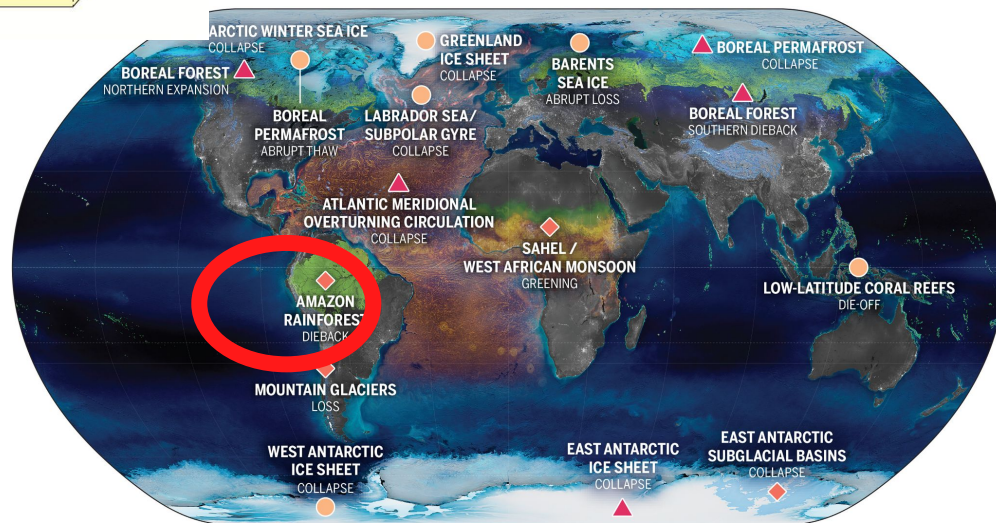
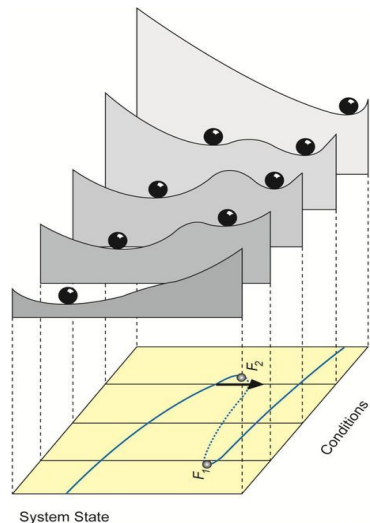


Tipping points

Multiple Earth systems
can (will?) tip

Potential forest/savanna bistability in the
Amazon rainforest



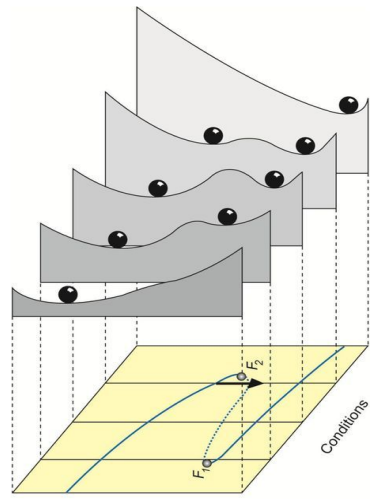
GLOBAL WARMING THRESHOLDS

● <2°C ◆ 2-4°C ▲ ≥4°C

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GLOBAL WARMING THRESHOLDS

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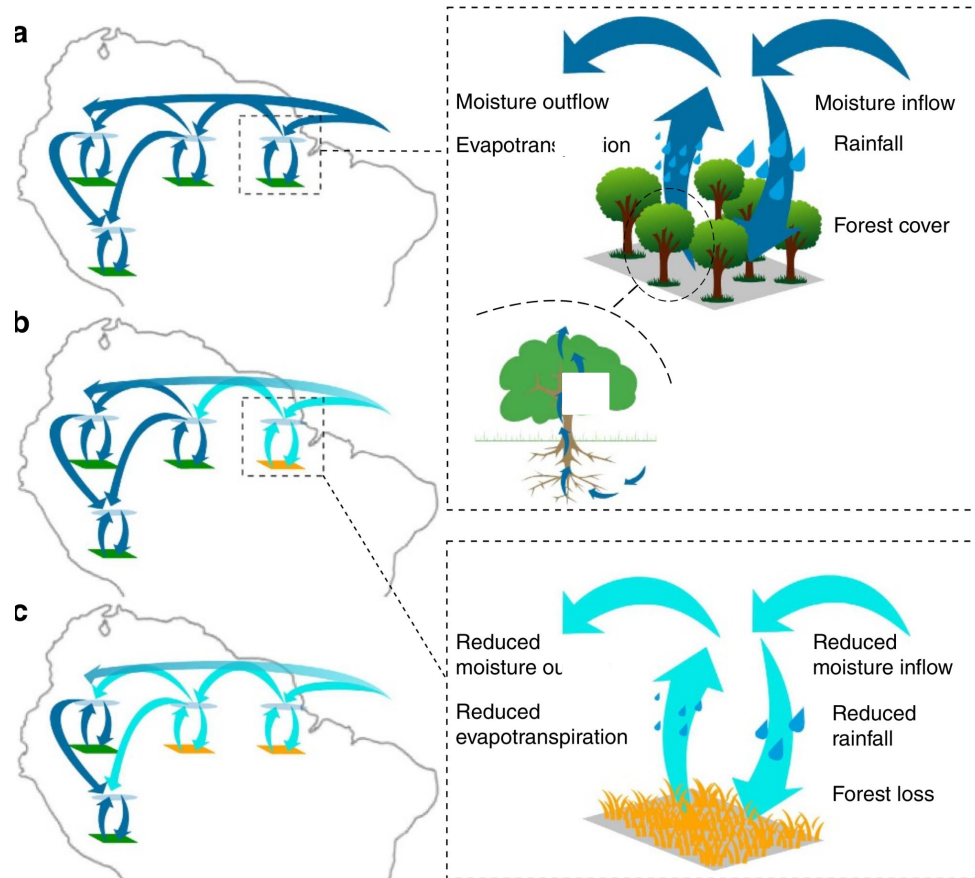
Global Tipping Points Report

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

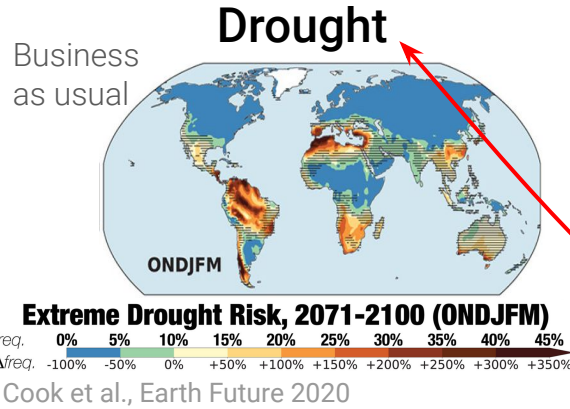
- 1) Earth system
- 2) Impacts
- 3) Governance
- 4) Positive social tipping points

Report was discussed at COP28!

Moisture recycling network



Amazon threats: amplified by network effects?

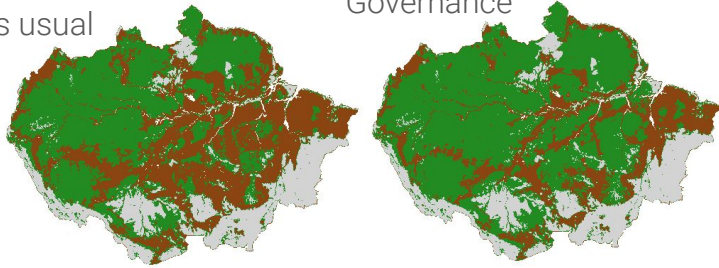


Deforestation

LBA-ECO LC-14 projections in 2050

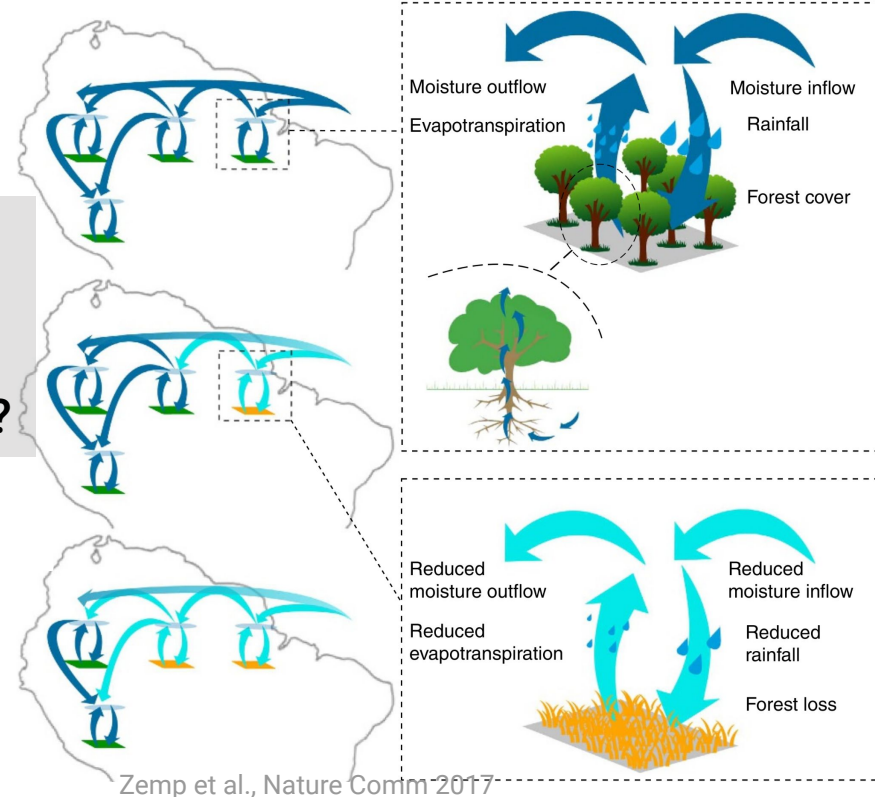
Business as usual

Governance



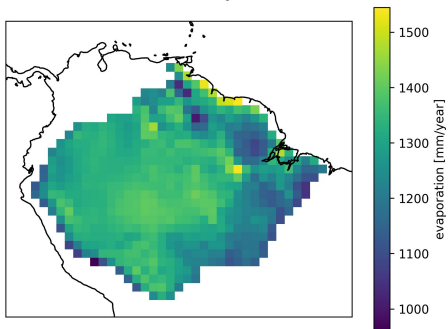
Is tipping
amplified
by the network?

Moisture recycling network

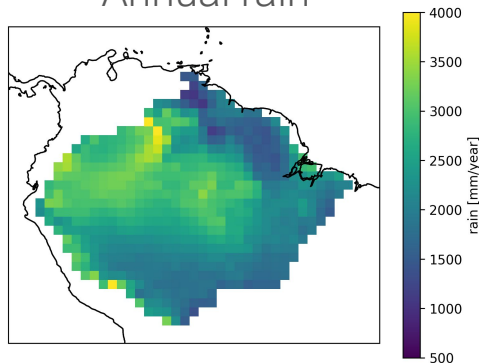


Spatial precipitation patterns

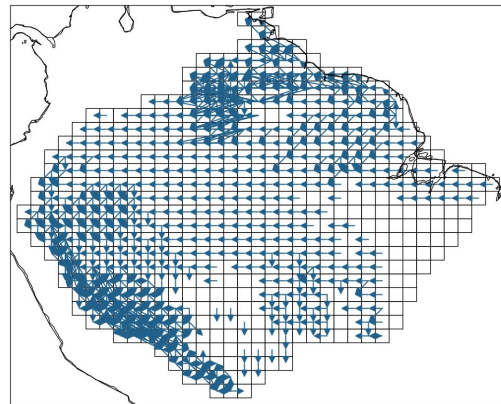
Annual evaporation



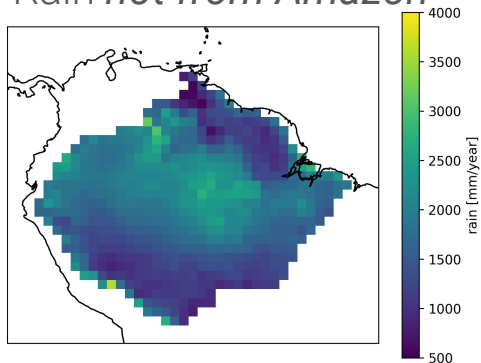
Annual rain



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:

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

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

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 shows two differential equations for biomass (u) and available water (v). The first equation is $\frac{du}{dt} = u^2 v - Bu$, where $\frac{du}{dt}$ is circled in red, $u^2 v$ is in a blue oval, Bu is in an orange oval, and the term Bu is labeled "death rate without water" with an orange arrow. The second equation is $\frac{dv}{dt} = -u^2 v + A - v$, where $\frac{dv}{dt}$ is circled in green, $-u^2 v$ is in a blue oval, A is in a brown oval, and $-v$ is in a pink oval. Labels with arrows point to various terms: "biomass" (red) points to u in the first equation; "available water" (green) points to v in the second equation; "plant growth" (blue) points to $u^2 v$ in the second equation; "rainfall" (brown) points to A in the second equation; and "evaporation" (pink) points to $-v$ in the second equation.

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

Labels and arrows in the diagram:

- biomass (red arrow pointing to u)
- available water (green arrow pointing to v)
- plant growth (blue arrow pointing to $u^2 v$)
- rainfall (brown arrow pointing to A)

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

biomass

available water

plant growth

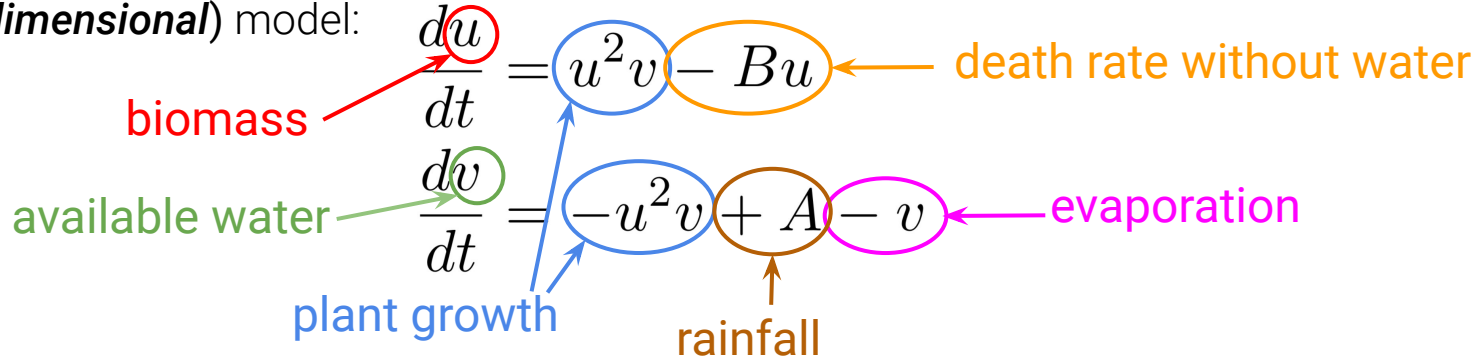
rainfall

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

A Klausmeier model for each cell

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

Original (**adimensional**) model:



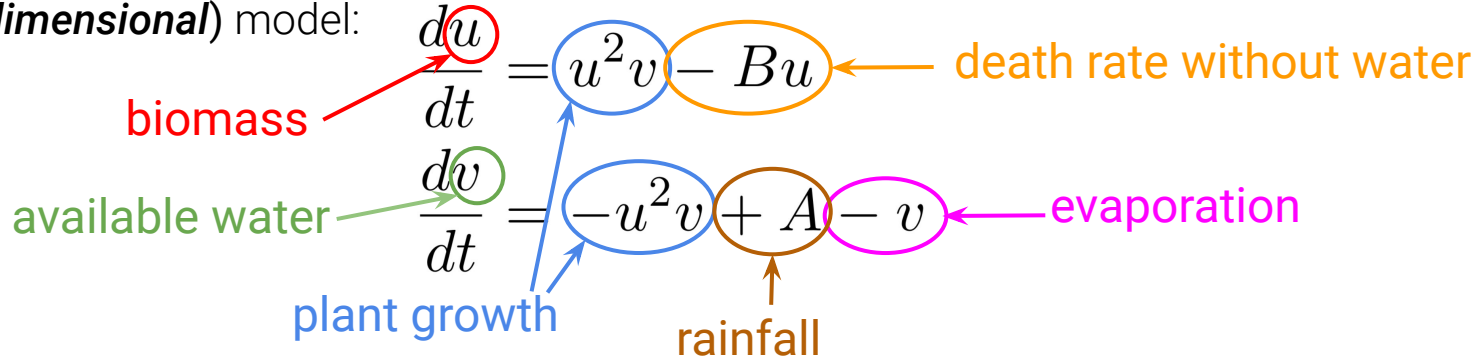
Thanks to trees: **tree transpiration** Tu and interception evaporation AIu
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The network $f_{i \rightarrow j}$ is the **fraction of evaporation** from cell i becoming rain in cell j

A Klausmeier model for each cell

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

Original (**adimensional**) model:



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))

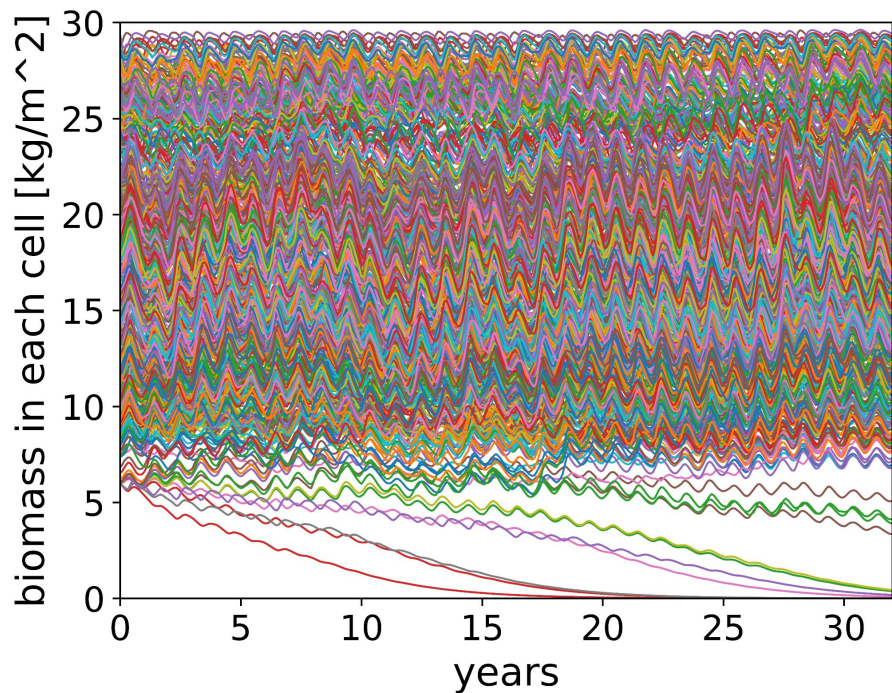
u_sol = solution[:, 0]
v_sol = solution[:, 1]
```

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

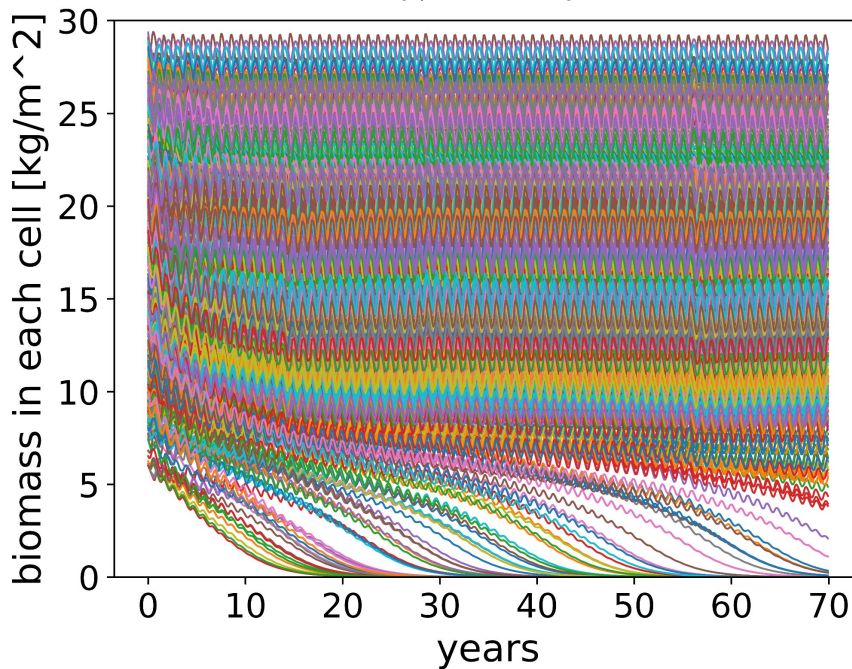
2 x 567 coupled ODE's on a network!

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

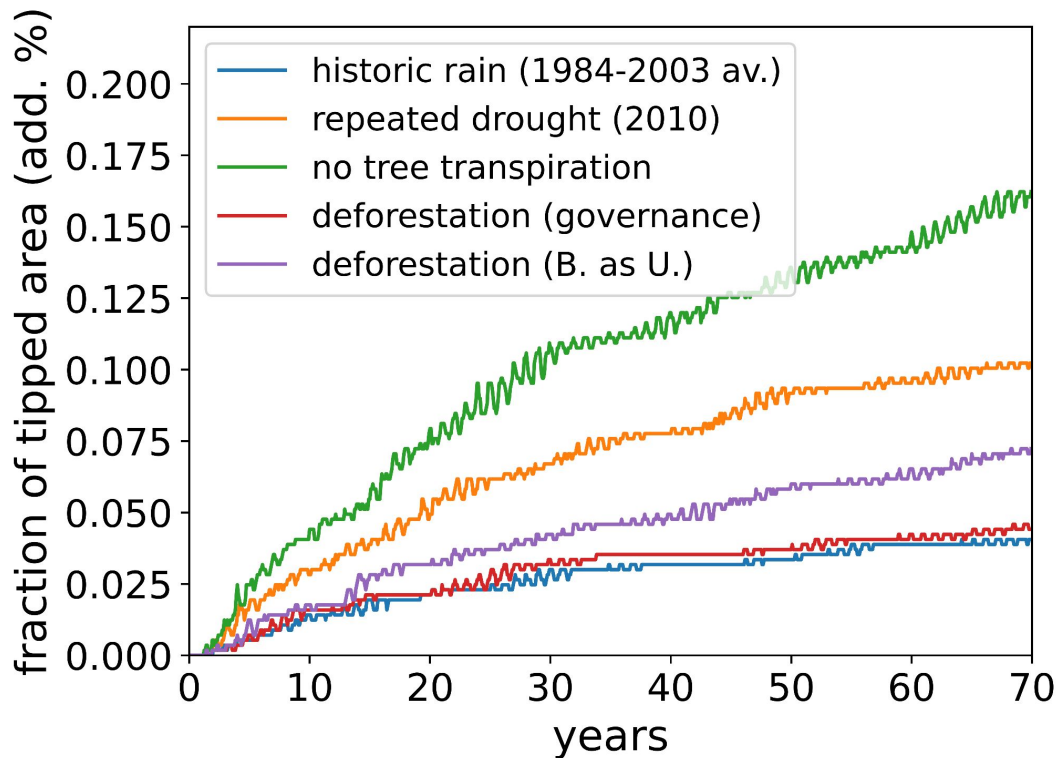
Historic rainfall data 1982 - 2014:



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

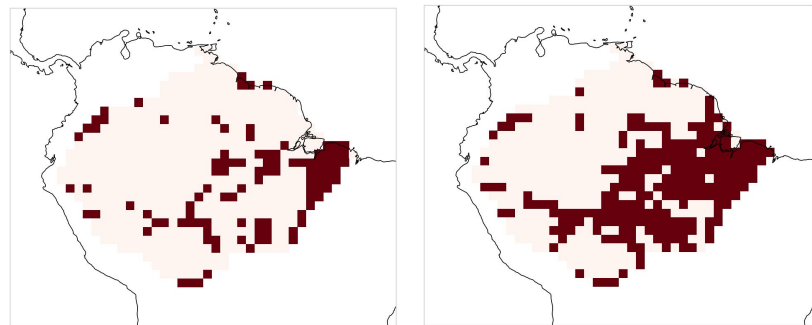


Tipping cascades from repeated droughts/deforestation

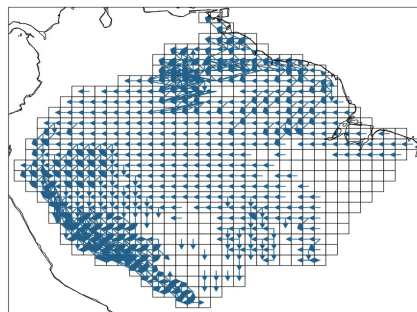


Geography of vulnerability

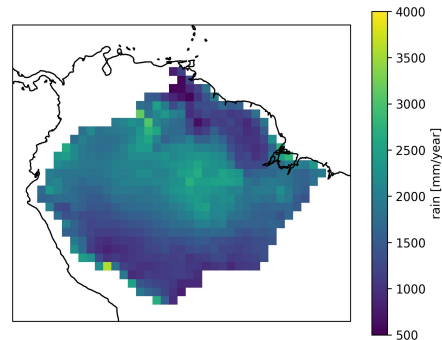
Deforestation initial perturbation



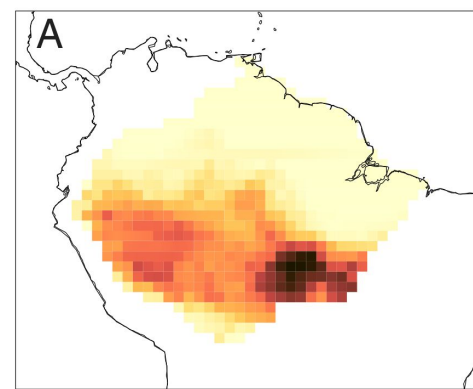
Moisture fluxes



Rainfall *not from Amazon*



Former paper (ad-hoc model)

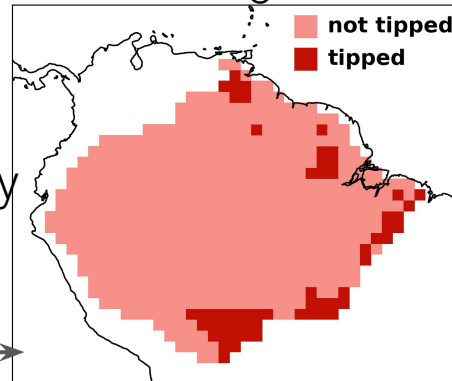


Tipping driven by:

dry season intensity

cumulated rainfall

Repeated 2010
drought



no tree
transpiration

