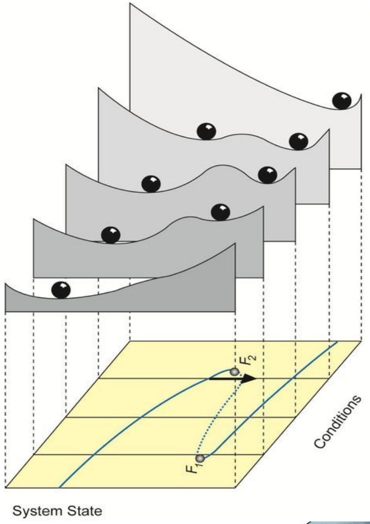
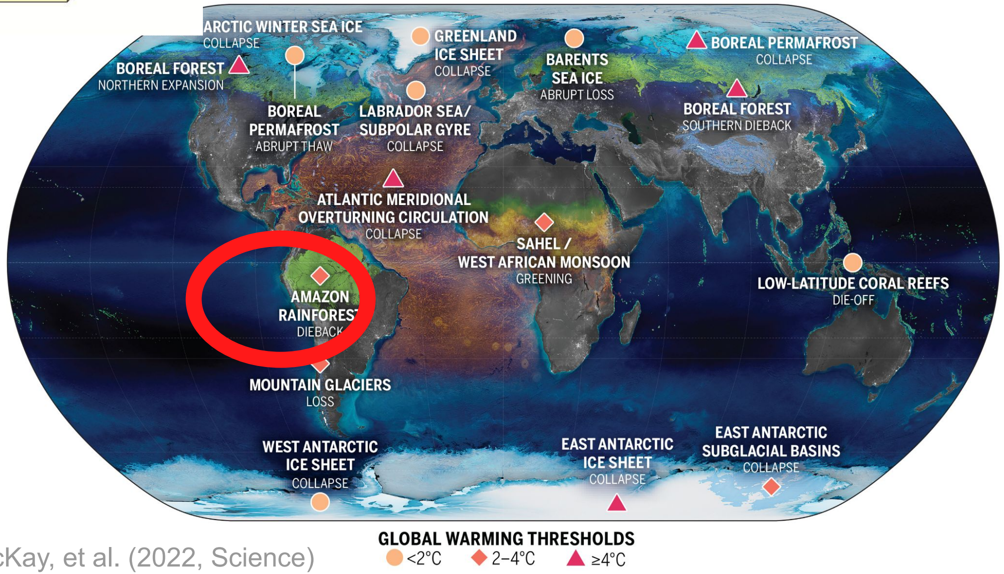
Tipping points



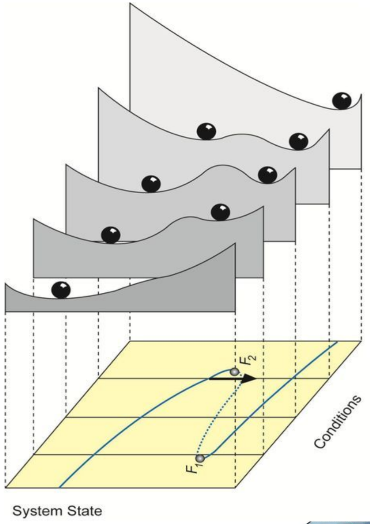
Multiple Earth systems
can (will?) tip

Potential forest/savanna bistability in the
Amazon rainforest



Armstrong McKay, et al. (2022, Science)

Tipping points



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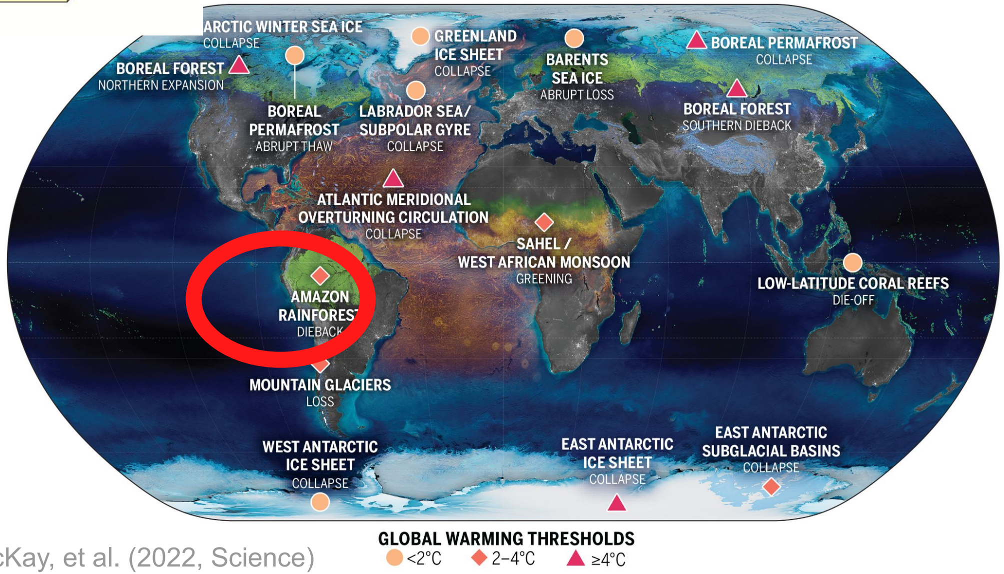
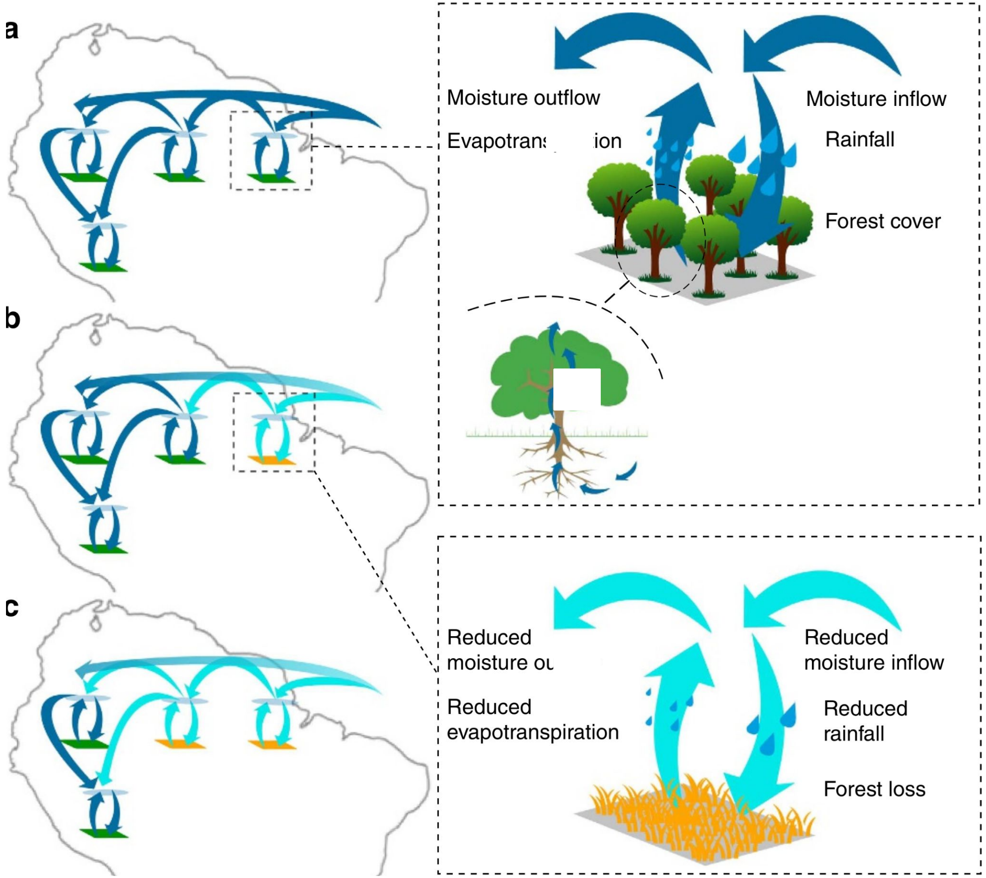


Armstrong McKay, et al. (2022, Science)

1) Earth system
2) Impacts
3) Governance
4) **Positive social tipping points**

Report was discussed at COP28!

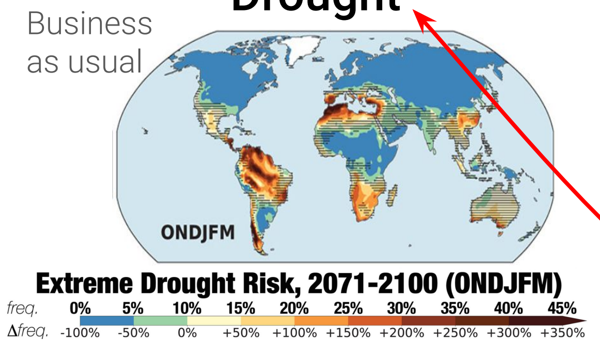
Moisture recycling network



Zemp et al., Nature Comm 2017

Amazon threats: amplified by network effects?

Drought

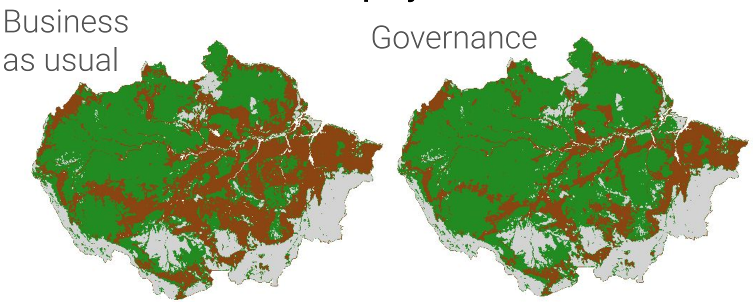


Cook et al., Earth Future 2020

Is tipping amplified by the network?

Deforestation

LBA-ECO LC-14 projections in 2050



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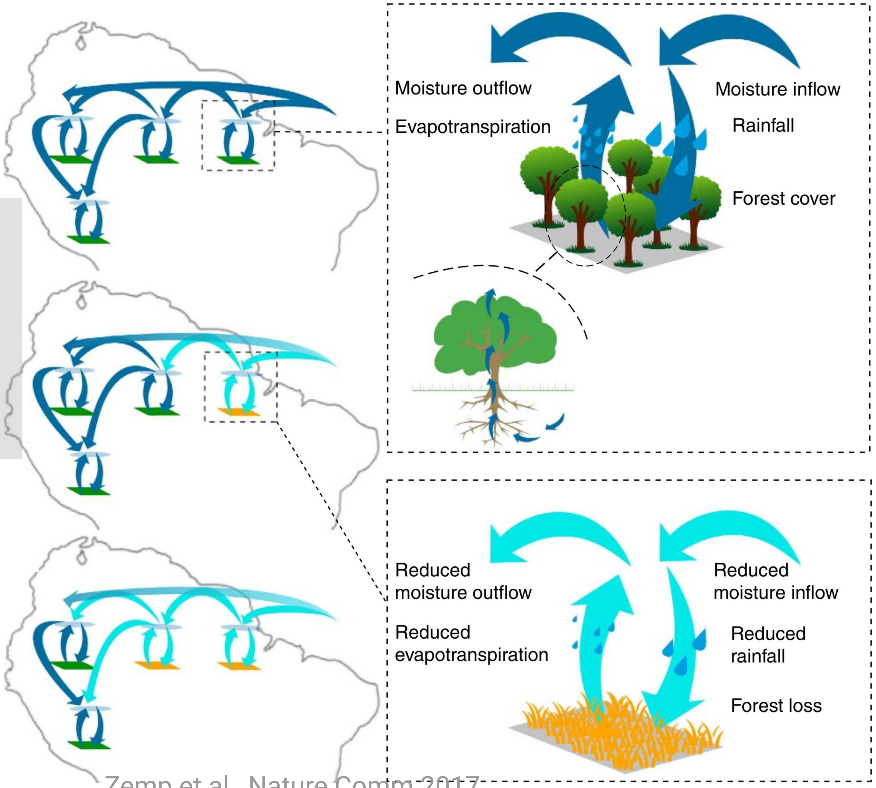
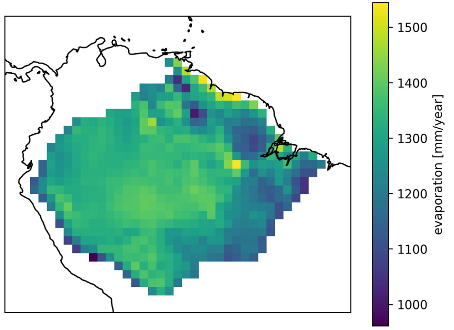


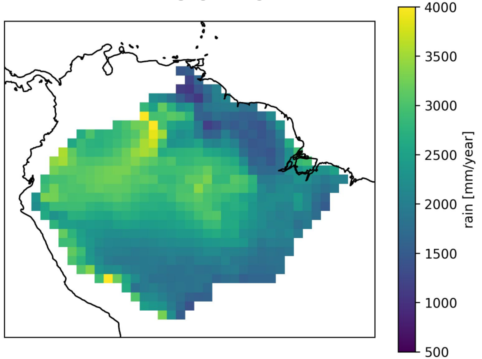
Zemp et al., Nature Comm 2017

Spatial precipitation patterns

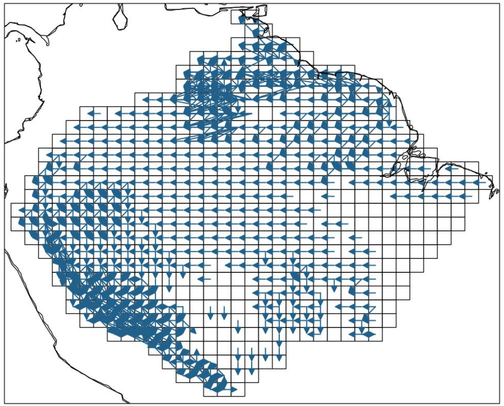
Annual evaporation



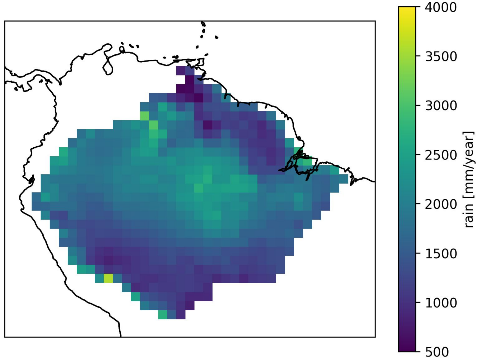
Annual rain



Moisture fluxes



Rain *not from Amazon*




```
import cartopy.crs as ccrs
import cartopy.feature as cfeature

ax = plt.axes(projection=ccrs.PlateCarree())
ax.set_extent([275, 320, -22, 15], crs=ccrs.PlateCarree())
ax.add_feature(cfeature.COASTLINE, linewidth=1)
ax.coastlines('50m')
plt.pcolor(longitude, latitude, values)
```

An ODE model for each cell

1 Klausmeier model in each cell, but non-spatial (smaller scale than 1 cell)

Original (***adimensional***) model:

$$\frac{du}{dt} = u^2 v - Bu$$

$$\frac{dv}{dt} = -u^2 v + A - v$$

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death rate without water

biomass

available water

$$\frac{dv}{dt} = -u^2 v + A - v$$

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plant growth

rainfall

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⇨ The precipitations in cell i become $A_i^{tot} = A_i^{ext} + \sum_j f_{j \to i} v_j + T \sum_j f_{j \to i} u_j$

Key part of solver

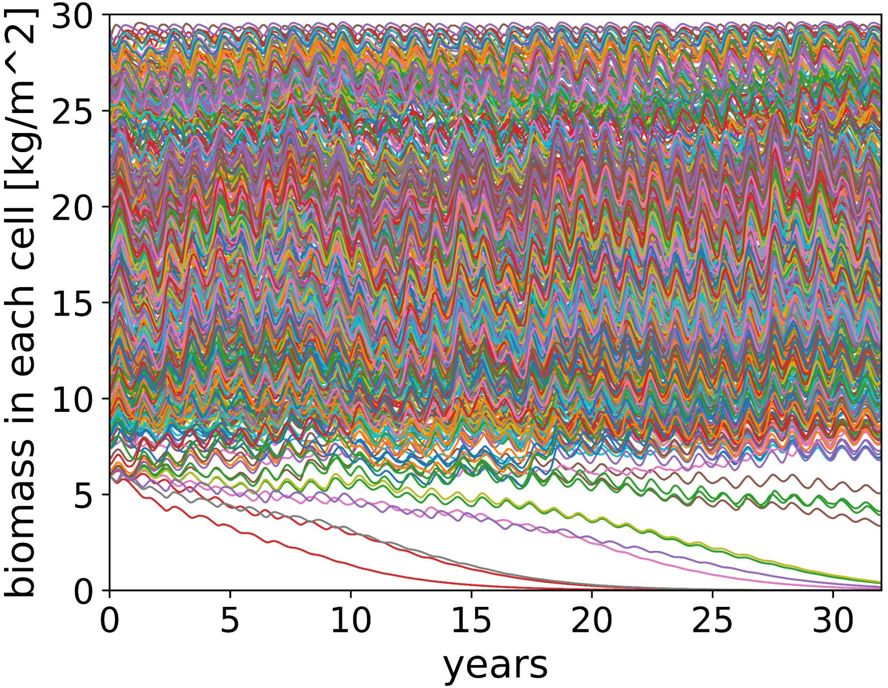
```
from scipy.integrate import odeint

def duvdt(y, t, A, B):
     return [u*u*v - B*u,
             -u*u*v + A - v]

A, B = 2, -0.1
solution = odeint(duvdt, [1, 1], t, args=(A, B))

u_sol = solution[:, 0]
v_sol = solution[:, 1]
```

Then should add the complications of the model,
and the **coupling between the ODEs of all cells!**

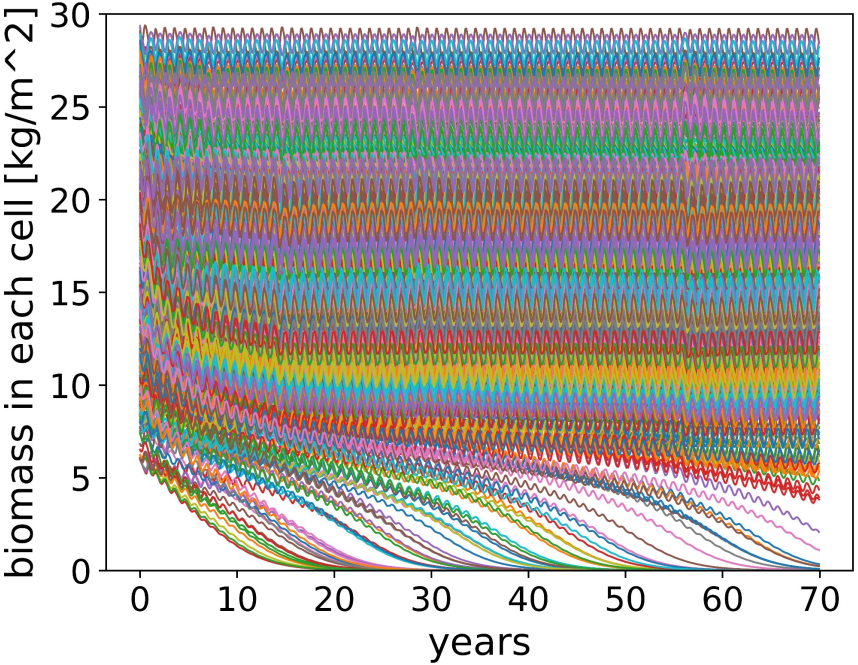
2 x 567 coupled ODE's on a network!

Input monthly rainfall in the coupled ODE's system… then observe biomass(t) in each cell

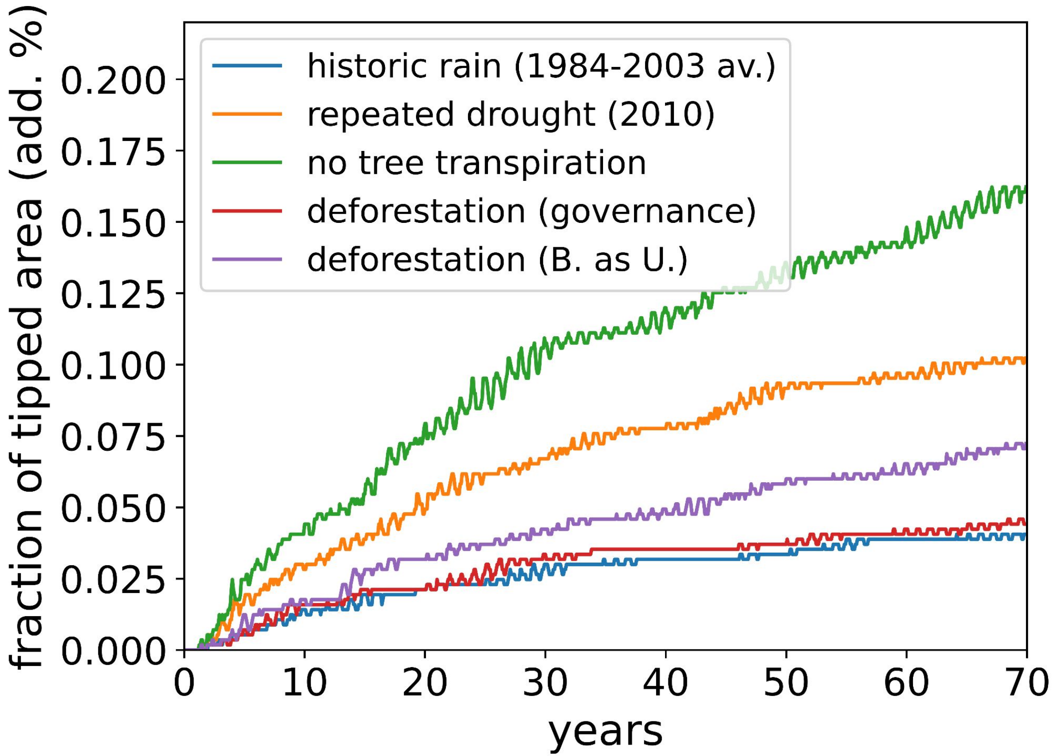
Historic rainfall data 1982 - 2014:



Repeat rainfall of 2010 ("drought of the century) for 70 years:

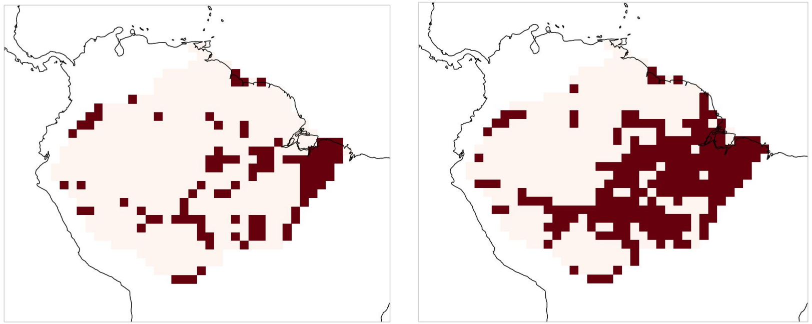


Tipping cascades from repeated droughts/deforestation

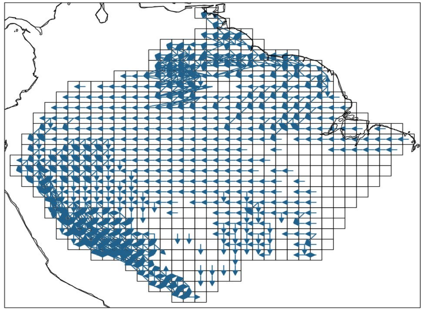


Geography of vulnerability

Deforestation initial perturbation



Moisture fluxes



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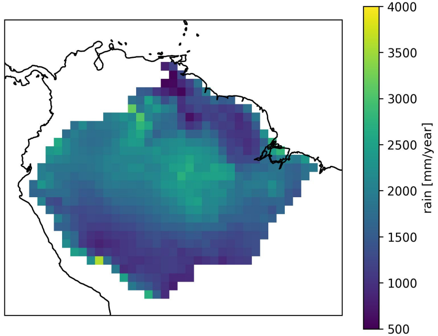
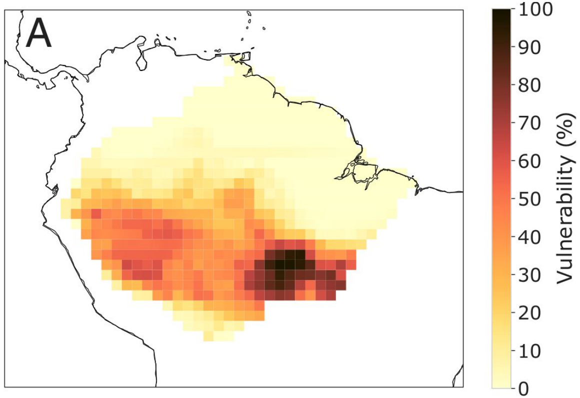


Former paper (ad-hoc model)

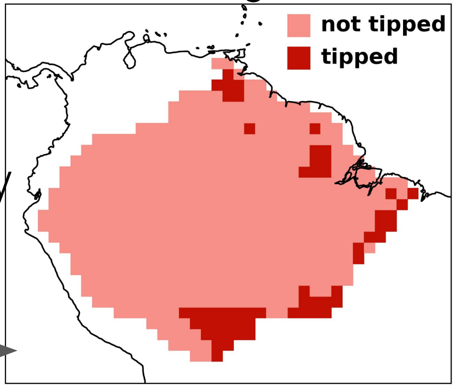


Tipping driven by:

dry season intensity

cumulated rainfall

Repeated 2010 drought



no tree transpiration