | Tipped area for constant evapotranspiration of 100mm/month. Tipped area across the 21st century for **a,** SSP2-4.5 and **b,** SSP3-7.0. This robustness check shows that SSP3-7.0 tipping risks, again, strongly increase for the decade 2090. More details on the setup of this robustness check, see methods: *robustness checks*.

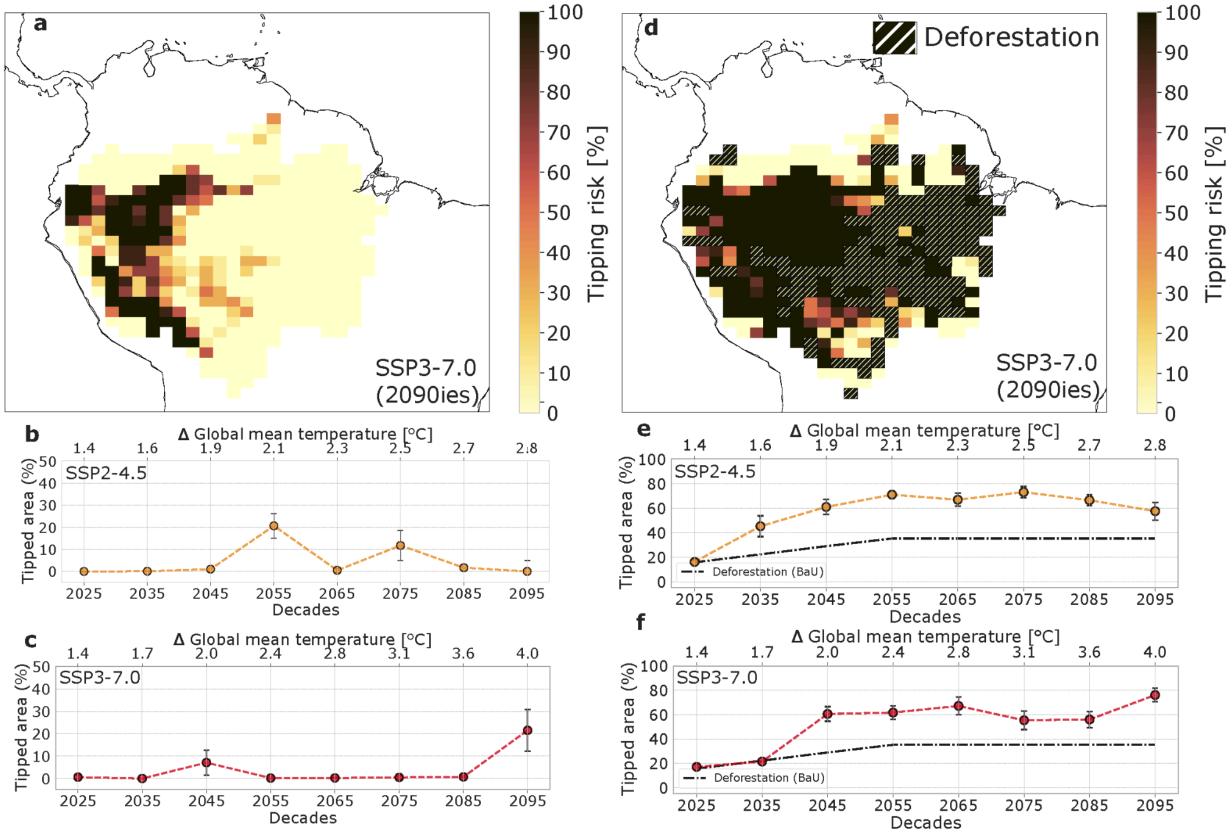

Figure S16 | Robustness check with remaining evapotranspiration of secondary vegetation after tipping and/or deforestation. a-c, Robustness check with global warming only and no additional deforestation. **a,** Regions of the Amazon forest most at risk of crossing critical thresholds (western part of the Amazon basin) for an SSP3-7.0 scenario at 4.0°C (2090ies decade) of global warming. **b,** Tipped area across the 21st century for SSP2-4.5 and **c,** for SSP3-7.0. **d-f,** Same as for a-c but including additional deforestation. These sensitivity analyses show robust results as compared to our result in the main manuscript (compare with Fig. 1).

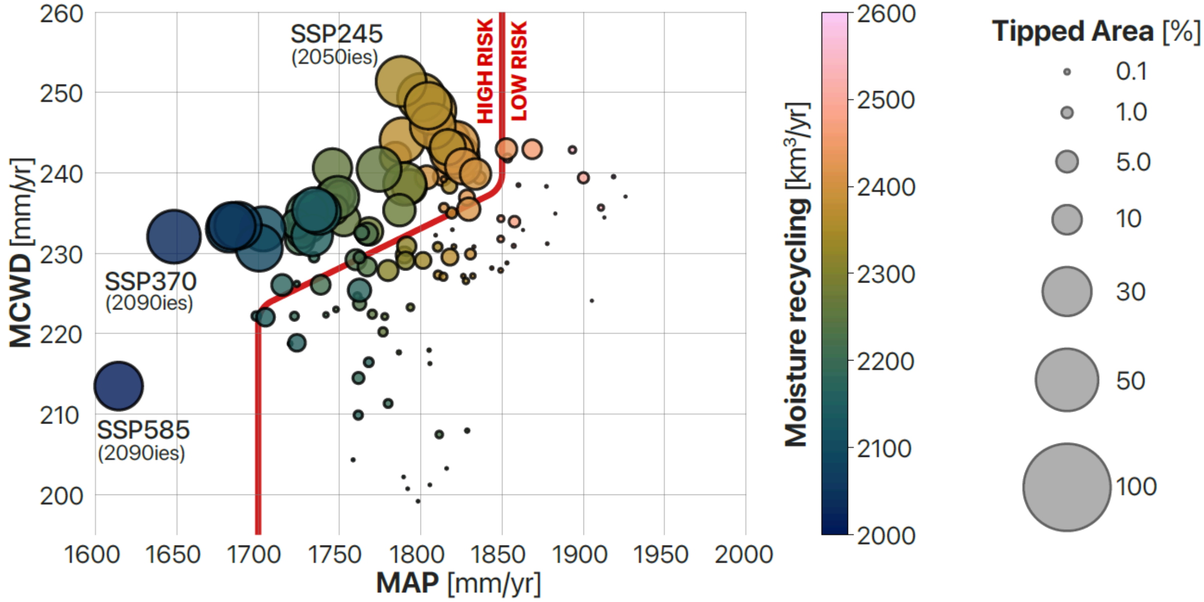

Figure S17 | Critical thresholds in annual water supply (MAP, MCWD) with respect to strength of the moisture recycling network. Tipped area (size of the circle; in percent of the entire Amazon basin) dependent on MAP and MCWD. The thick red line separates low tipping risks from high tipping risks in the 2D-plane of MAP and MCWD. The colour of the circle depicts the strength of the moisture transport network across the entire Amazon basin that responds essentially linearly to MAP levels.

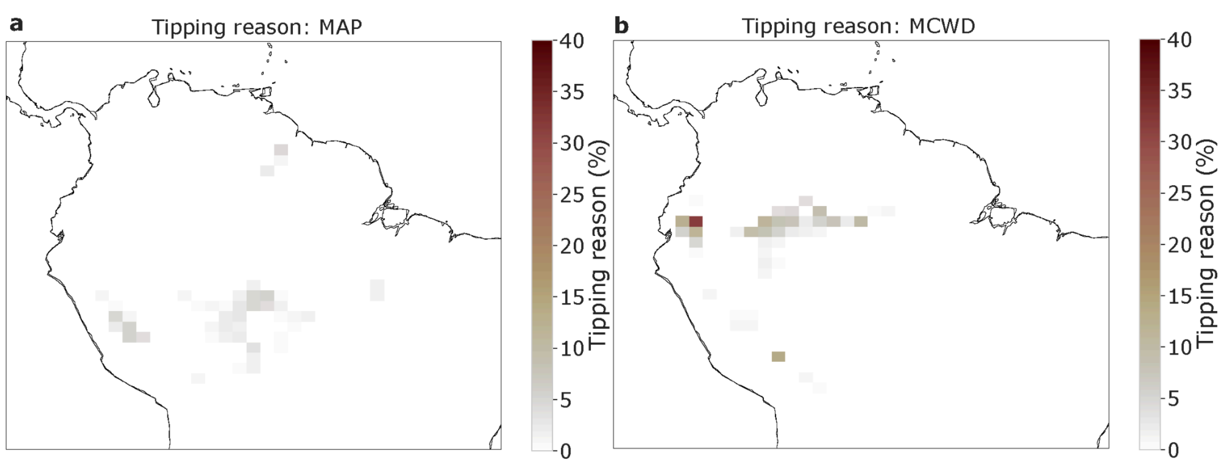

Figure S18 | Tipping reason across all investigated emission scenarios. a, Tipping reason: MAP. **b,** Tipping reason: MCWD.

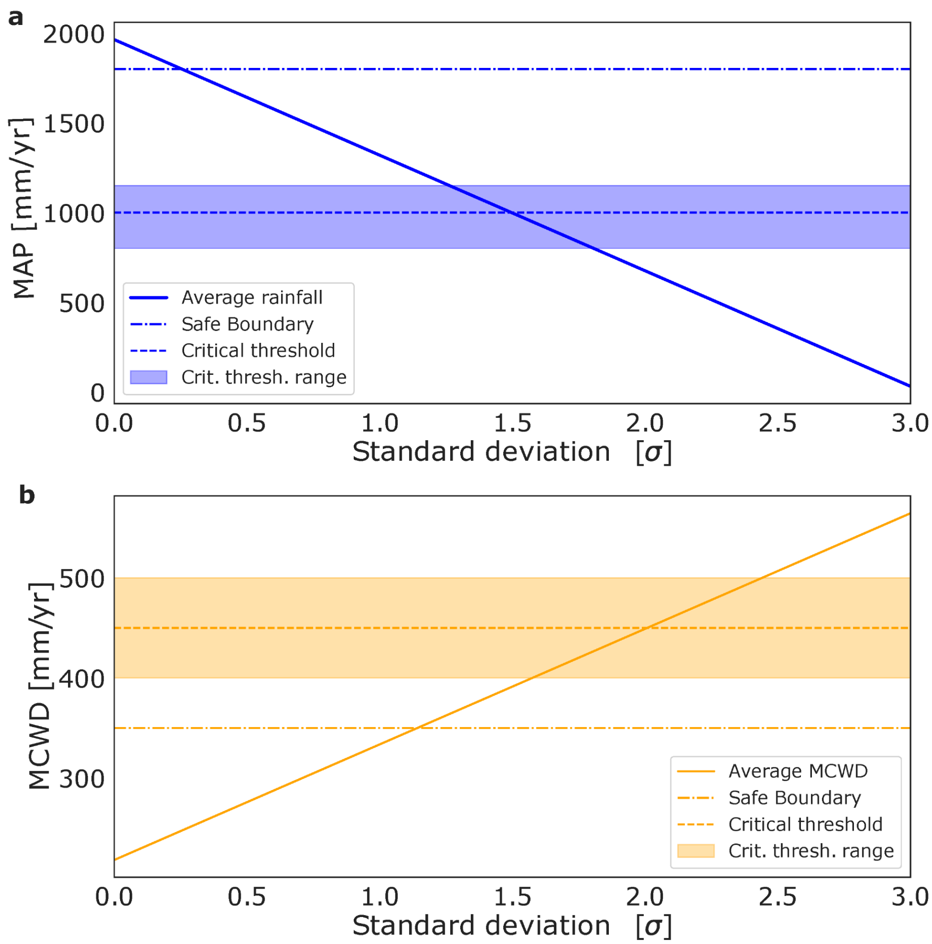

Figure S19 | Safe boundaries of MAP and MCWD for experiments with local adaptations and fixed critical thresholds. a, The solid line shows the basin-wide average for MAP in dependence of the standard deviation. At $\sigma = 0.0$, the average rainfall is around 2000 mm/yr. For $\sigma = 1.0$, the solid line denotes the MAP minus one standard deviation, etc.. The dash-dotted line shows the safe boundary (following Flores et al. (2024)[2]) above which there is no tipping allowed in the experiments with local adaptations and fixed critical thresholds, and the dashed line (and shading) the critical threshold and its ranges. **b,** Same as in panel a but for MCWD.

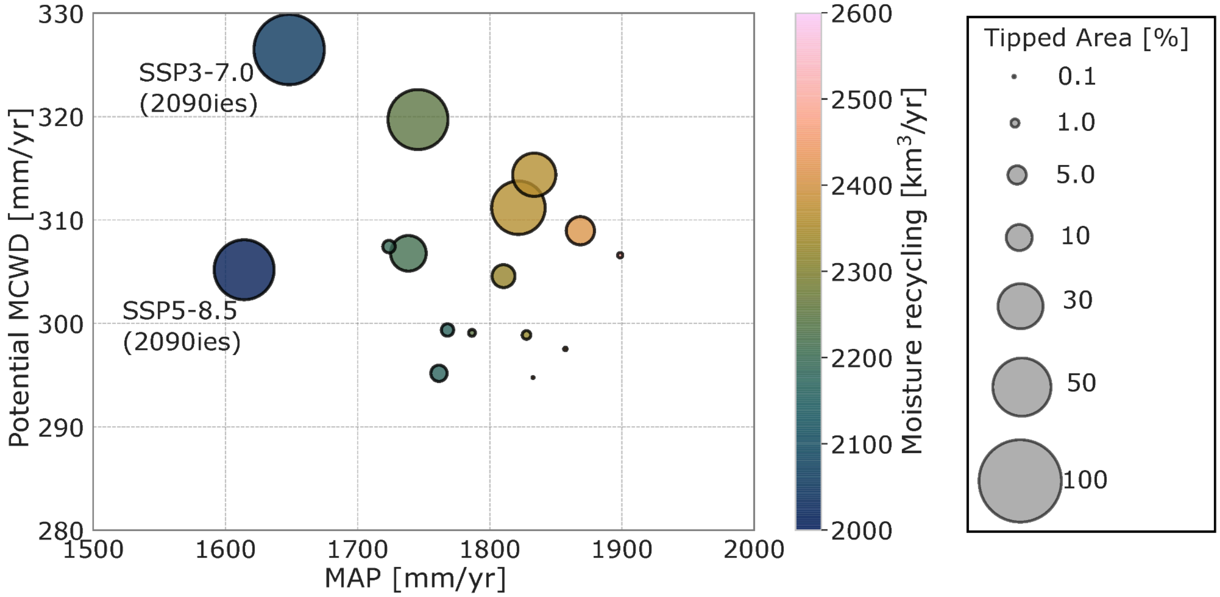

Figure S20 | Critical thresholds in annual water supply (MAP, MCWD) for constant evapotranspiration of 100 mm/month. Tipped area (size of the circle; in percent of the entire Amazon basin) dependent on the MAP and MCWD. The color of the circle depicts the moisture recycling strength across the entire Amazon basin.

Supplementary References

1. Soares-Filho, B. et al. LBA-ECO LC-14Modeled Deforestation Scenarios, Amazon Basin: 2002-2050. *ORNL DAAC, doi: 10.3334/ORNLDAAC/1153* (2013).
2. Flores, B. M. et al. Critical transitions in the amazon forest system. *Nature* **626**, 555–564 (2024).