Potsdam Institute for Climate Impact Research

Co-evolutionary conceptual models of global pre-industrial societies

Jan Nitzbon

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Leibniz-Gemeinschaft

copan coevolutionary pathways

Outline

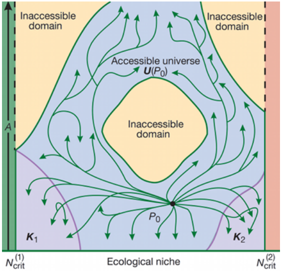
Introduction

Global carbon cycle sub-model

Co-evolutionary sub-model for pre-industrial societies

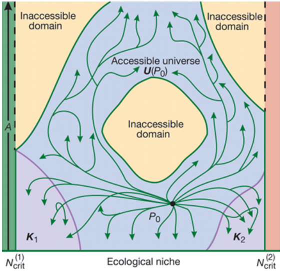
Conclusion and Outlook

Co-evolutionary modeling



Schellnhuber 1998

Co-evolutionary modeling



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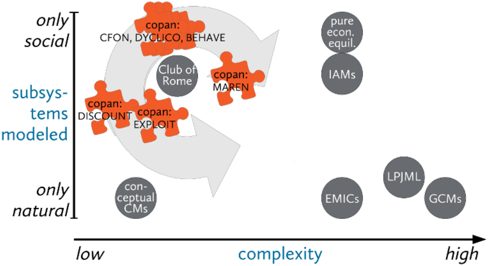
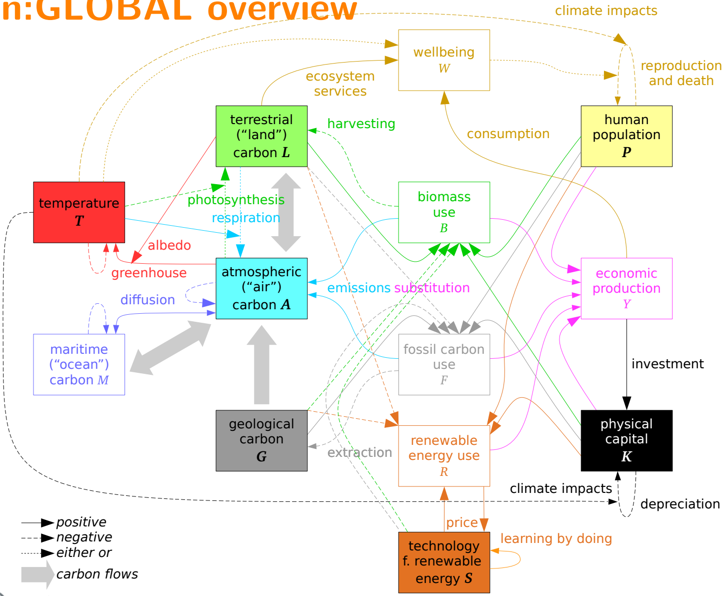
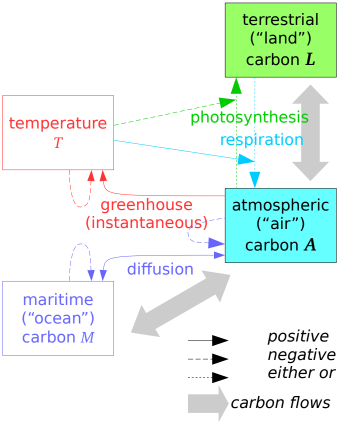


copan:GLOBAL overview



Global carbon cycle sub-model



Global carbon cycle sub-model

Inspired by *Anderies et al. 2013*, but simpler functional forms for **state variables**:

$$\text{land:} \qquad \dot{L} = \underbrace{(l_0 - l_T T)\ \underbrace{\sqrt{A/\Sigma}}_{\text{fertilization}}\ L}_{\text{photosynthesis}} - \underbrace{(a_0 + a_T T)L}_{\text{respiration}} \tag{1}$$

$$\text{atmosphere:} \qquad \dot{A} = -\dot{L} + \underbrace{\delta\,(M - mA)}_{\text{diffusion}} \tag{2}$$

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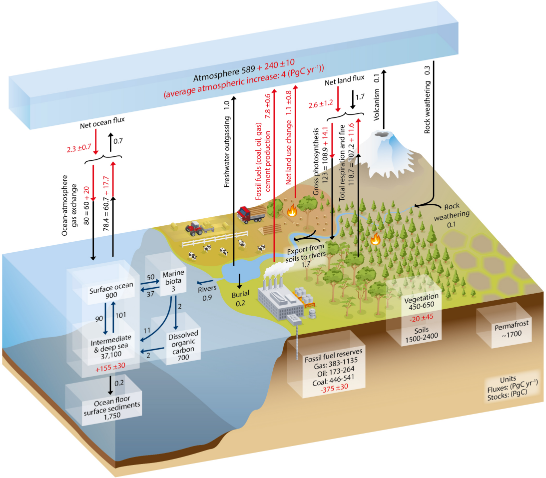
with the **derived quantities** (instantaneous greenhouse effect):

$$\text{temperature:} \qquad T = A \tag{3}$$

$$\text{ocean:} \qquad M = C^* - L - A \tag{4}$$

Parameter adjustment to IPCC data



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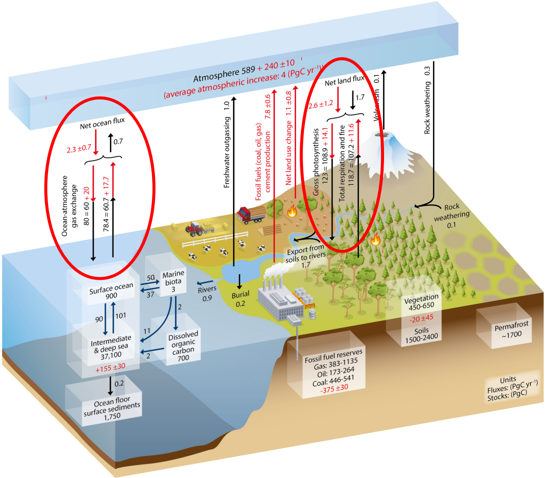
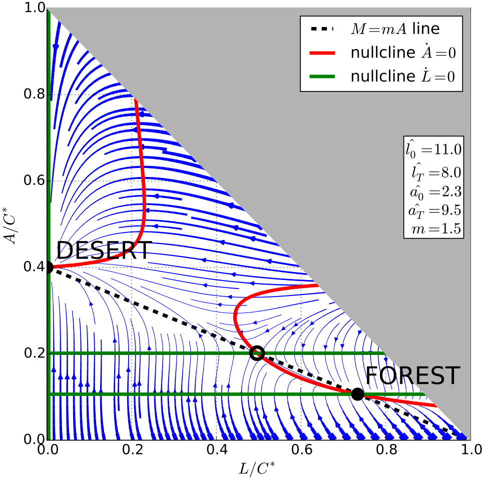


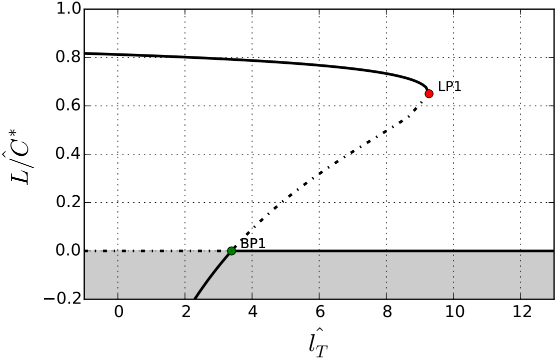
→ main processes (photosynthesis, respiration, diffusion) included

Multistable phase portrait



→ **bistable system** with attracting **"desert"** and **"forest" states**

Bifurcation analysis to get the full picture



- **three regimes** with one, two or three equilibria
- **hysteresis** effect possible if parameter changes

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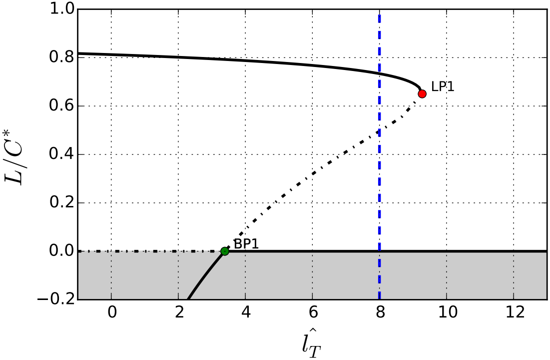

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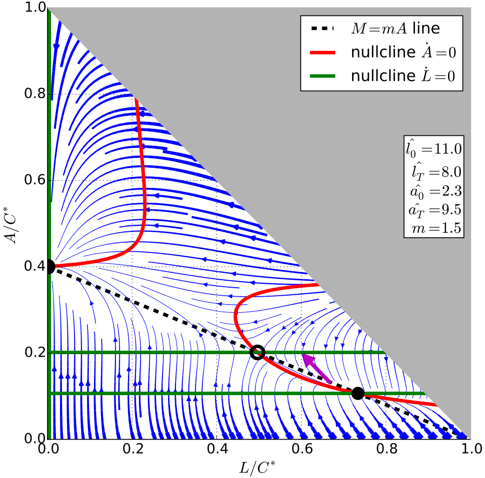
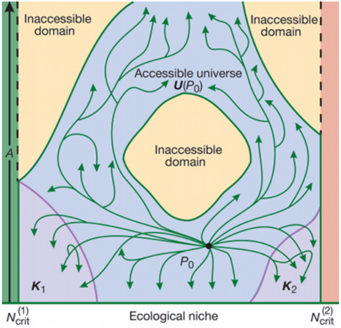
Evolution from pre-industrial to present time



$\rightarrow$ need to **model human impact** explicitly

Co-evolutionary model with humans



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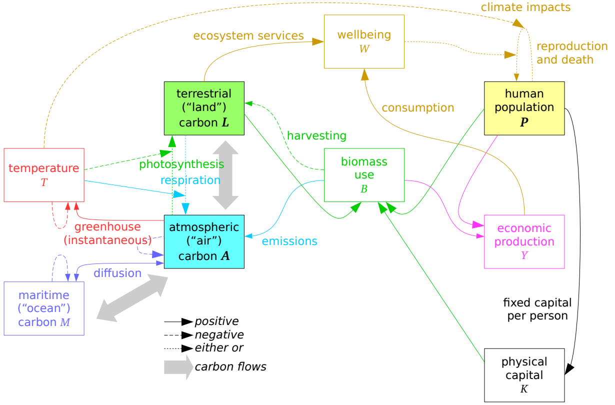

- assume fixed capital per person, **no capital accumulation**
- comparable to hunter-gatherer or **agricultural societies**

Harvesting of biomass by humans

$$\dot{L} = L\left((l_0 - l_T A)\sqrt{A/\Sigma} - (a_0 + a_T A)\right) - B \qquad (5)$$

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- from economic **general equilibrium model**:

$B = X_B Z / e'_B \quad Z = z_0 P^{3/4}(X_Y + X_B)^{-4/5} \quad X_B = a'_B L^{5/4} \quad X_Y = a_Y \Sigma^{5/4}$

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- assuming $X_Y \ll X_B$ gives expression similar to *Brander and Taylor 1998* model of renewable resource use:

$$\text{copan:GLOBAL:} \quad B = bL^{\frac{1}{4}} P^{\frac{3}{4}} \tag{6}$$

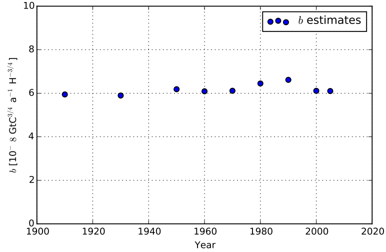
$$\text{Brander, Taylor:} \quad B = bLP \tag{7}$$

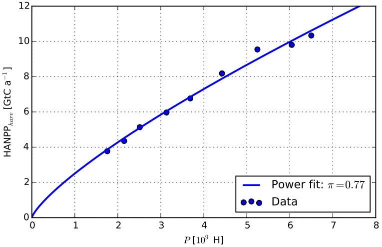
$\rightarrow$ **correct scaling** when extensive quantities are doubled

Estimation of biomass harvesting parameter b

$$b = \frac{B}{L^{\frac{1}{4}} P^{\frac{3}{4}}} \approx \frac{HANPP_{\text{harvest}}}{L^{\frac{1}{4}} P^{\frac{3}{4}}} \approx 0.35 \, \frac{\text{tC}^{\frac{3}{4}}}{\text{H}^{\frac{3}{4}} \text{ a}} \tag{8}$$

- historical data from *Krausmann et al. 2013*

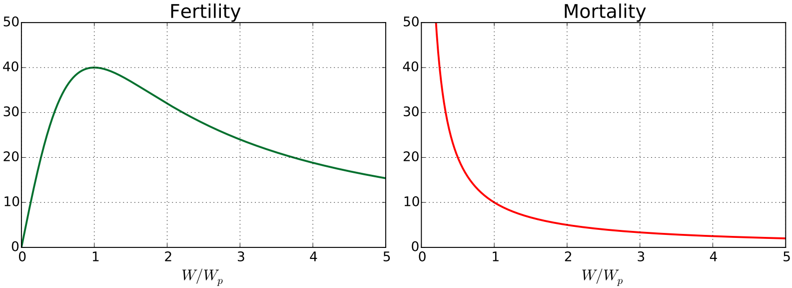




Population dynamics

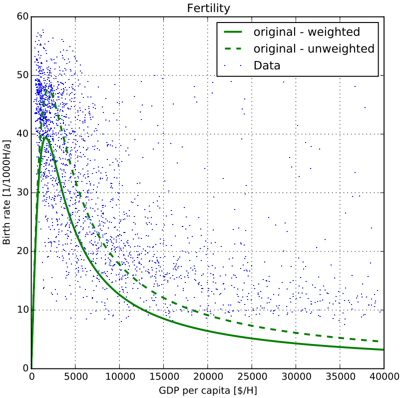
- Goal: linear increase in fertility for very small consumption, decrease for large consumption, simple functional form

$$\dot{P} = P(\underbrace{\frac{2pWW_p}{W_p^2 + W^2}}_{\text{fertility}} - \underbrace{\frac{q_0}{W}}_{\text{mortality}}) \tag{9}$$



Estimation of demographic parameters

- GDP used as estimator for wellbeing (no ecosystem services)
- Data from *Gapminder World* and *World Bank*



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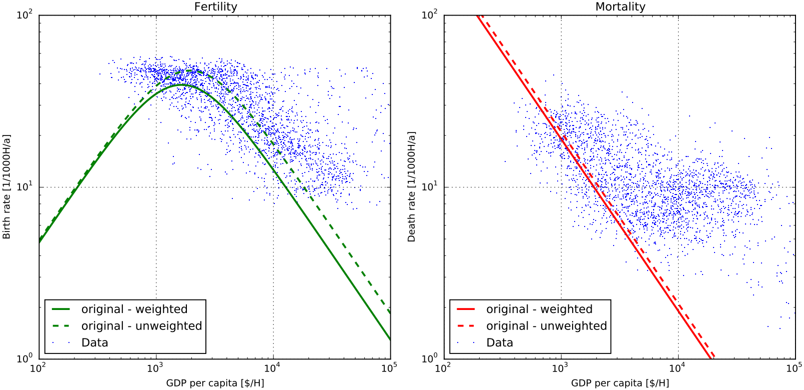


Composition of wellbeing W

$$W = \underbrace{y\,\frac{B}{P}}_{\text{per-capita consumption}} + \underbrace{w_L\,\frac{L}{\Sigma}}_{\text{ecosystem services}} \tag{10}$$

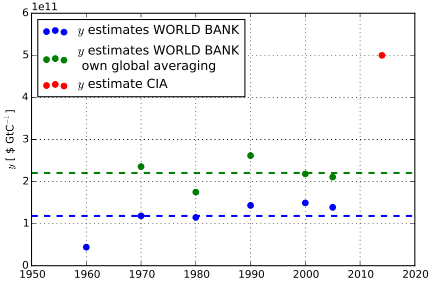
Source: `hunter-gatherer.org`

Source: `GolfLynks.com`

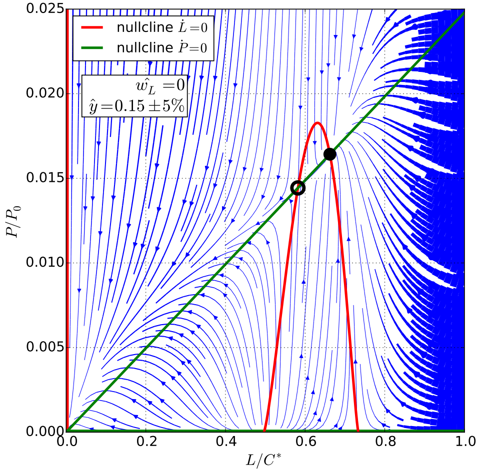
Estimation of wellbeing parameter y

$$y = \frac{WP}{B} \approx \frac{(WP)_{\text{agricultural}}}{HANPP_{\text{harvest}}} = \frac{GWP_{\text{agricultural}}}{HANPP_{\text{harvest}}} \approx 100\,\frac{\$}{\text{tC}} \qquad (11)$$

- GDP data from *World Bank* and *CIA*, HANPP data from *Krausmann et al. 2013*

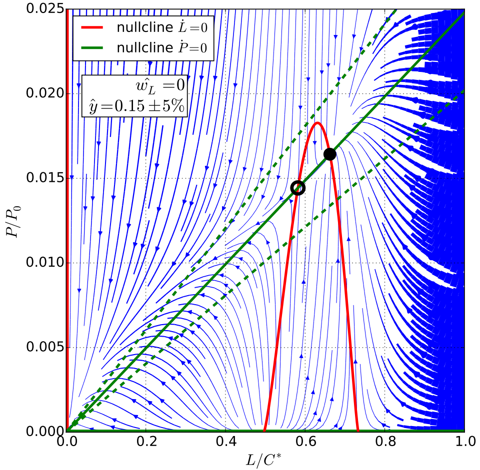


Phase portrait for best parameter estimates



- no net regeneration of land carbon above $P \approx 0.75\,\text{bn}$
- global equilibrium population of $P^* \approx 0.65\,\text{bn}$

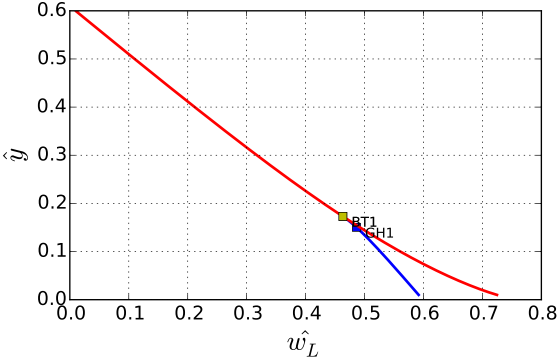
Phase portrait for best parameter estimates



- no net regeneration of land carbon above $P \approx 0.75$ bn
- global equilibrium population of $P^* \approx 0.65$ bn
- up to two **coexistence equilibria** (extremely sensitive to parameters)

$\rightarrow$ bifurcation analysis!

Bifurcation diagram of the coexistence equilibria



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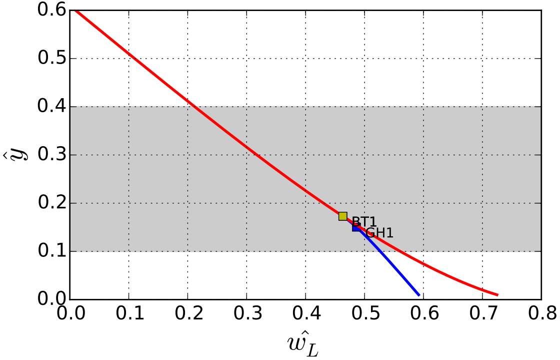

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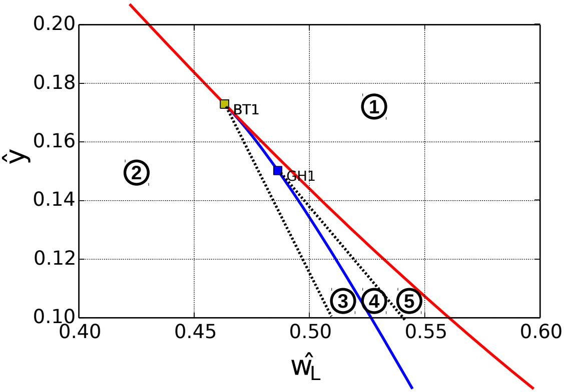

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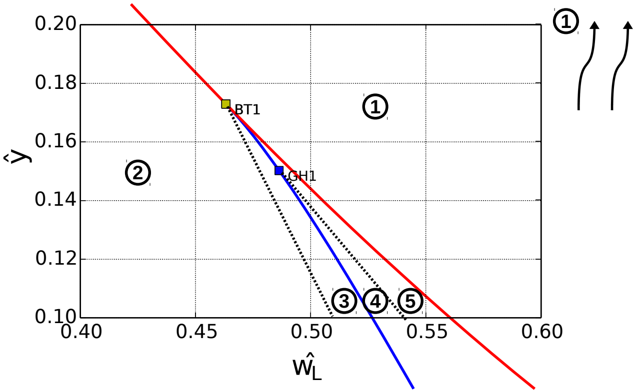

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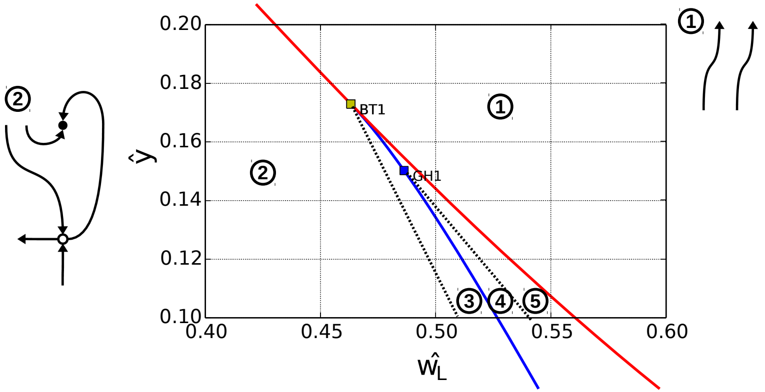

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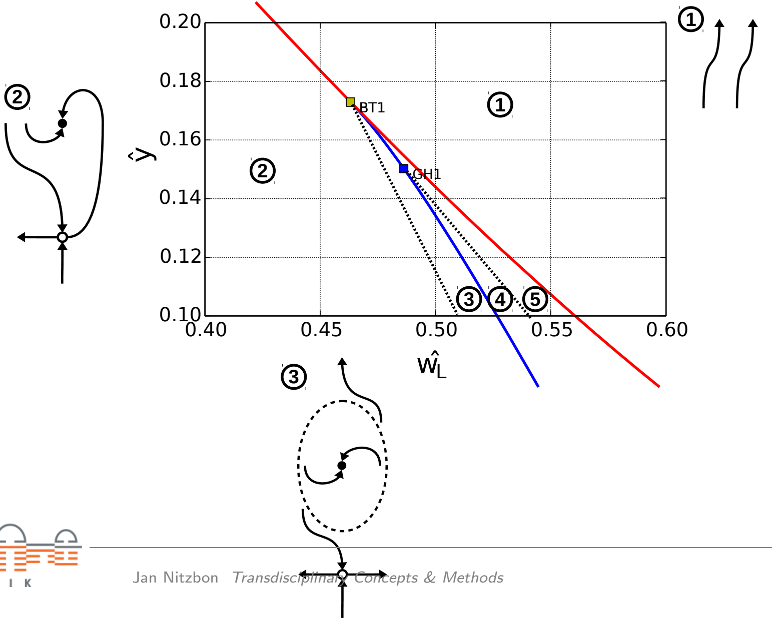

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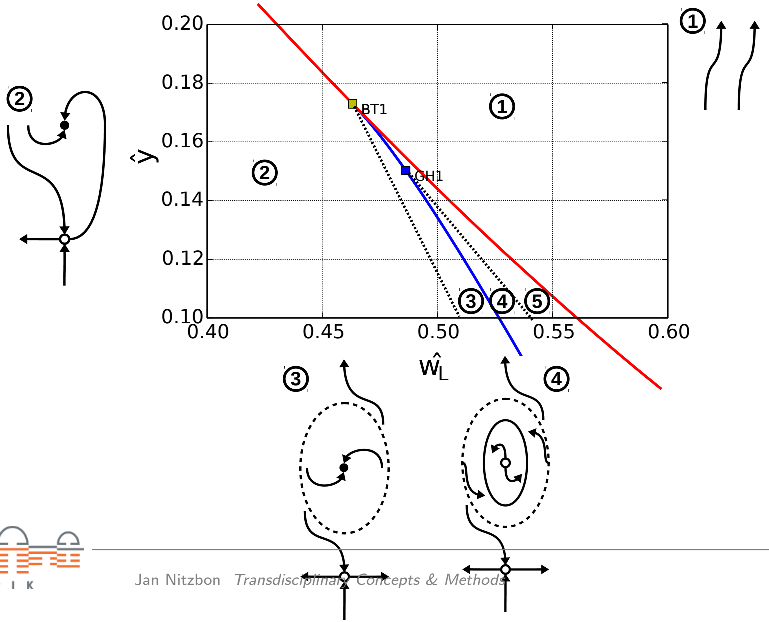

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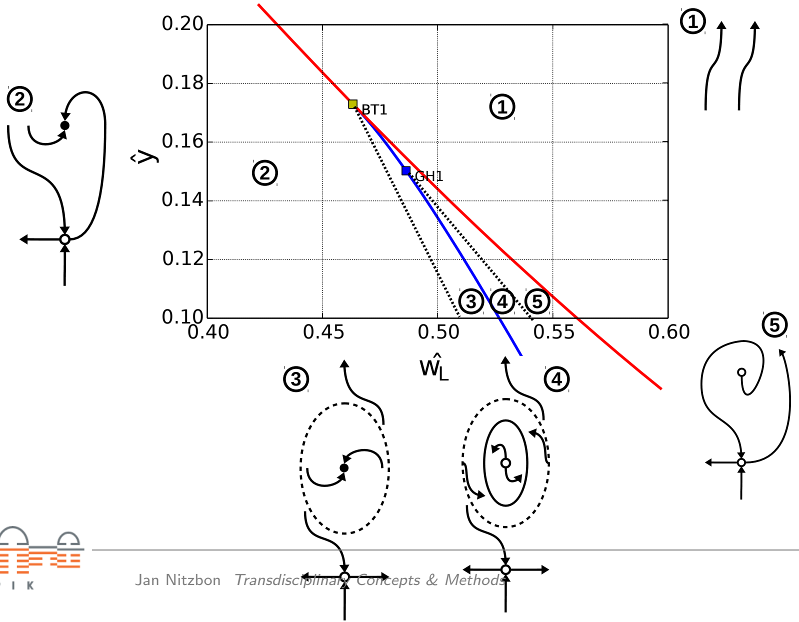
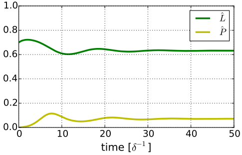
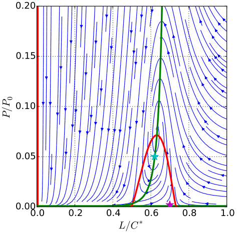
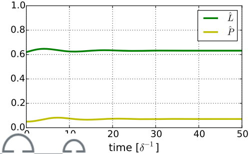


Example trajectories for different regimes

sustainable coexistence







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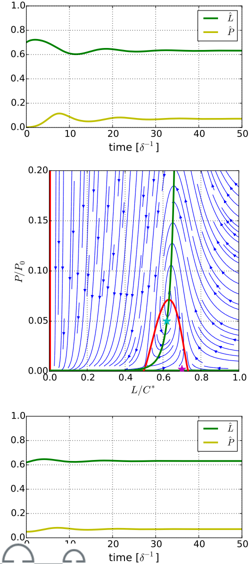
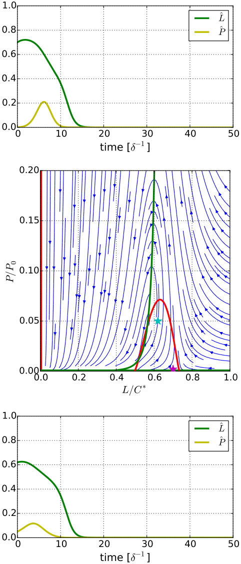


transient coexistence



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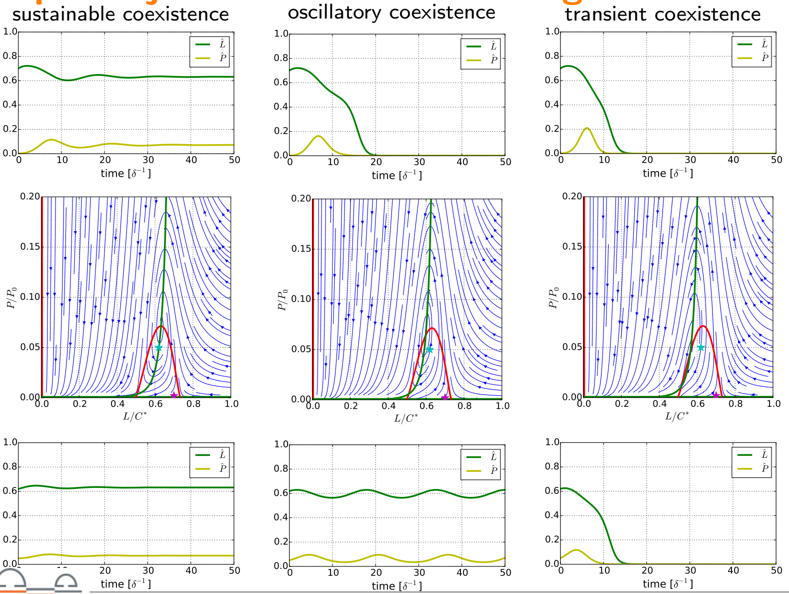
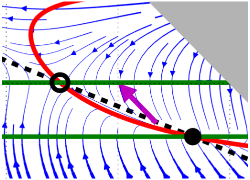


Conclusion and Outlook

necessity of
co-evolutionary modeling



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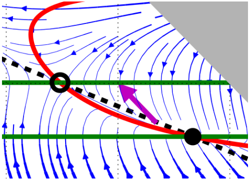

realistic orders
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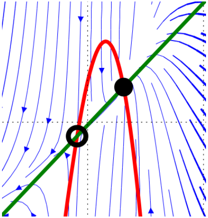

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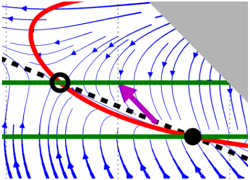

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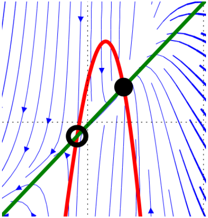
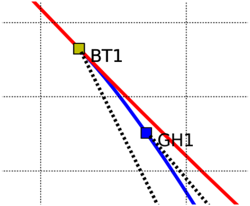


manifold behavior



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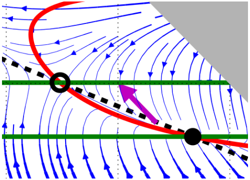

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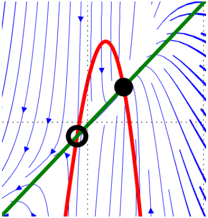

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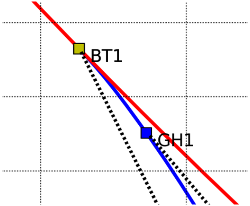

Regionalization
(networks, trade,
migration)

Source: `nationofchange.org`

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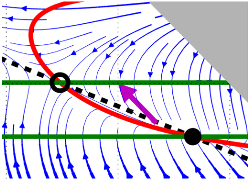

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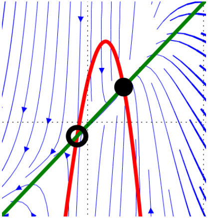

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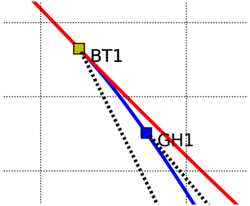

Regionalization
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Industrialization
(capital, fossils)

Source: `princetion.edu`

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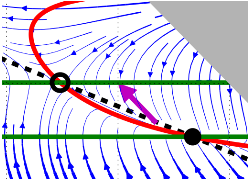

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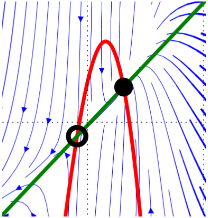

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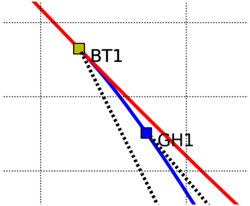


Regionalization
(networks, trade,
migration)

Source: `nationofchange.org`

Industrialization
(capital, fossils)

Source: `princetion.edu`

Green transition
(climate impacts,
renewables)

Source: `leeds.ac.uk`

Thank you
for your attention!

Overview model equations

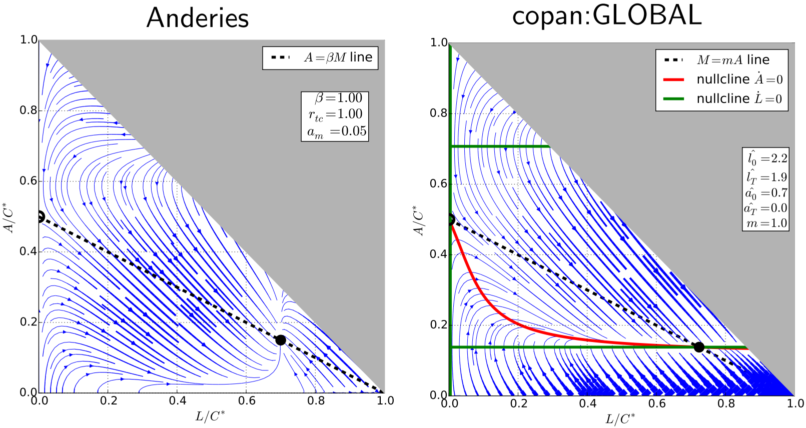
$$\dot{L} = L\left((l_0 - l_T A)\sqrt{A/\Sigma} - (a_0 + a_T A)\right) - bL^{\frac{1}{4}}P^{\frac{3}{4}} \tag{12}$$

$$\dot{A} = -\dot{L} + \delta(C^* - L - (1+m)A) \tag{13}$$

$$\dot{P} = P\left(\frac{2pW_p(yL^{\frac{1}{4}}P^{-\frac{1}{4}} + w_L\Sigma^{-1}L)}{W_p^2 + (yL^{\frac{1}{4}}P^{-\frac{1}{4}} + w_L\Sigma^{-1}L)^2} - \frac{q_0}{yL^{\frac{1}{4}}P^{-\frac{1}{4}} + w_L\Sigma^{-1}L}\right) \tag{14}$$

14 parameters, 5 independent units $\Rightarrow$ 9 dimensionless parameters

Parameter adjustment to Anderies model

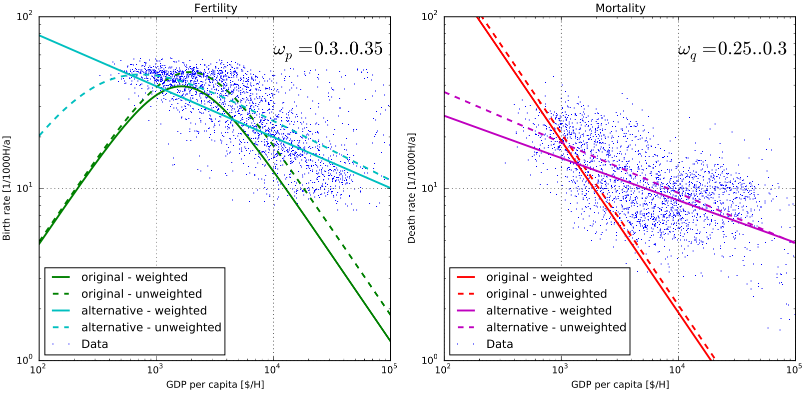


→ one globally attracting **"forest" state**

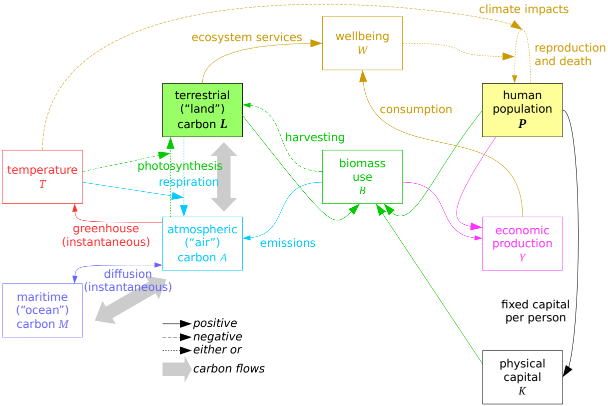
→ **topologically equivalent** phase portrait

Alternative model for population dynamics

$$\text{fertility} = \frac{2pWW_p^{\omega_p}}{W^{1+\omega_p} + W_p^{1+\omega_p}} \qquad \text{mortality} = \frac{q_0}{W^{\omega_q}} \tag{15}$$



Reduction to two dimensions



- assuming **instantaneous diffusion** makes A derived variable