The Globe as a Network

Geography and the Origins of the World Income Distribution

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What determines population, GDP of a location?

One answer: history of connections to other locations

- trade flows
- technology flows
- population growth

long-run global transport network $\approx$ **natural infrastructure**

- mountains, rivers, oceans
- water/land transport cost changes $\rightarrow$ changes in network

Question: How important is natural topography for

- growth patterns over last 1000 years?
- income per capita differences today?

Overview

Quantitative dynamic spatial model

- **the globe**: 17,000 discrete locations
- **two sectors**: Ancient and Modern
- **inputs**: transport network + $\underbrace{\text{local fundamentals}}_{\textit{(e.g. agricultural potential)}}$
- **outputs**: population growth + innovation + diffusion

Simulate global development

- $(-\infty\ ,\ 1000$ CE$]$: Malthusian steady state
- $(1000$ CE $,\ 2000$ CE$]$:
  - declining transport costs
  - endogenous growth takeoff

Roadmap for today (work in progress)

1. updated model
2. calibration to year 1000
3. some simple counterfactuals
4. an old version of full simulation

Related lit

- **Dynamic spatial models of development**
  - *Desmet, Nagy & Rossi-Hansberg (2018, JPE), Nagy (2017)*

- **Natural topography → development**
  - *Gallup, Sachs & Mellinger (1999), Henderson, Squires, Storeygard & Weil (2018, QJE)*

- **Transport infrastructure/trade → development**
  - *Donaldson & Hornbeck (2016, QJE), Redding & Venables (2004, JIE)*

- **Endogenous income & population growth**
  - *Galor & Weil (2000, AER), Hansen & Prescott (2002, AER)*

Desirable model characteristics

- rich enough to capture spatial interactions
- transparent
- few free parameters
- easily computable for thousands of locations

Model

n locations in the set $N \equiv \{1, 2, ..., n\}$

Two sectors: Ancient and Modern

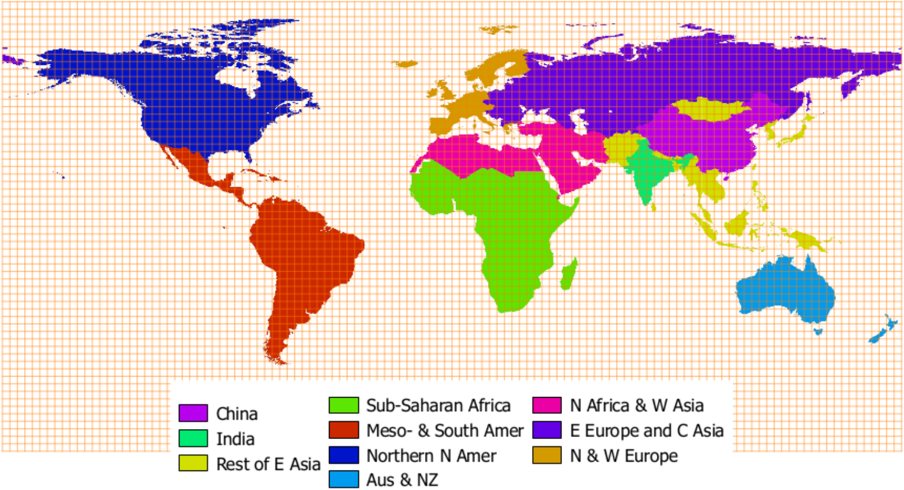
Exogenous:

- $\gamma_{ij} \in [0, 1]$, **bilateral transport costs**
- λ_i, **available land** - used in production, innovation
- α_i, **Ancient TFP**
- ω_i, **Modern TFP**

Endogenous:

- $m_i(t)$, **idea stocks**
  - boosts productivity of Modern sector
  - determined by innovation, diffusion
- $a_i(t)$, **idea stocks**, Ancient sector
  - determined by innovation, diffusion
  - slow growth, compared to Modern sector
- $x_i(t)$, **people**
  - produce things, invent ideas
  - determined by fertility

Major regions and 3° resolution grid



- 2,249 3° $\times$ 3° quadrangles ($\approx$300km $\times$ 300km)
  - *now: 17,300 1° $\times$ 1° quadrangles*

Consumers

- live one 25-year period, don't care about next generation

- **real income:** $y_i(t) = \omega_i \left(\int_0^A c_{i,l}(t)^\rho dl + \int_A^1 c_{i,l}(t)^\rho dl \right)^{\frac{1}{\rho}}$
  - goods indexed $l \in [0, 1]$
  - $[0, A]$ - Ancient goods
  - $(A, 1]$ - Modern goods
  - ω_i - "final goods sector" TFP

- **utility**: $u_i(t) = y_i(t) \left(\frac{x_i(t)}{\lambda_i} \right)^{-\zeta}$
  - $\zeta \geq 0$: strength of negative population externality

- **fertility rate:** increasing function of utility $u_i(t)$

Armington-style goods

Normalize $\sum_{i \in N} \lambda_i = 1$.

Each little bit of land produces a unique ancient, modern good

In a location i:

- a mass $A\lambda_i$ of ancient varieties
- a mass $(1-A)\lambda_i$ of modern varieties

Why not Eaton-Kortum?

- Armington allows greater specialization across locations without explicity modeling additional sectors
- Because goods are an input to innovation, the two assumptions are not isomorphic

Firms

Ancient, good k in location i:

$$q_{i,k} = \alpha_i a_i(t) \hat{s}_{i,k} \left(b_{i,k}^{\eta} l_{i,k}^{1-\eta-\sigma} \left(\int_0^1 z_{i,k,l}^{\rho} dl \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1}{2}}$$

Modern, good k in location i:

$$q_{i,k} = m_i(t) \hat{s}_{i,k} \left(b_{i,k}^{\eta} l_{i,k}^{1-\eta-\sigma} \left(\int_0^1 z_{i,k,l}^{\rho} dl \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1}{2}}$$

- $b_{i,k}$: labor employed in production
- $l_{i,k}$: land employed in production
- $z_{i,k,l}$: good l employed in production
- $\hat{s}_{i,k}$: current innovaiton

Innovation

Current innovation, boosts current efficiency:

$$\hat{s}_{i,k} = s_{i,k} \left(b_{i,k,I}^{\eta} l_{i,k,I}^{1-\eta-\sigma} \left(\int_0^1 z_{i,k,l,I}^{\rho} dl \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1}{2}},$$

- $b_{i,k,I}$: labor employed in innovation
- $l_{i,k,I}$: land employed in innovation
- $z_{i,k,l,I}$: good l employed in innovation

New ideas generated as an externality.

Production equilibrium

- production $\times$ innovation $\rightarrow$ constant returns to scale
- equilibrium unit (average) cost of production P_i
- cost/competitive price of producing, sending good l from i to j:

$$p_{i,l} = \frac{P_i}{\gamma_{ij}^{\kappa}\alpha_i a_i}, \text{ ancient sector} \qquad p_{i,l} = \frac{P_i}{\gamma_{ij} m_i}, \text{ modern sector}$$

"Market access" (aka, an inverse price index):

$$\begin{aligned}\mathbb{M}_i &\equiv \int_0^1 \left(\frac{P_i}{p_{i,l}}\right)^{\frac{\rho}{1-\rho}} dl \\ &= A \sum_{j\in N} \lambda_j \left(\frac{P_i}{P_j}\gamma_{ji}^{\kappa}\alpha_j a_j\right)^{\frac{\rho}{1-\rho}} + (1-A)\sum_{j\in N}\lambda_j\left(\frac{P_i}{P_j}\gamma_{ji} m_j\right)^{\frac{\rho}{1-\rho}}.\end{aligned}$$

Evolution of technology

Integrating over all firms' efforts, total ideas generated in location i:

$$\left[\frac{\sigma^{\frac{\sigma}{1-\sigma}} x_i^{\frac{\eta}{1-\sigma}} \lambda_i^{1-\frac{\eta}{1-\sigma}} \mathbb{M}_i^{\frac{1-\rho}{\rho}\frac{\sigma}{1-\sigma}}}{\lambda_i}\right]^{\phi} = \left[\sigma^{\frac{\sigma}{1-\sigma}} \left(\frac{x_i}{\lambda_i}\right)^{\frac{\eta}{1-\sigma}} \mathbb{M}_i^{\frac{1-\rho}{\rho}\frac{\sigma}{1-\sigma}}\right]^{\phi}$$

Modern sector idea stock law of motion:

$$m_i(t) = (1-\delta)m_i(t-1) + \left[\sigma^{\frac{\sigma}{1-\sigma}} \left(\frac{x_i(t-1)}{\lambda_i}\right)^{\frac{\eta}{1-\sigma}} \mathbb{M}_i(t-1)^{\frac{1-\rho}{\rho}\frac{\sigma}{1-\sigma}}\right]^{\phi}$$

- $\phi > 0$, $\delta \in [0,1]$
- *implicit diffusion:* access to cheap traded goods increases innovation
- *diminishing returns:* if population doesn't grow, neither do ideas

Spillovers into ancient sector

$$a_i(t) = (1-\delta)a_i(t-1) + \left[\sigma^{\frac{\sigma}{1-\sigma}} \left(\frac{x_i(t-1)}{\lambda_i}\right)^{\frac{\eta}{1-\sigma}-\psi} \mathbb{M}_i(t-1)^{\frac{1-\rho}{\rho}\frac{\sigma}{1-\sigma}}\right]^{\phi}$$

- $\psi > 0 \implies$ slower growth rate than $m_i(t)$

Four simplifying assumptions

1. Ancient sector is non-tradable.
   - $\kappa = \infty$
2. Long-run effect of market access on terms of trade (-) and technology level (+) balance out.
   - $\phi = \frac{\rho - \sigma}{\sigma}$
3. Long-run elasticity of Ancient component of market access to *own* population same as Modern.
   - $\psi = \frac{\eta\rho}{(\rho-\sigma)(1+\rho)}$
4. For a given set of fundamentals, utility $u_i(t)$ does not grow in the long run.
   - $\zeta = \eta\left[\frac{\rho}{\sigma(1-\rho)} - \frac{\sigma}{1-\sigma}\right] - 1$

Balanced growth path utility

$$u_i^\rho = \frac{\overbrace{A_i\Omega_i}^{\text{Ancient}} + \overbrace{\Omega_i \sum_{j \in N} G_{ji}\lambda_j \left(x_j/\lambda_j\right)^b}^{\text{Modern}}}{\underbrace{\left(x_i/\lambda_i\right)^b}_{\text{congestion}}}$$

$$A_i \equiv \alpha_i \frac{A}{1-A}$$

$$\Omega_i \equiv \omega_i^\rho (1-A)(1-\sigma)^\rho \sigma^{\frac{\rho^2}{1-\rho}}$$

$$G_{ji} \equiv \gamma_{ij}^{\frac{\rho^2}{1-\rho^2}} \gamma_{ji}^{\frac{\rho}{1-\rho^2}}$$

$$b \equiv \frac{\eta}{\sigma} \frac{\rho^2}{1-\rho^2}$$

fertility increases in $u_i \implies$ utility equalization, $u_i = \bar{u}$

Steady state/BGP

spillovers $\underset{n\times n}{\mathbf{\Omega G}}$	agriculture $\underset{n\times 1}{\mathbf{A}}$	$\bar{U}_0 \equiv U$ such that pop. growth $= 0$

Malthusian steady-state allocation: $\mathbf{x}, \bar{u} = \bar{U}_0$

$$\underset{n\times 1}{\mathbf{x}} = \overbrace{\left[\bar{U}_0 \cdot \underset{n\times n}{\mathbf{I}} - \underset{n\times n}{\mathbf{\Omega}} \cdot \underset{n\times n}{\mathbf{G}}\right]^{-1}}^{\text{geom. series of 1}^{\text{st}}\text{, 2}^{\text{nd}}\text{, ... -order spillovers}} \cdot \underset{n\times 1}{\mathbf{A}}$$

BGP allocation: $\tilde{\mathbf{x}}, \bar{u} = \tilde{U}$

- $\tilde{U}$: largest eigenvalue of $\mathbf{\Omega G}$
- $\tilde{\mathbf{x}}$: eigenvector associated with $\bar{U}$

Nec. and suff. condition: BGP $\iff \tilde{U} > \bar{U}_0$

- transport costs low enough $\rightarrow$ spillovers strong enough

Year 1000 calibration

Transport costs:

- find least cost paths given rivers, oceans, ruggedness
- cost over land, water same as 14th C. England *(Masschaele 1993)*

Ancient sector TFP: interpreted as agriculture

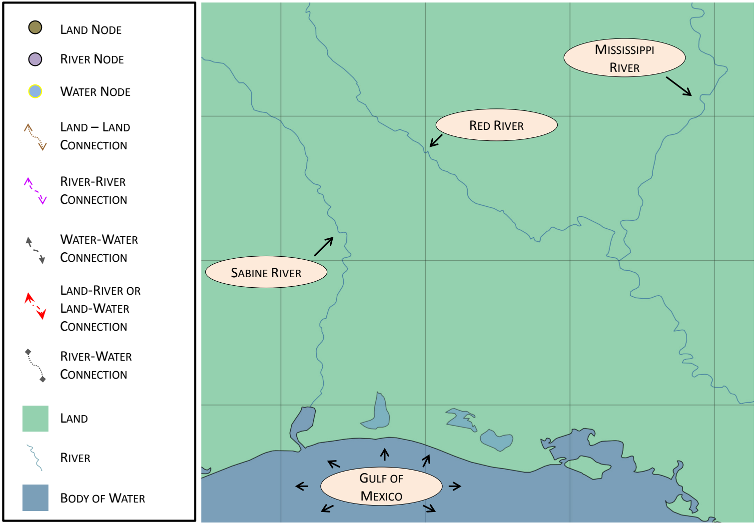
- parameterized $\leftarrow$ plausibly exogenous geological characteristics

Model parameters:

1. level of mean productivity of agriculture
2. level of mean productivity of modern sector
3. level of mean cost of distance
4. elasticity of substitution between goods
   $\longrightarrow$ dispersion of population density, ceteris paribus

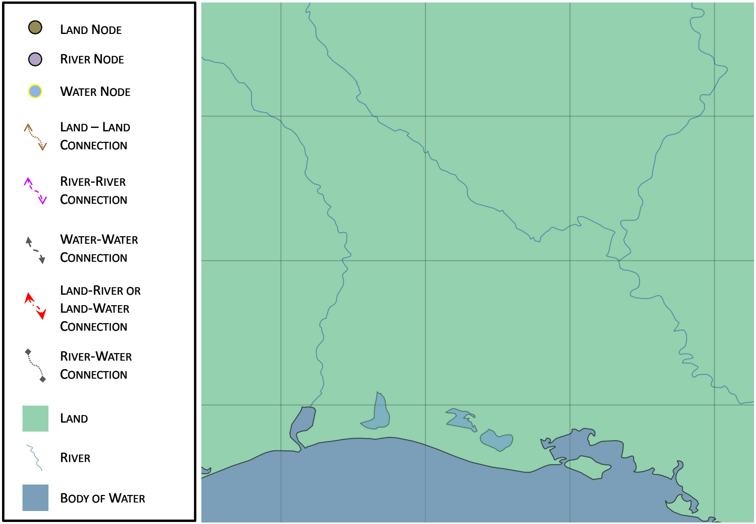
Agricultural, model params calibrated to explain year 1000 pop. density

Transport costs $\leftarrow$ data



1. Given N, calculate ***lowest-cost paths*** τ^*_{ij} for $\forall i, j \in N$.
2. Following Allen and Arkolakis (2014), set $\boldsymbol{\gamma}_{ij} = \exp(-\tau^*_{ij})$.

Transport costs ← data



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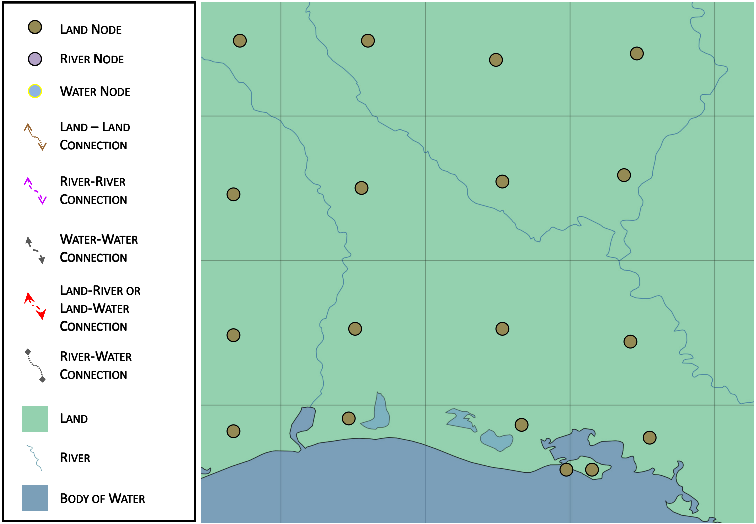

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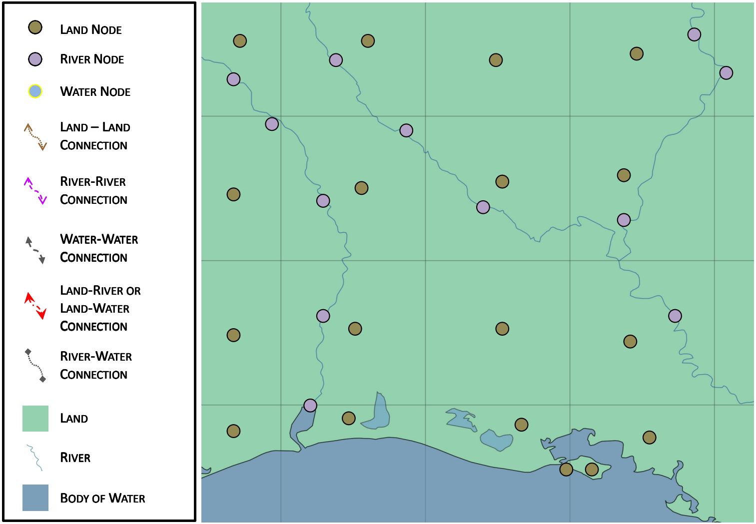

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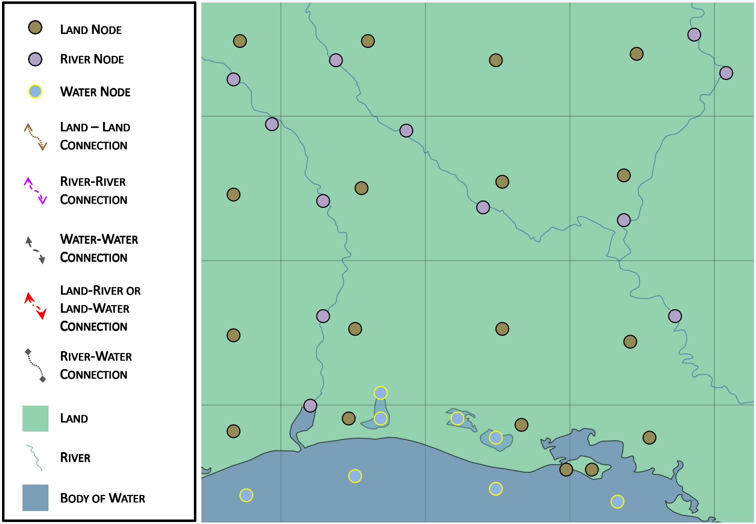

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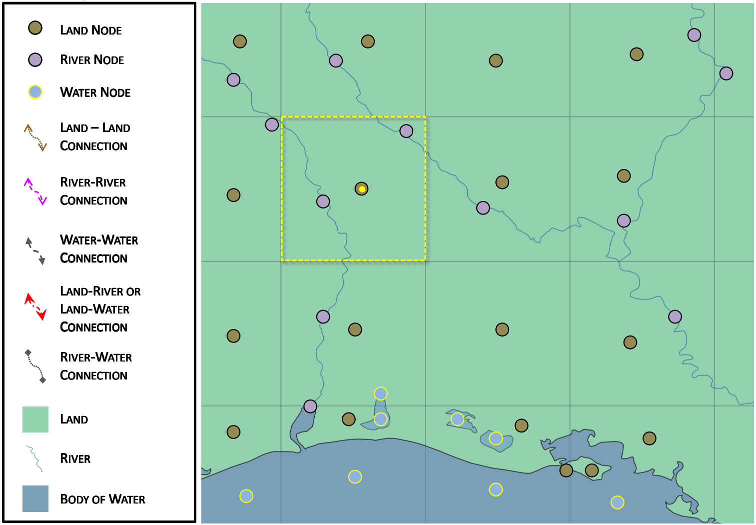

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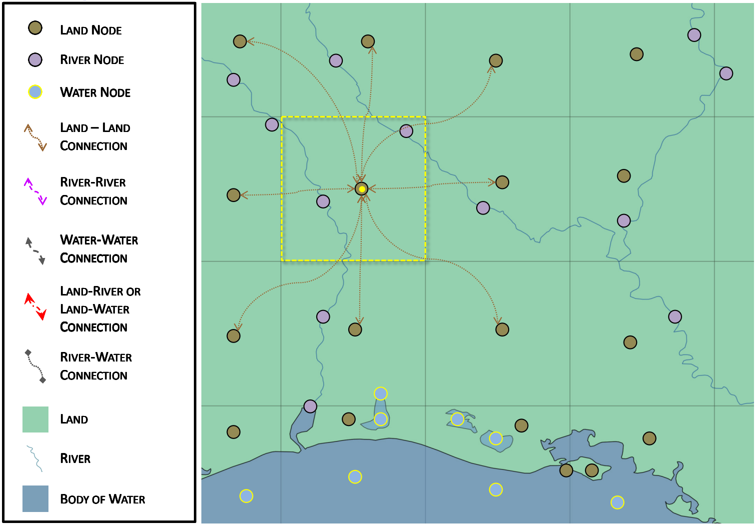

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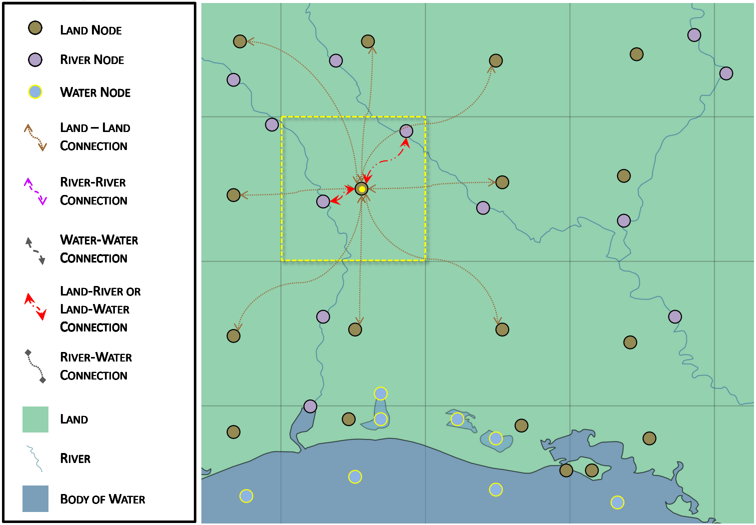

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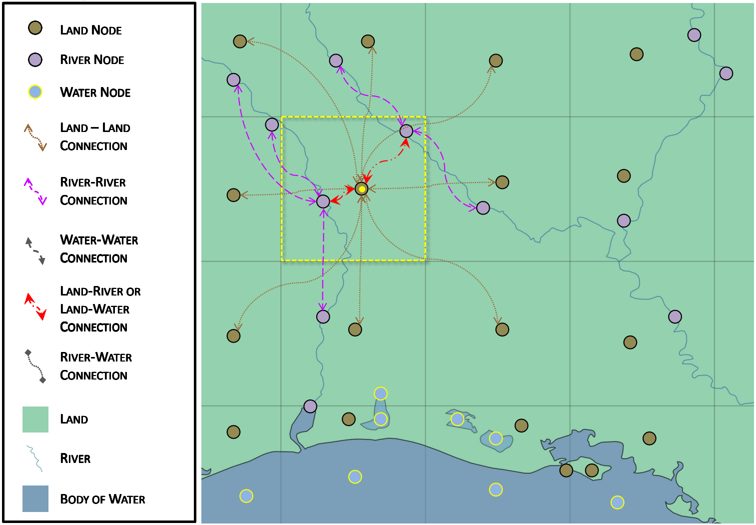

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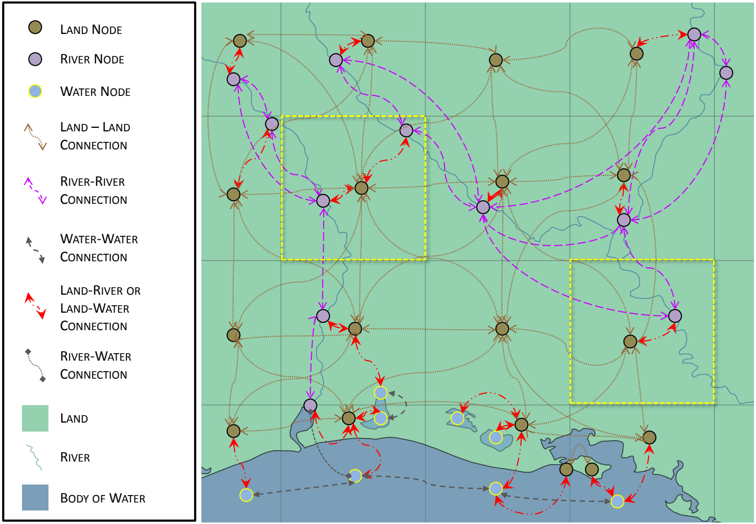

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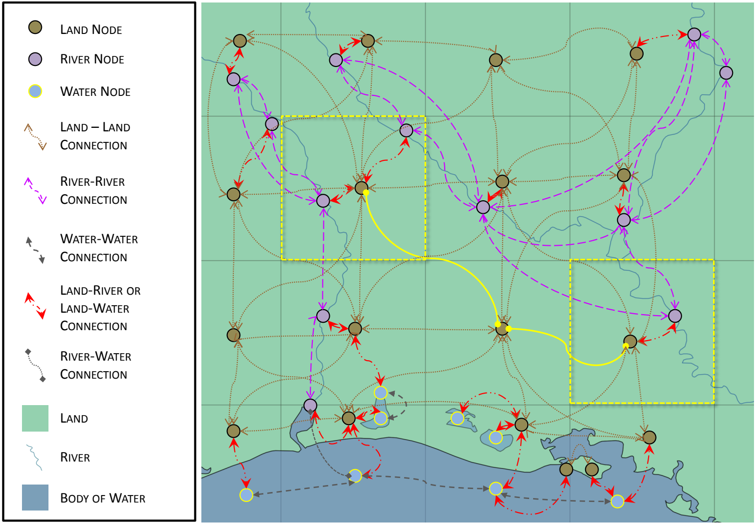

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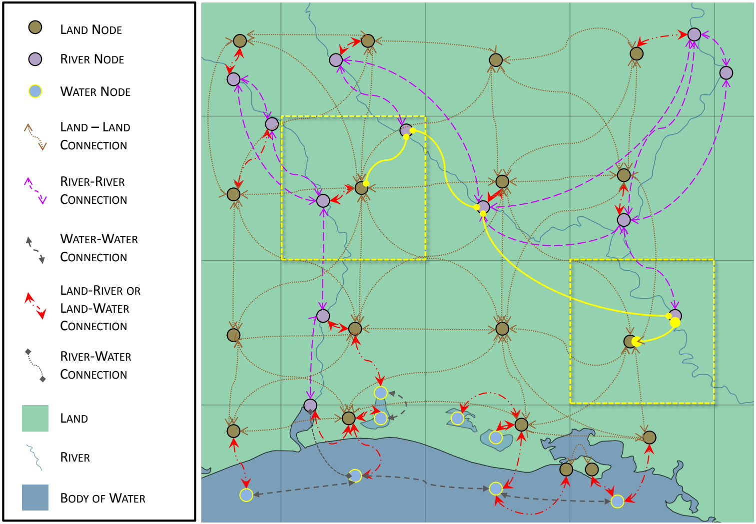

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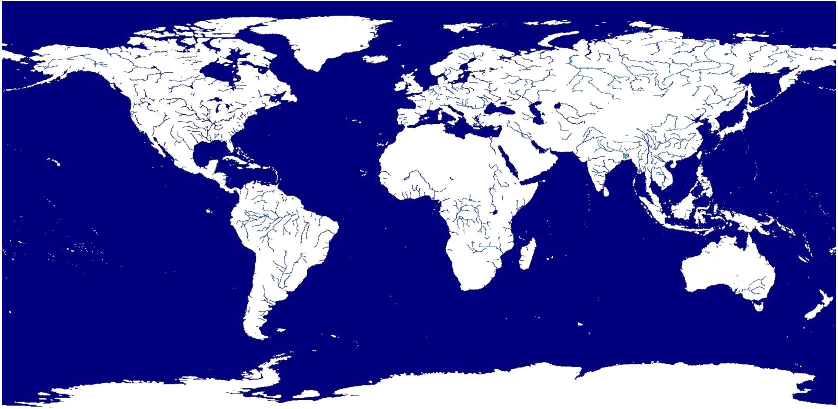
Topography data

Rivers



Data sources

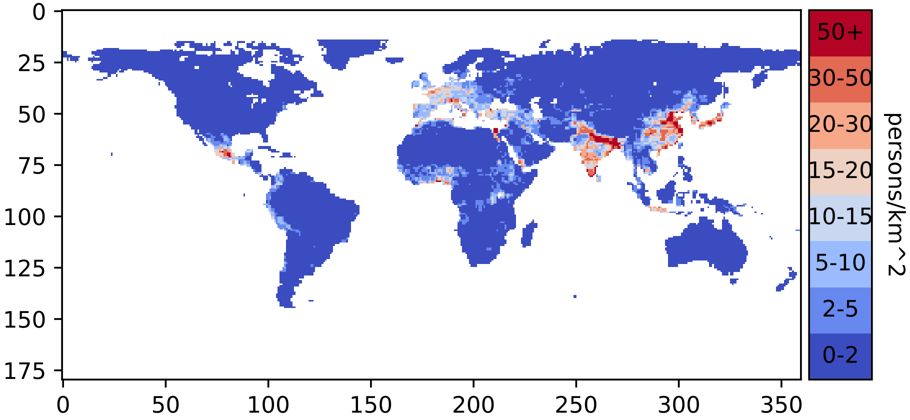
Model inputs:

- **Geology, climate:**
  - FAO Harmonized Soil Database 1.2, *Fischer, et al (2008)*
  - USDA Natural Resources Conservation Center, World Soils Database (2005)
  - NDVI: NASA LP DAAC (2016), Feb 2000 - Jan 2016
- **Topographical features:**
  - location of land, bodies of water $\leftarrow$ Naturalearth database
  - location and size classification of rivers $\leftarrow$ Naturalearth database
  - Terrain Ruggedness Index $\leftarrow$ *Riley, DeGloria, and Elliot (1999)*
  - mean wave heights $\leftarrow$ *Barstow et al. (2009)*

Model outputs:

- **Population:** HYDE 3.1 Database
  - *Goldewijk, Beusen & Janssen (2010)*
  - population in each $\frac{1}{12}^\circ$ by $\frac{1}{12}^\circ$ quadrangle, 10000 BCE - 2000 CE

Population per sq. km, 1000 CE (**Data**)



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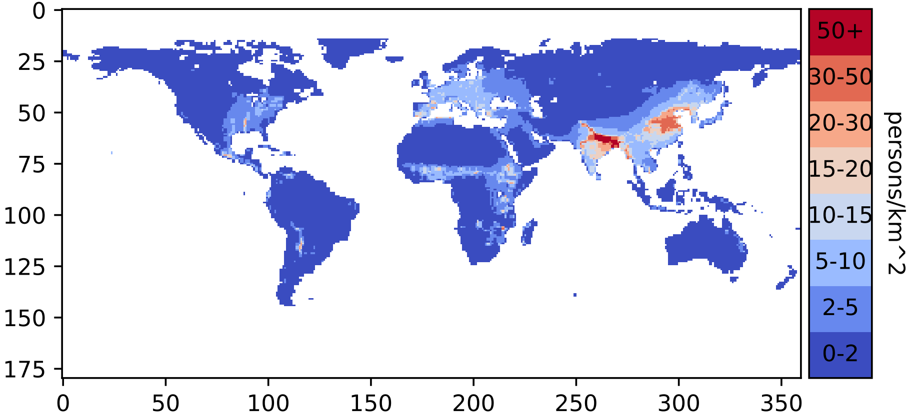
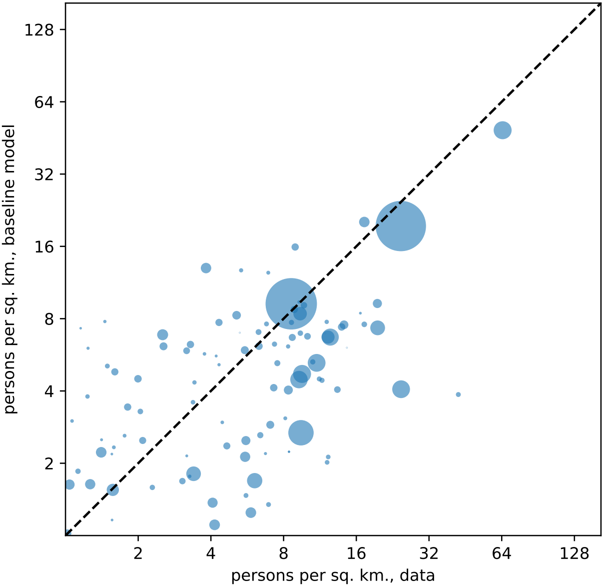


$\mathbf{R^2}$: 41.7% **Corr.:** 64.6%

Population per sq. km, modern country boundaries



$\mathbf{R^2}$: 53.1% **Corr.:** 75.3%

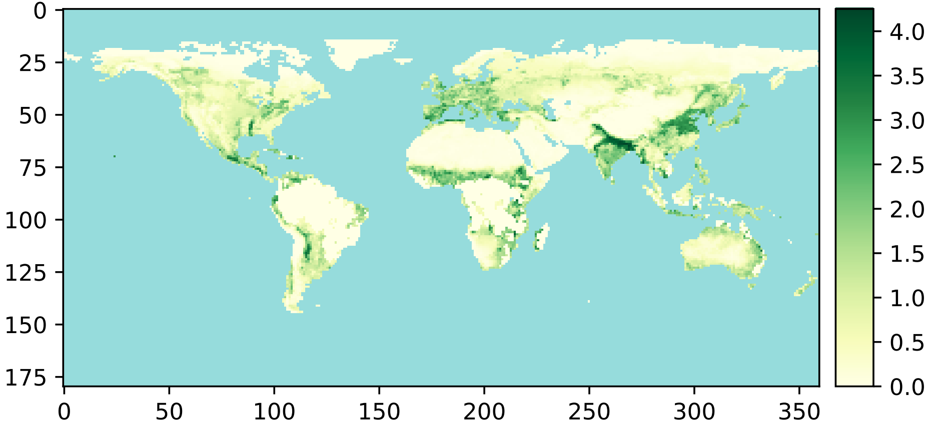
Calibrated model parameters

- ρ: 0.7187
- mean α_i: 0.6412
- mean (uniform) ω_i: 0.00027
- distance multiplier: 0.4144

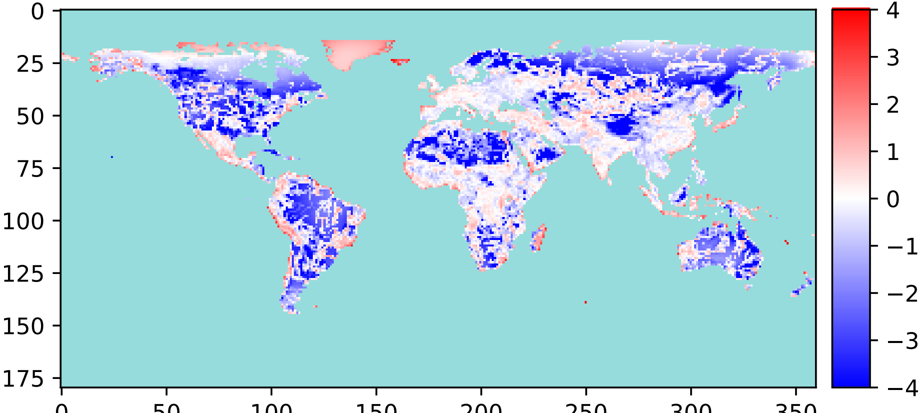
Normalized:

- $\rho^2 = \sigma$ *(zero growth in Ancient sector ideas)*
- $1 - \eta - \sigma = 0.2$ *(land share = 20%)*

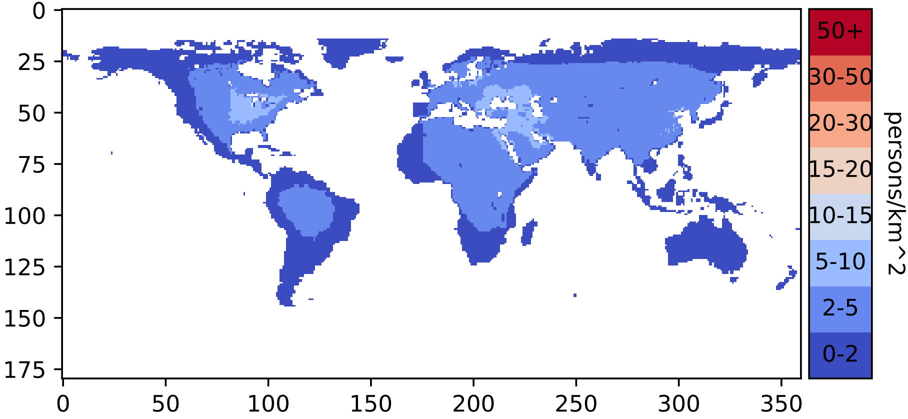
Calibrated Ancient sector TFP



Wedges implied to match year 1000 population

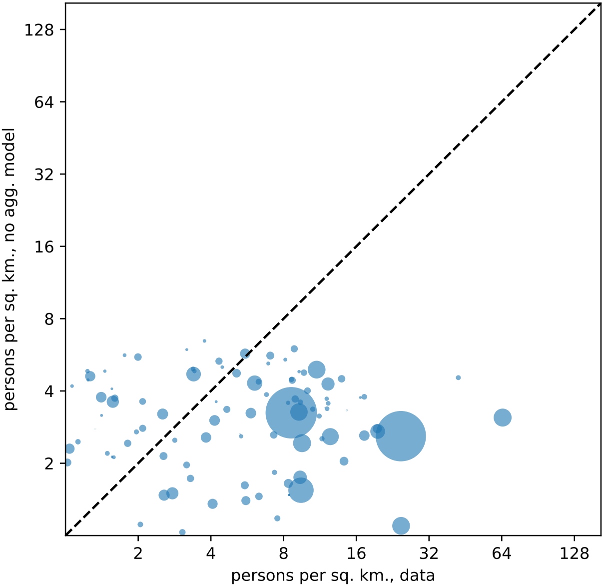


Pop. per sq. km, 1000 CE (**uniform geology/climate**)



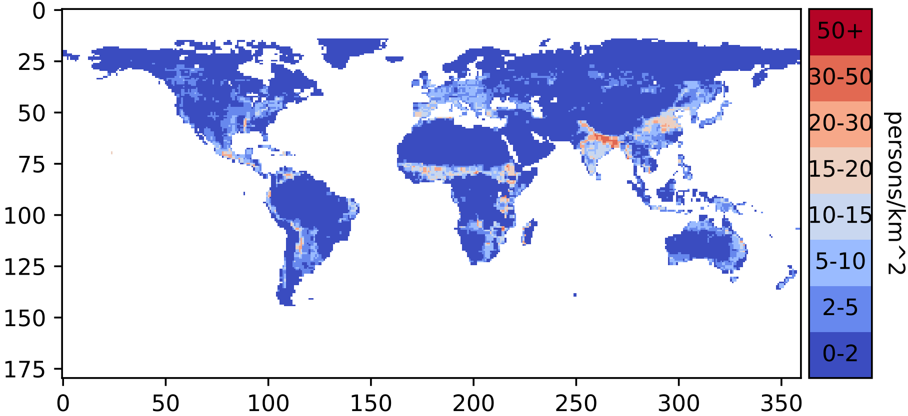
$\mathbf{R^2}$: 1.2% **Corr.:** 12.6%

Pop. per sq. km, modern boundaries, unif. climate



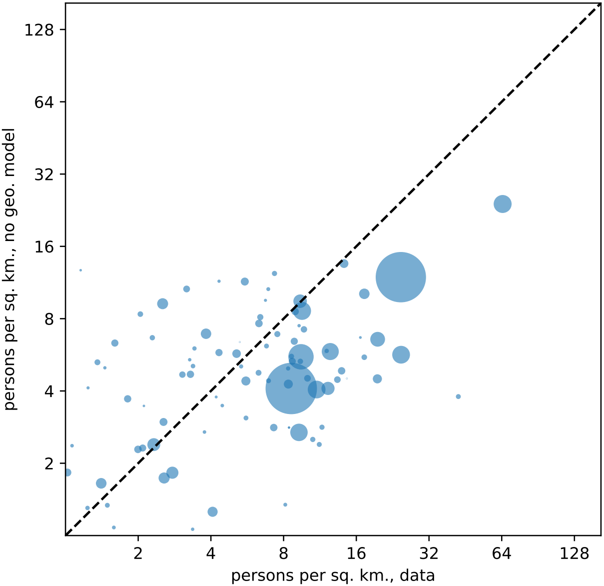
$\mathbf{R^2}$: -6.4% **Corr.:** 23.2%

Population per sq. km, 1000 CE (**uniform geography**)



$\mathbf{R^2}$: 23.2% **Corr.:** 48.4%

Pop. per sq. km, modern boundaries, unif. geography



$\mathbf{R^2}$: 26.2% **Corr.:** 55.1%

Quantitative exercise

currently being revised

$-\infty \to$ 1000 CE:

- transport costs constant, *Malthusian Steady State*

1000 CE $\to$ 2000 CE

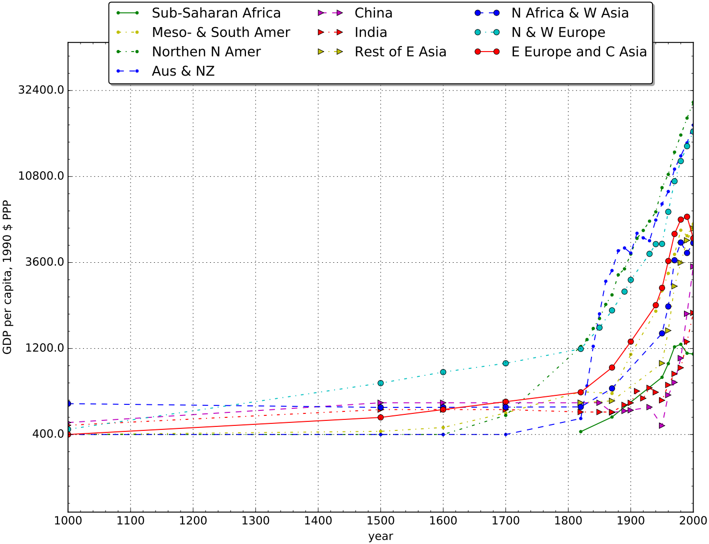
- transport costs falling
- population, technology *grows endogenously*

A_i: "agricultural potential"

- taken from ecology literature *(Ramankutty et al. 2012)*

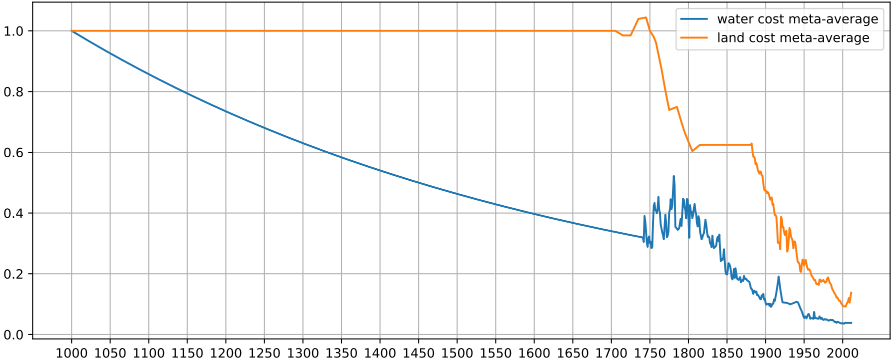
Ω_i: same everywhere

Evolution of income per capita across the world



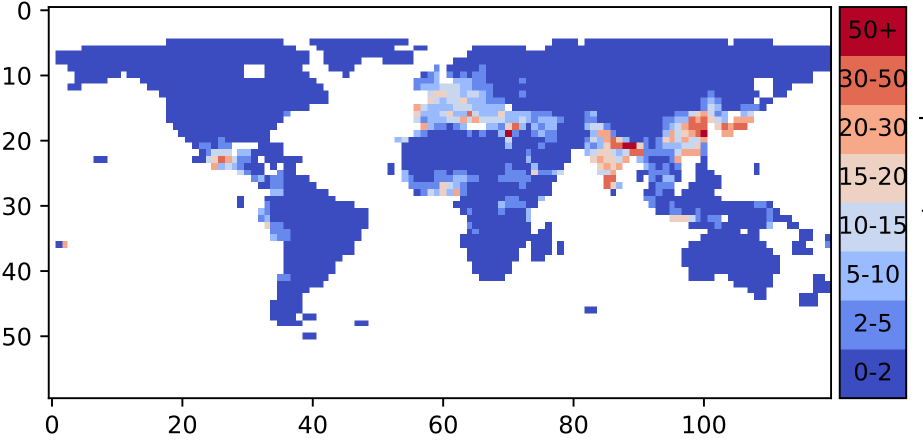
- **Source:** Maddison Database 2010
- **Population data:** HYDE 3.1 Database

Falling transport costs

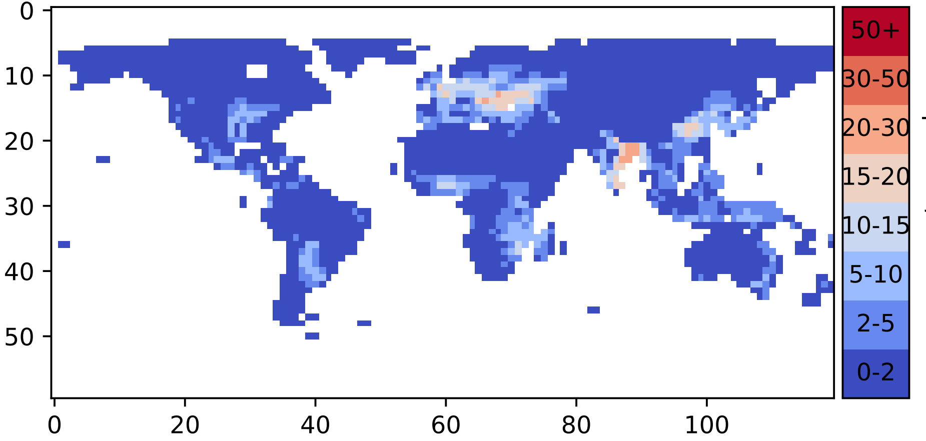


- calculated from mean rate-of-change across available fragments of data
- **initial transport costs:** 14^{th} century Britain, *Masschaele (1993)*
- same initial costs, same reductions, everywhere in the world

Population per sq. km, 1000 CE (**Data**)

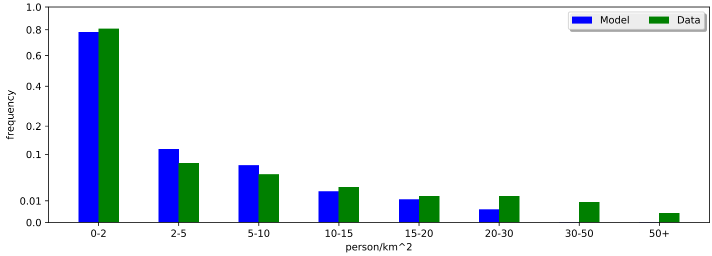


Population per sq. km, 1000 CE (**Model**)

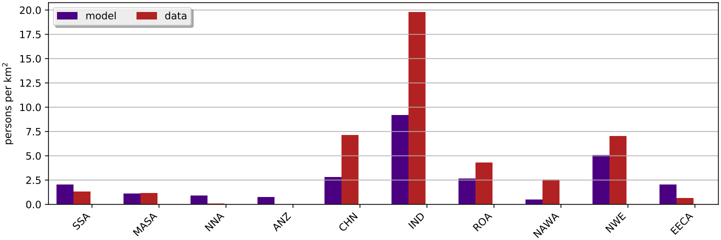


Results, 1000 CE

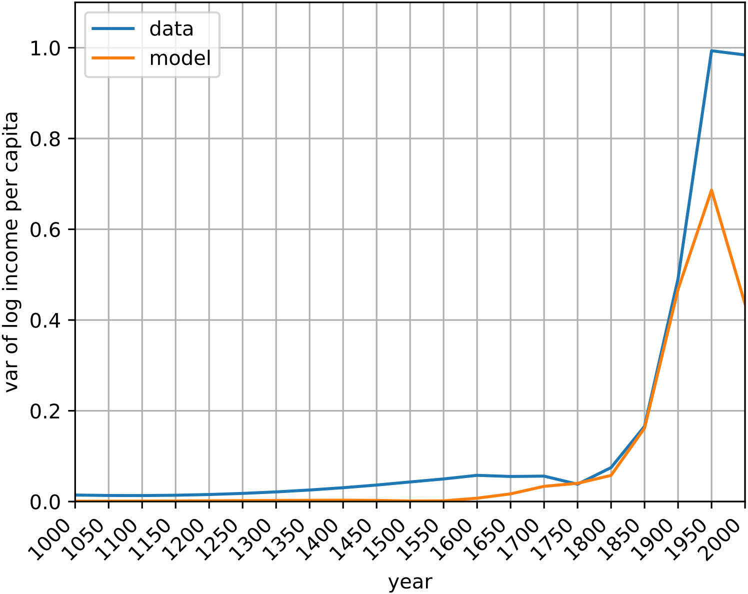
3° × 3° grid squares: **R^2:** .31 **weighted corr:** .57



regions: **R^2:** .55 **weighted corr:** .88

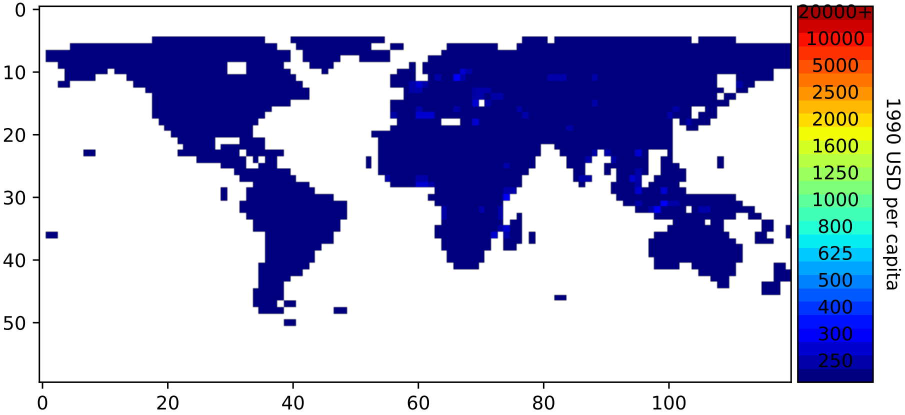


Evolution of income dispersion

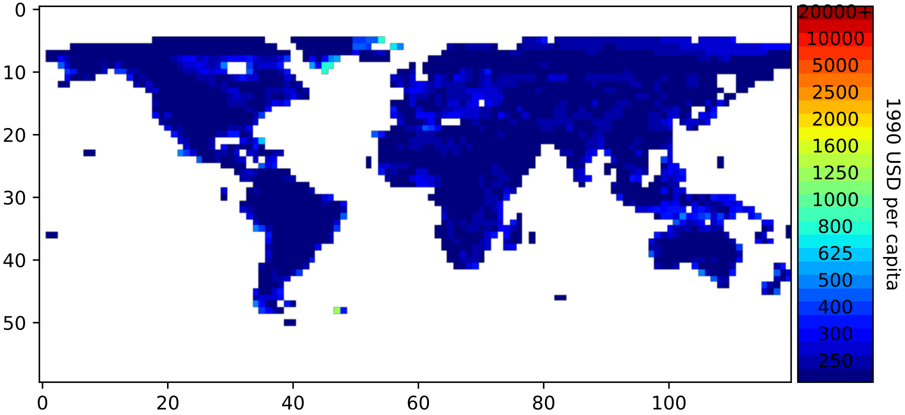


(world population, world income)

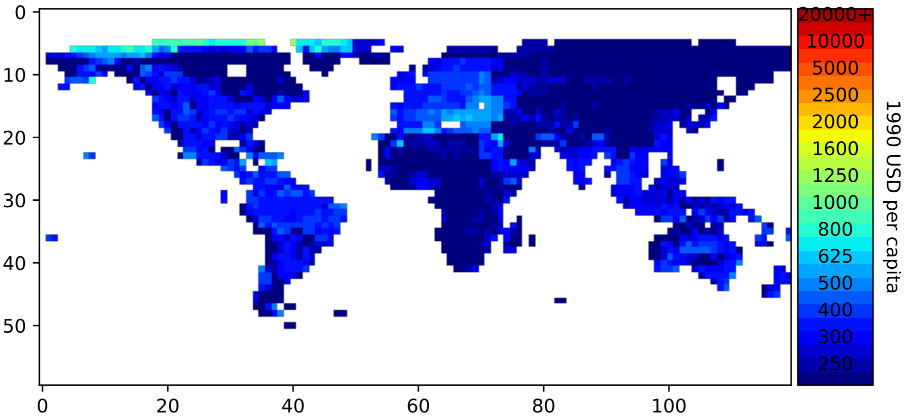
Predicted real income, 1000 CE



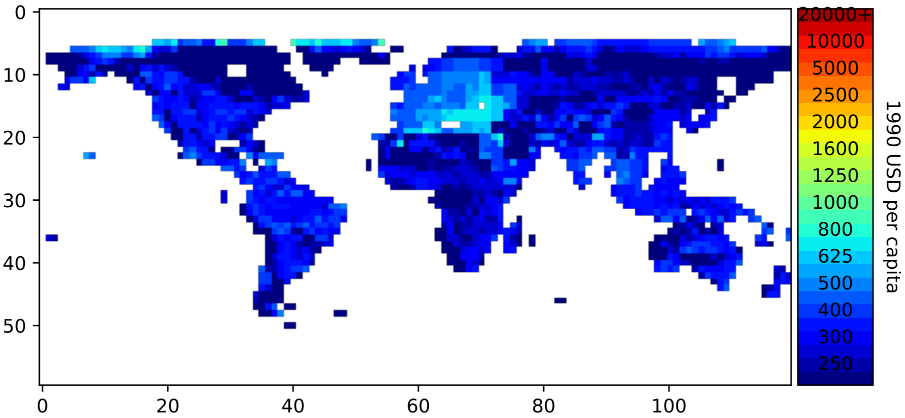
Predicted real income, 1500 CE



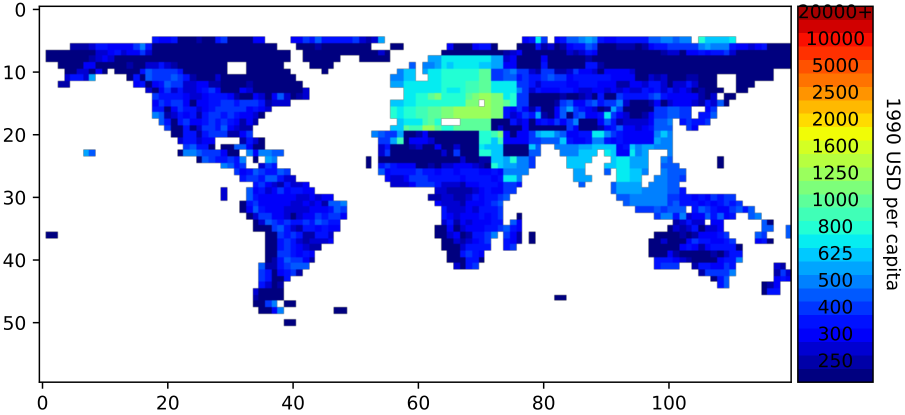
Predicted real income, 1750 CE



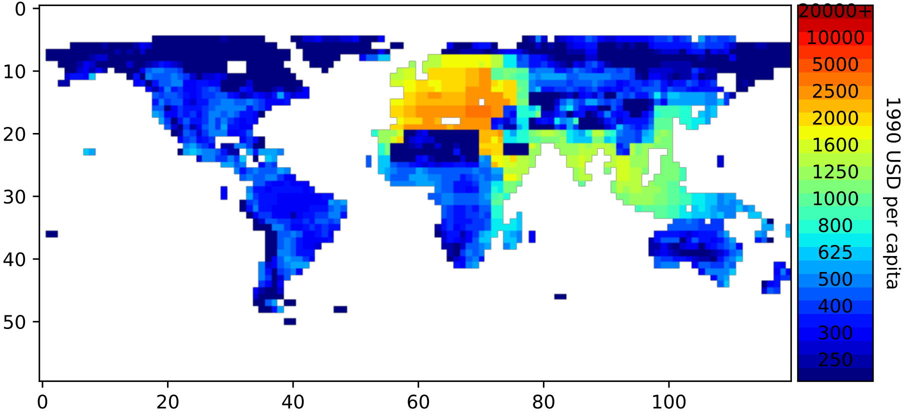
Predicted real income, 1800 CE



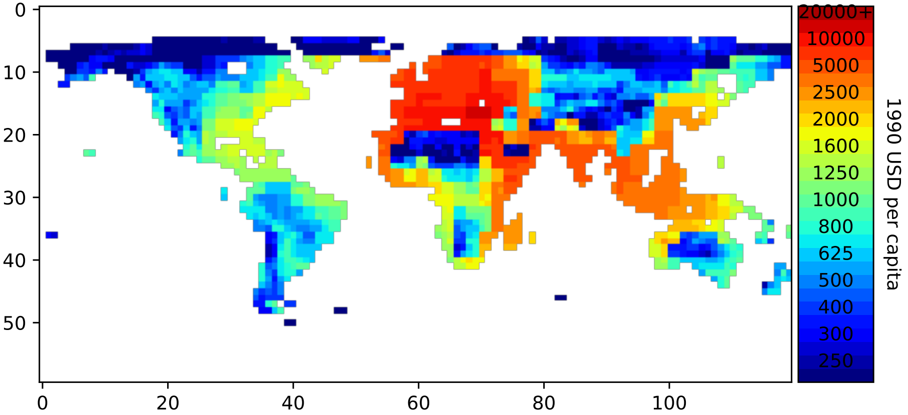
Predicted real income, 1850 CE



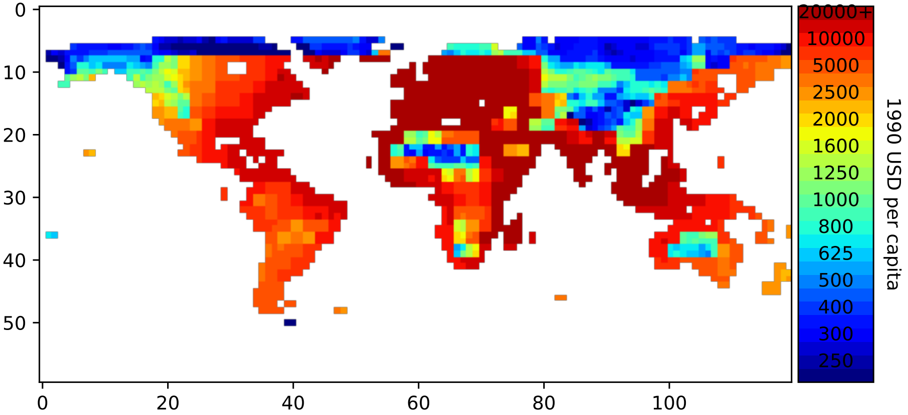
Predicted real income, 1900 CE



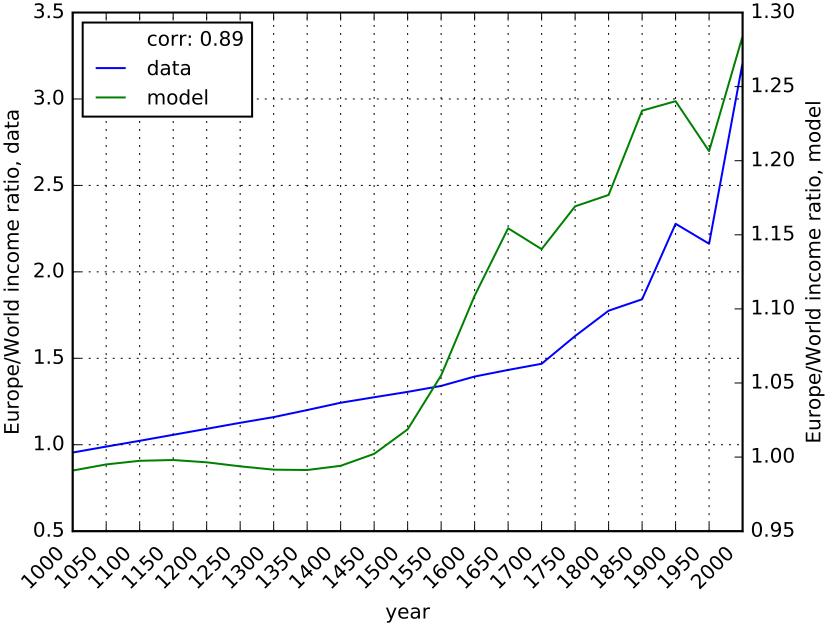
Predicted real income, 1950 CE



Predicted real income, 2000 CE



Income: Europe/World



Conclusion

- topography + agriculture accounts well for population and income in
  - ancient times
  - early modern era
- accounts less well for 20th-century developments

Thank you