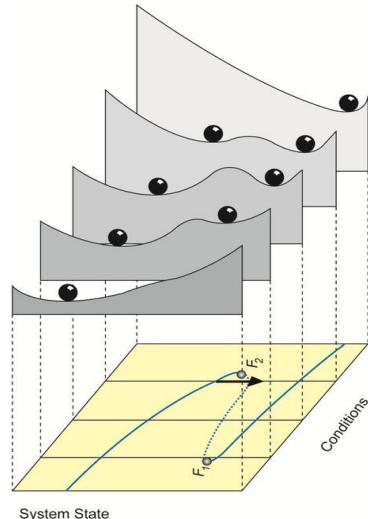
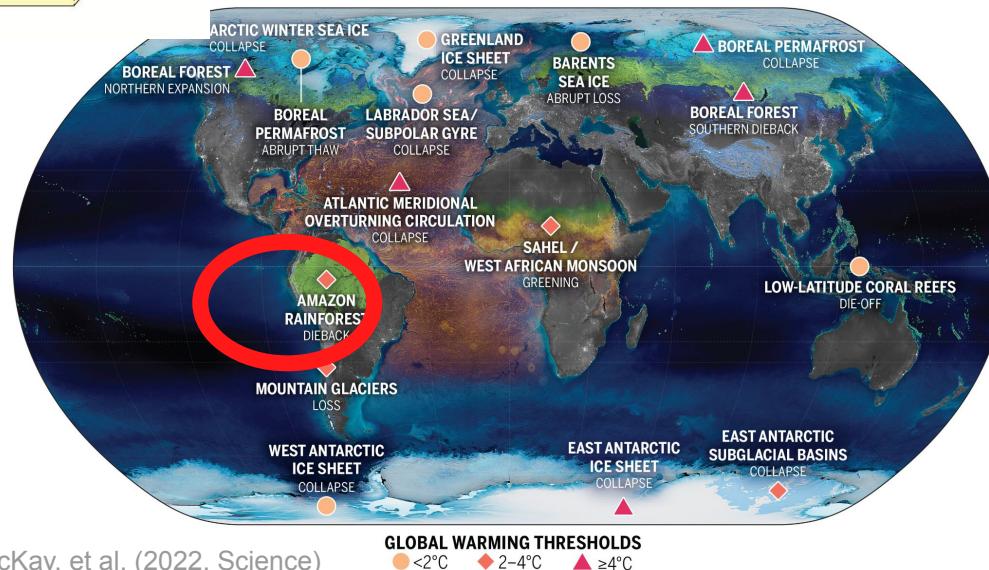


# Tipping points

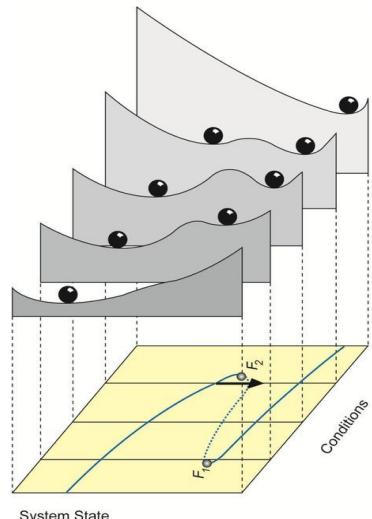


Multiple Earth systems  
can (will?) tip

Potential forest/savanna bistability in the  
Amazon rainforest



# Tipping points



Multiple Earth systems  
can (will?) tip

Potential forest/savanna bistability in the  
Amazon rainforest



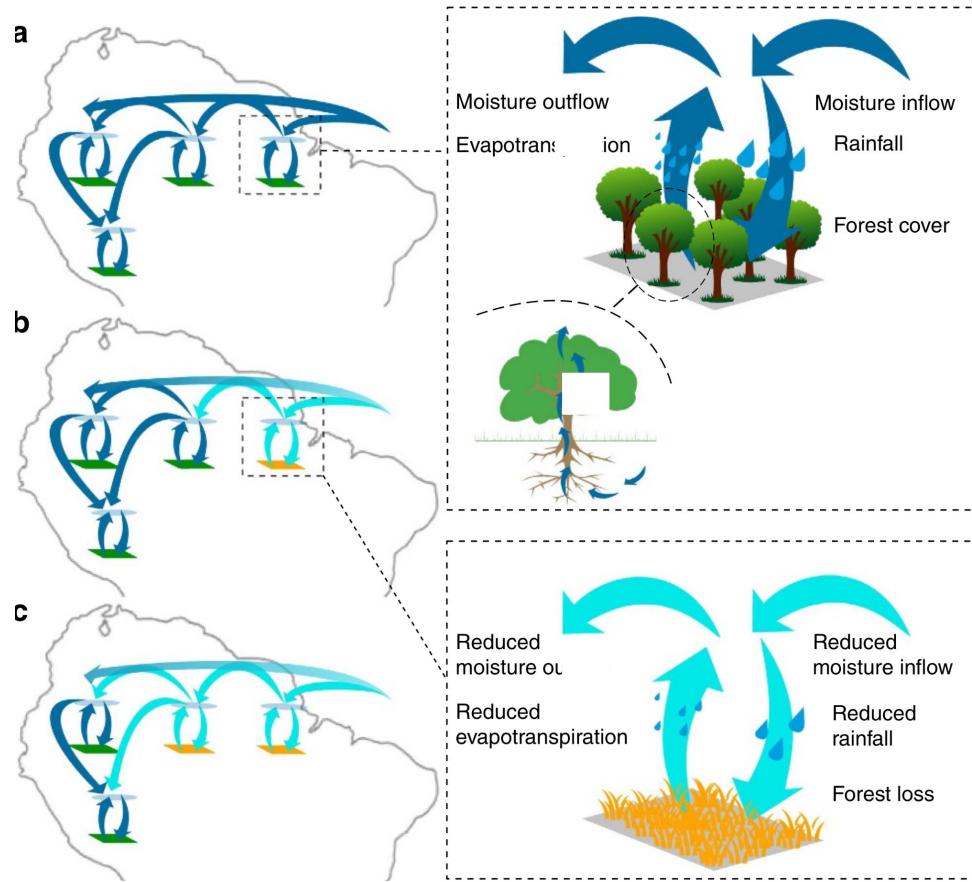
# Global Tipping Points Report

The authoritative assessment  
of the risks and opportunities of  
negative and positive tipping points  
in the Earth System and society.

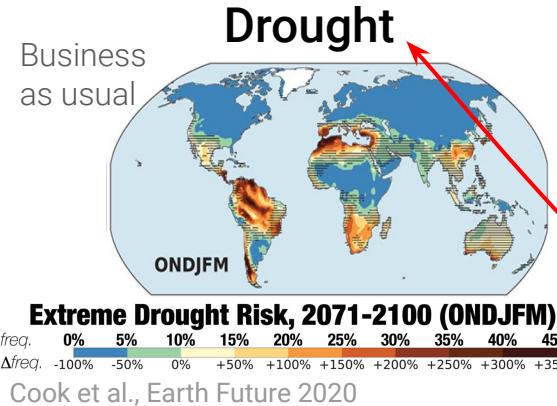
- 1) Earth system
- 2) Impacts
- 3) Governance
- 4) Positive social tipping points

Report was discussed at COP28!

# Moisture recycling network



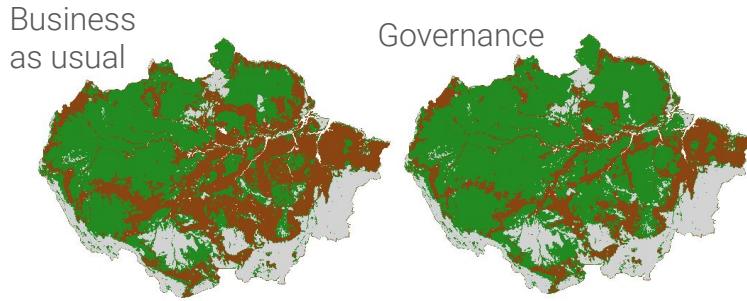
# Amazon threats: amplified by network effects?



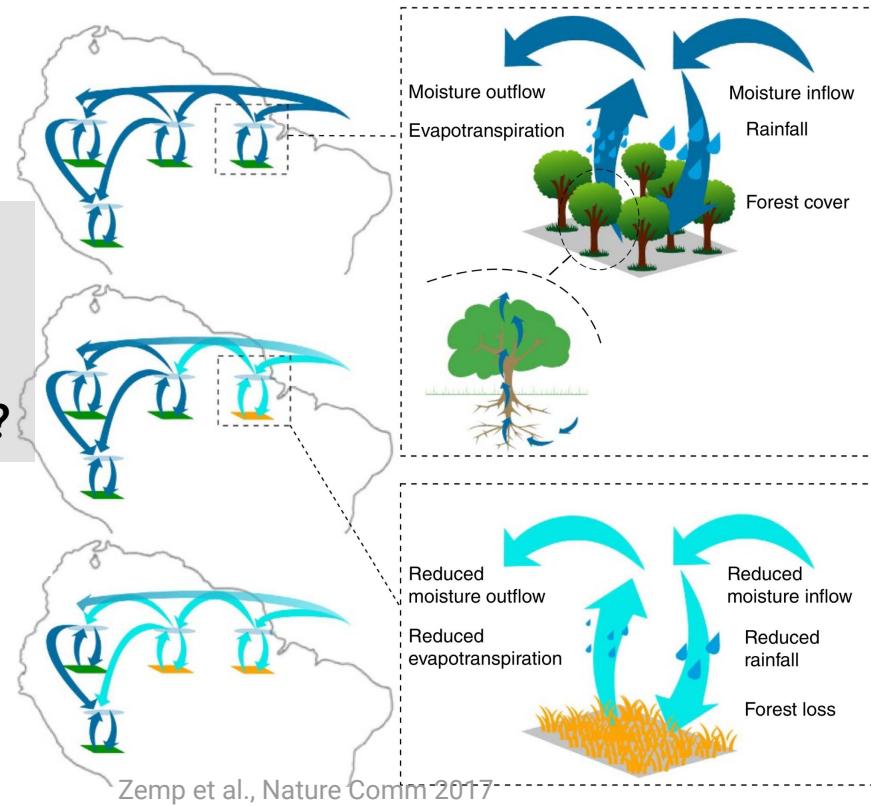
Is tipping  
amplified  
by the network?

**Deforestation**

LBA-ECO LC-14 projections in 2050

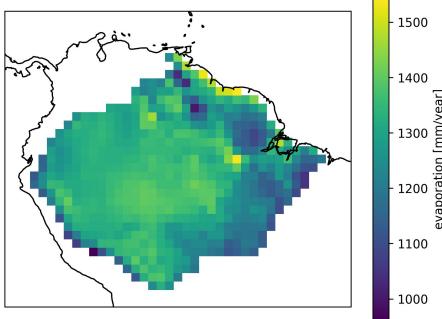


**Moisture recycling network**

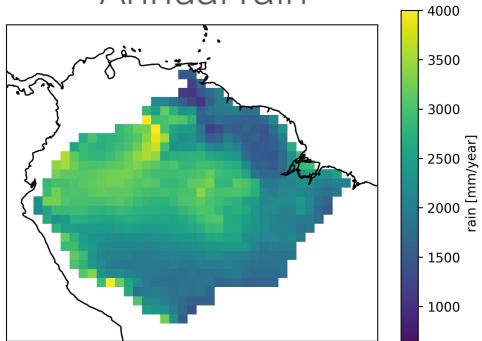


# Spatial precipitation patterns

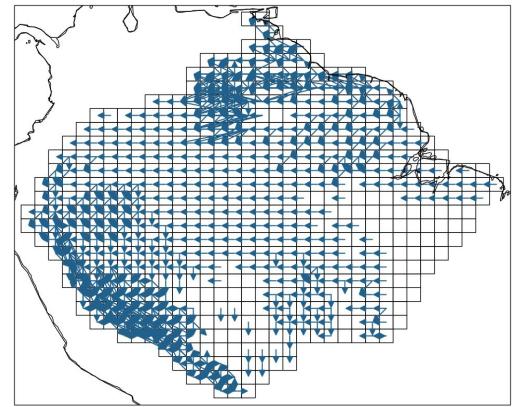
Annual evaporation



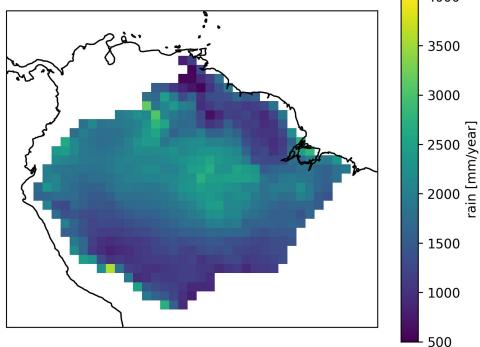
Annual rain



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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Original (**adimensional**) model:

$$\begin{aligned} \frac{du}{dt} &= u^2 v - Bu && \text{death rate without water} \\ \text{biomass} \quad \frac{dv}{dt} &= -u^2 v + A - v && \text{evaporation} \\ \text{available water} \quad \text{plant growth} \end{aligned}$$

rainfall

The diagram illustrates the Klausmeier model with two coupled differential equations. The top equation,  $\frac{du}{dt} = u^2 v - Bu$ , represents the change in biomass over time. The term  $u^2 v$  is labeled 'plant growth' in blue, and the term  $-Bu$  is labeled 'death rate without water' in orange. The bottom equation,  $\frac{dv}{dt} = -u^2 v + A - v$ , represents the change in available water over time. The term  $-u^2 v$  is labeled 'plant growth' in blue, the term  $+A$  is labeled 'rainfall' in brown, and the term  $-v$  is labeled 'evaporation' in pink. Red arrows point from the labels 'biomass', 'available water', and 'plant growth' to their respective terms in the equations.

# A Klausmeier model for each cell

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Thanks to trees: **tree transpiration**  $Tu$  and interception evaporation  $AIu$   
(interception is included for now in tree transpiration)

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The network  $f_{i \rightarrow j}$  is the **fraction of evaporation** from cell  $i$  becoming rain in cell  $j$

# A Klausmeier model for each cell

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

Original (**adimensional**) model:

The diagram illustrates the Klausmeier model equations. It features two coupled differential equations:

$$\frac{du}{dt} = u^2 v - Bu \quad \text{death rate without water}$$
$$\frac{dv}{dt} = -u^2 v + A - v \quad \text{evaporation}$$

Annotations with arrows point to specific terms:

- A red arrow labeled "biomass" points to the term  $u^2 v$  in the first equation.
- A green arrow labeled "available water" points to the term  $-u^2 v$  in the second equation.
- A blue arrow labeled "plant growth" points to the term  $v$  in the second equation.
- An orange oval labeled "rainfall" has an arrow pointing to the term  $A$  in the second equation.
- An orange oval labeled "death rate without water" has an arrow pointing to the term  $Bu$  in the first equation.
- A pink oval labeled "evaporation" has an arrow pointing to the term  $v$  in the second equation.

Thanks to trees: **tree transpiration**  $Tu$  and interception evaporation  $AIu$   
(interception is included for now in tree transpiration)

The network  $f_{i \rightarrow j}$  is the **fraction of evaporation** from cell  $i$  becoming rain in cell  $j$

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

# 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]
```

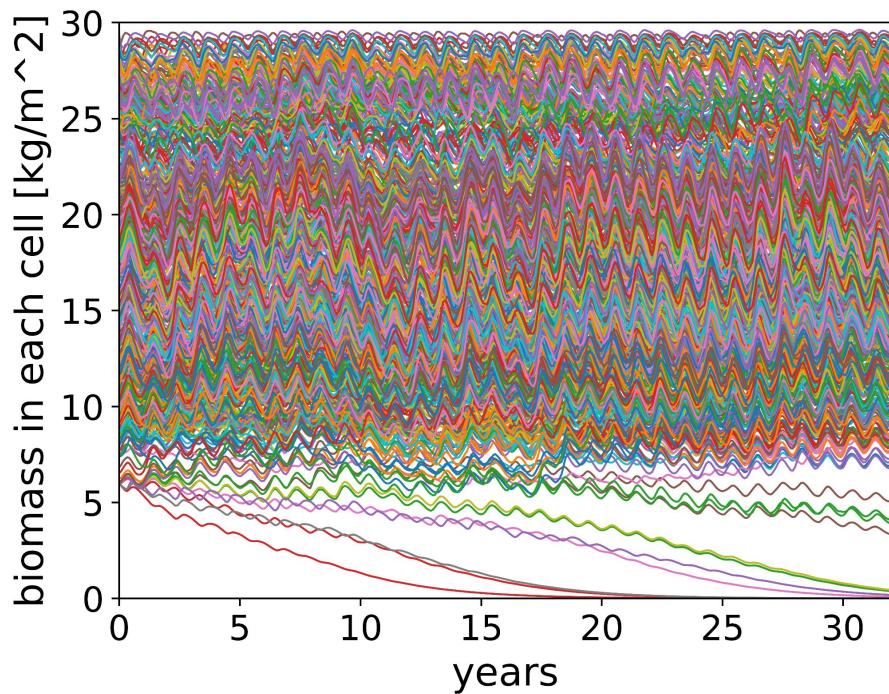
Then should add the complications of the model,  
and the **coupling between the ODEs of all cells!**

# **2 x 567 coupled ODE's on a network!**

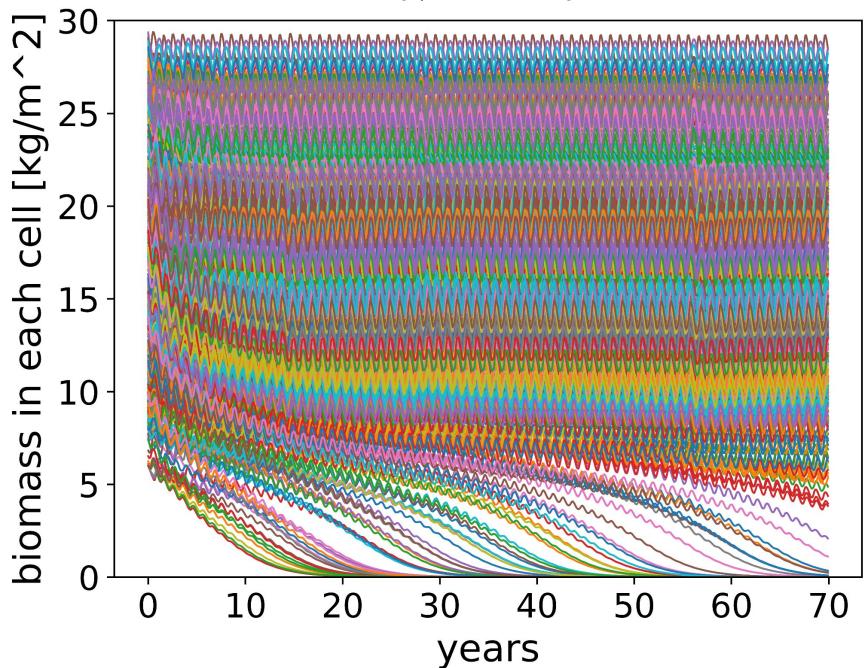
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Input monthly rainfall in the coupled ODE's system... then observe biomass(t) in each cell

Historic rainfall data 1982 - 2014:

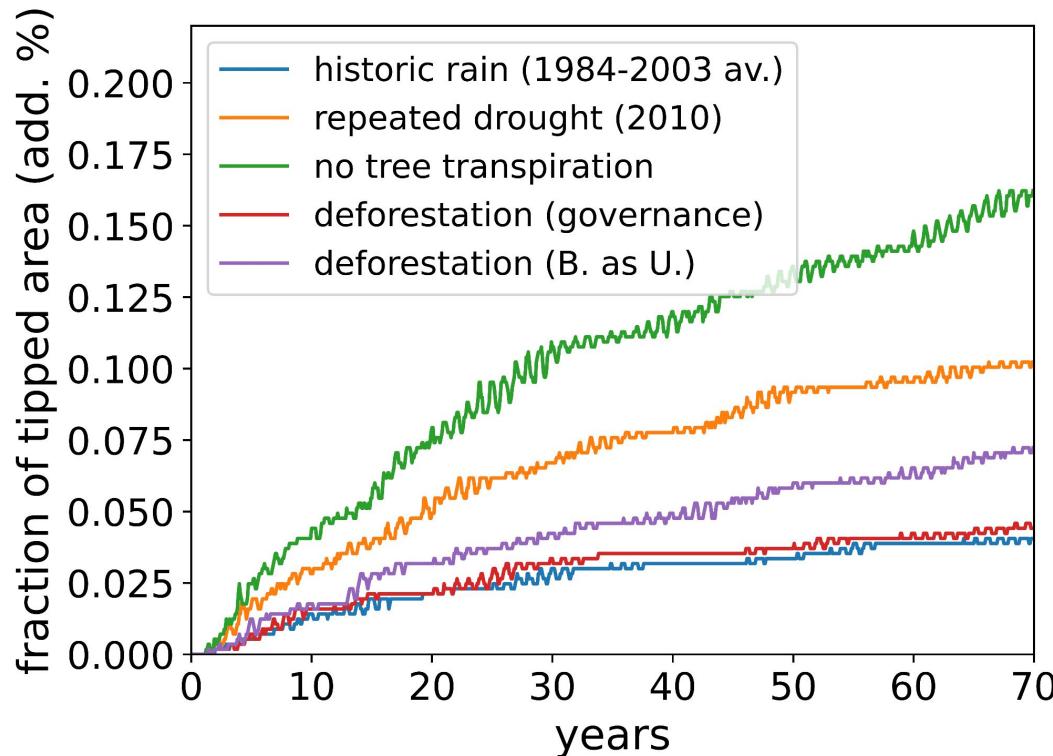


Repeat rainfall of 2010 ("drought of the century) for 70 years:



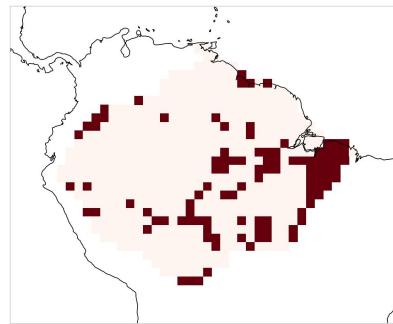
# Tipping cascades from repeated droughts/deforestation

---

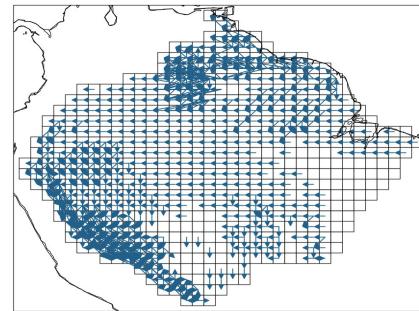


# Geography of vulnerability

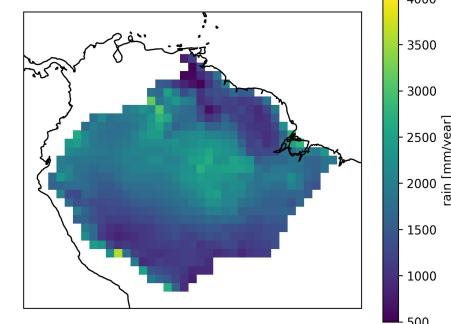
Deforestation initial perturbation



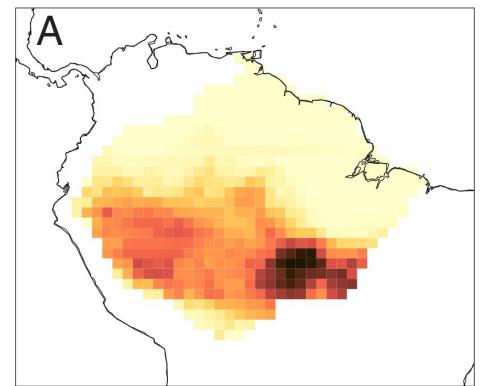
Moisture fluxes



Rainfall not from Amazon



Former paper (ad-hoc model)

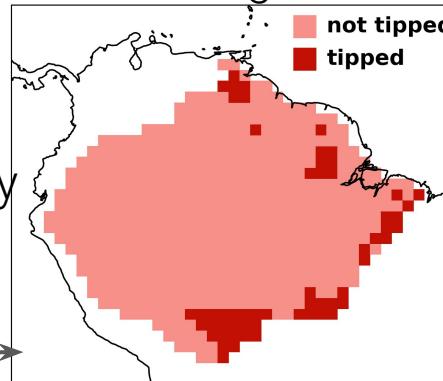


Tipping driven by:

dry season intensity

cumulated rainfall

Repeated 2010  
drought



no tree  
transpiration

