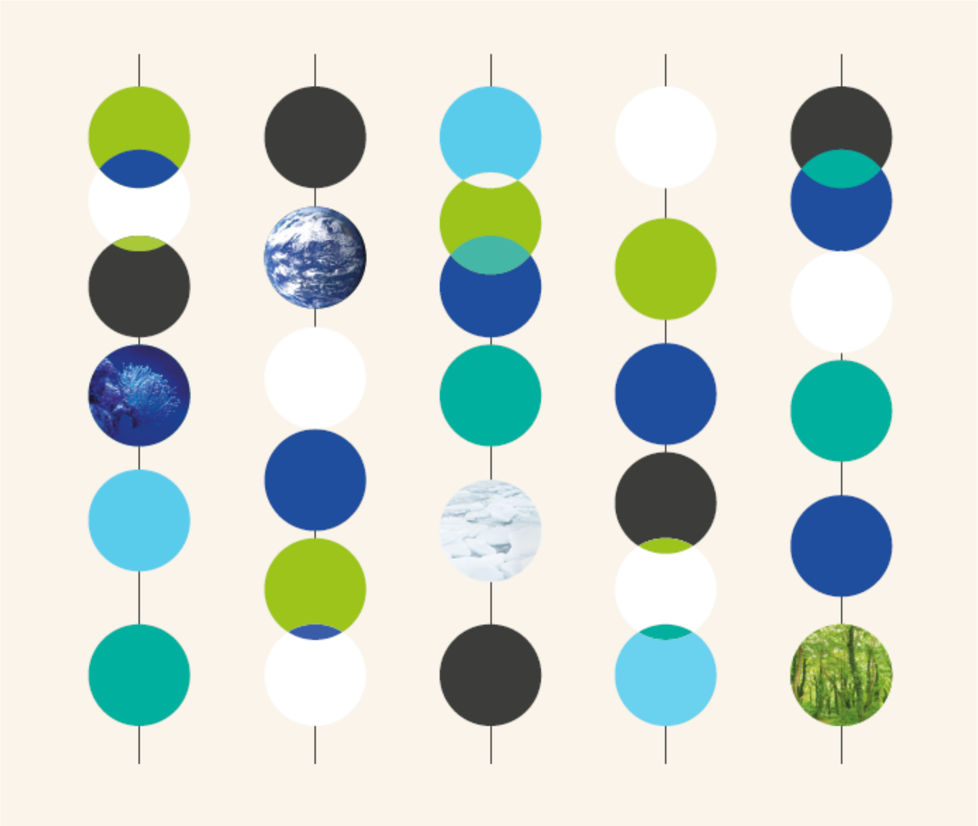
Global Earth-Economy Modeling



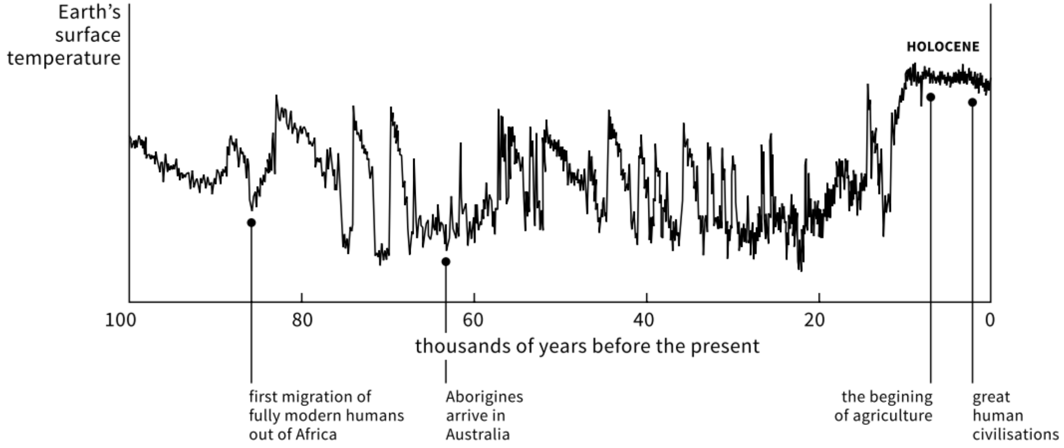
Justin A. Johnson, based on work with co-authors Uris Baldos, Thomas Hertel, Stephen Polasky, Erwin Corong, Giovanni Ruta, Raffaello Cervigni, and many others.

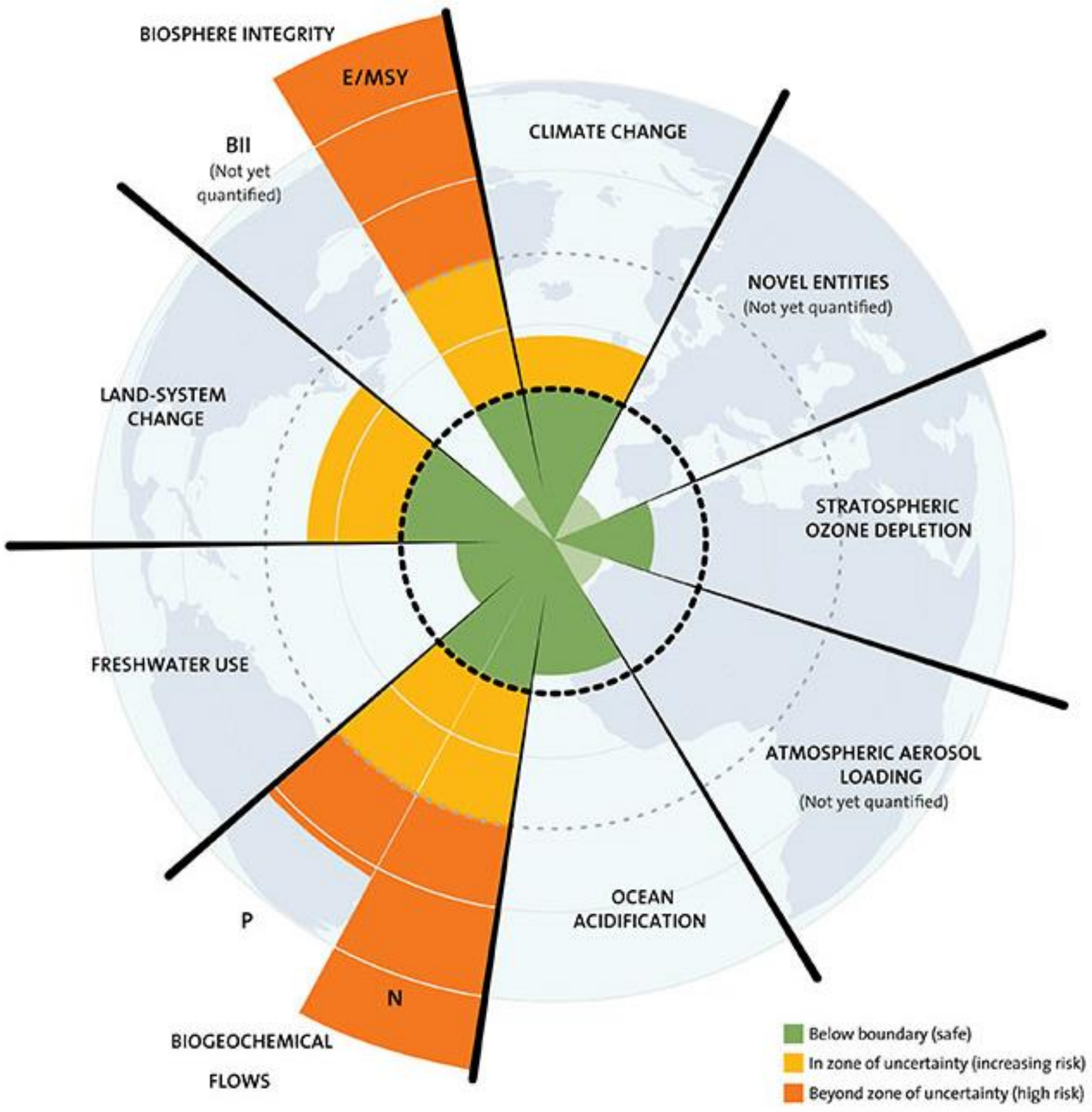
Overview

- Introduction and context of why we need new models
- What is Earth-Economy modelling?
- Introducing one Earth-Economy model: GTAP-InVEST
- Three important methods points
- Five key results that have emerged
- Tomorrow: Preview and discuss new research directions

Flying blind

- We are currently flying blind in the Anthropocene
  - We have no adequate navigational system to help guide us to sustainable development

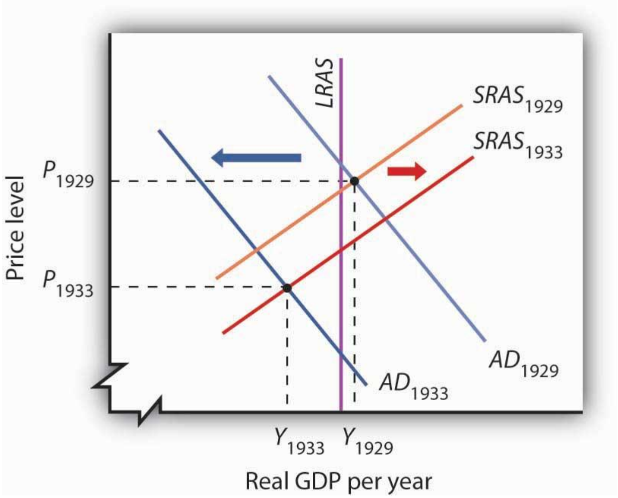




The past provides perspective

- We've faced huge challenges before like the great depression
  - Economics built tools to navigate out of the depression
    - System of national accounts (SNA) responsible for GDP
    - Computable general equilibrium (CGE) models

The Great Depression



Economics created **navigational tools** that helped "build back" from the depression

Success of economics

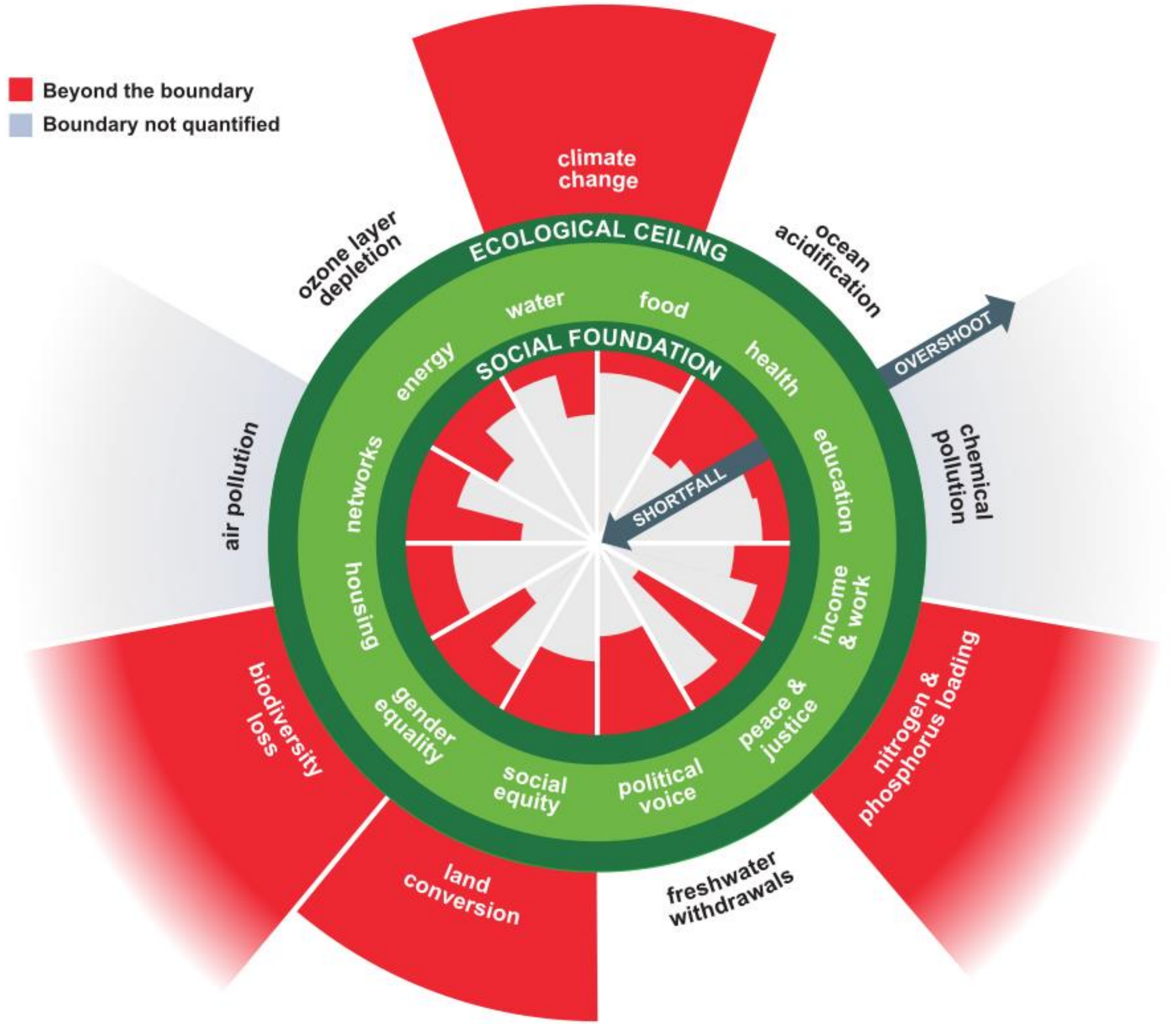
- Economics did phenomenally well at improving physical consumption and the wellbeing that comes from that
  - Huge poverty reductions in U.S. and worldwide
  - But success here raised new challenges (*over*-consumption instead of under-consumption)
- Economics has a massive blind spot – the economy is embedded in the biosphere
  - Challenges now are global, interconnected and based on common resources (illustrated well by Covid).
  - We need a broader model. A more *general* general equilibrium.

Doughnut Economics

- Kate Raworth (2017) book
  - Combined planetary boundaries framework with socioeconomic dimensions of wellbeing.
- Quantified both the ceiling and the floor

Wonderful but limited framework

Doesn't answer "What policies we should pursue"

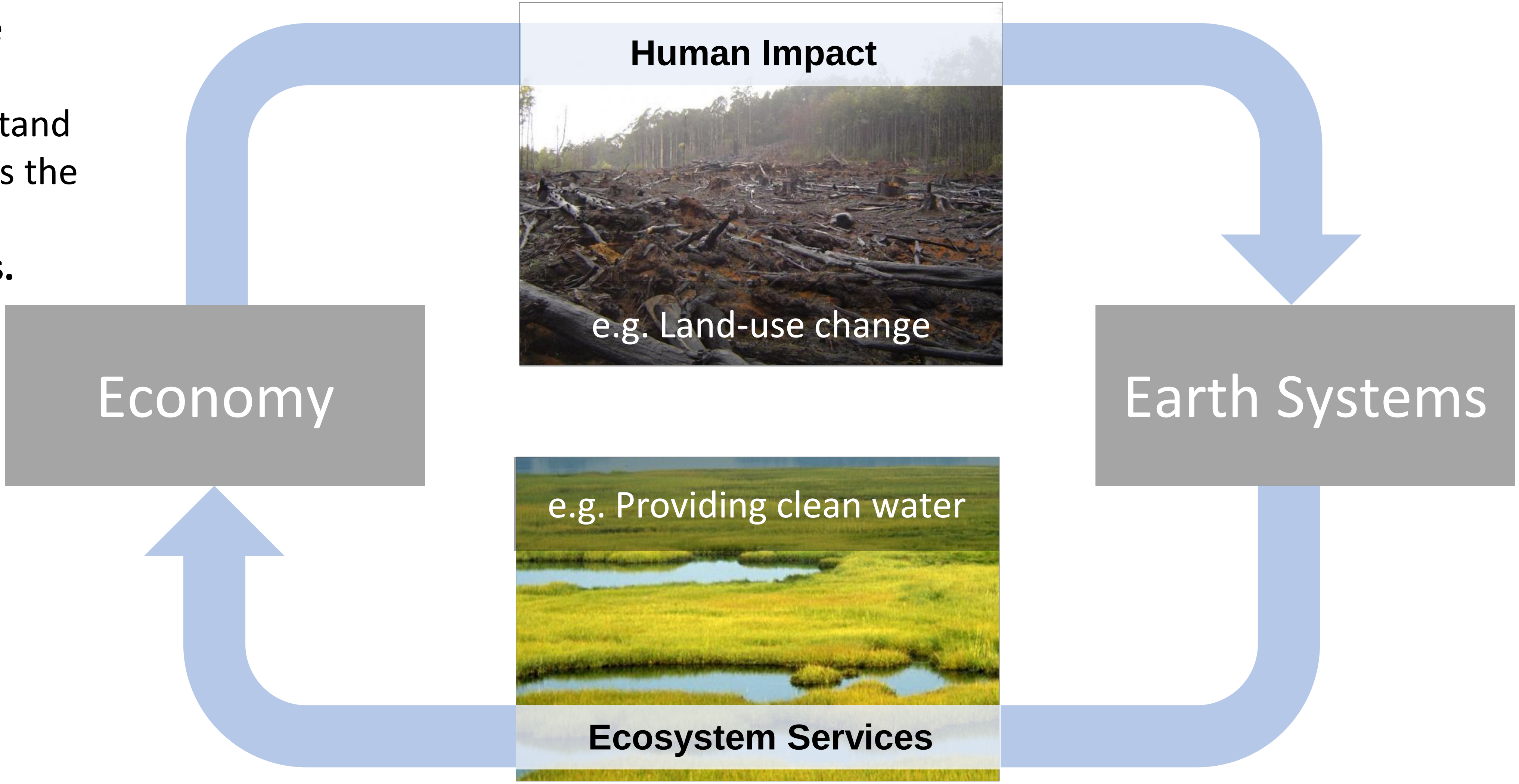


Economics has an undue focus on GDP

- Economics to date obsesses over GDP, a powerful indicator of a country's production
  - Has little meaning in terms of sustainability.
- But, at least etymologically, economics is the study of our home, which should include the Earth on which we live.
  - This is an old intuition: Classical economists held that labor, (produced) capital, and **land**, were the basic inputs of the economy.
- Many approaches are extending GDP to fix this error
  - Comprehensive wealth, inclusive GDP, GEP (gross ecosystem product), and new systems of accounts that include nature, such as the United Nation's system of Environmental Economic Accounting (SEEA)

Sustainability cannot consider Earth and the economy as separate. We need integrated "**Earth-Economy**" modeling.

- Prior focus was on how humans impact the environment.
- We need to understand environment affects the economy through **ecosystem services.**



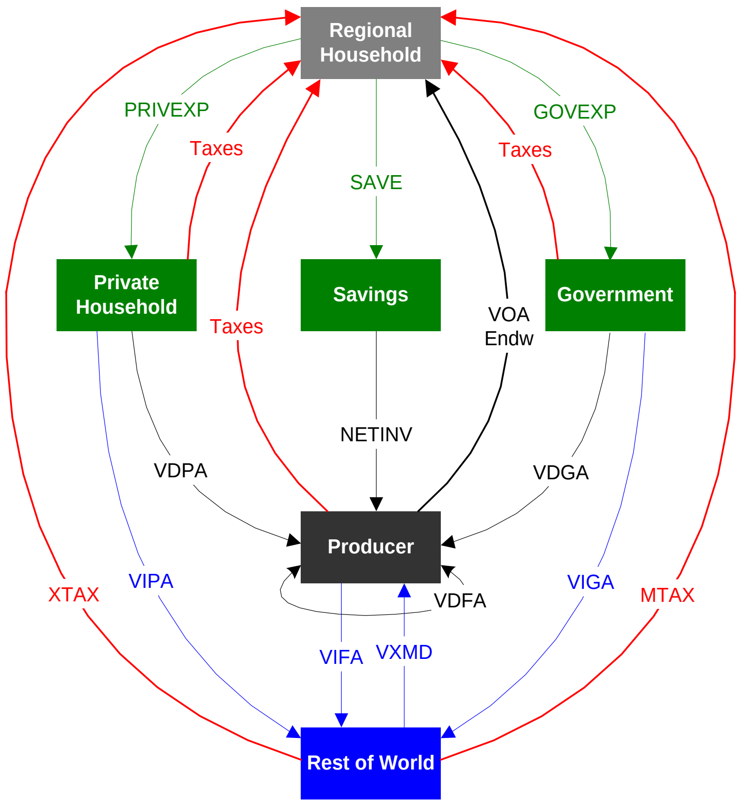
Why is this so hard?

Why haven’t we made more progress on linking earth sciences and economics?

A Tale of Two Disciplines

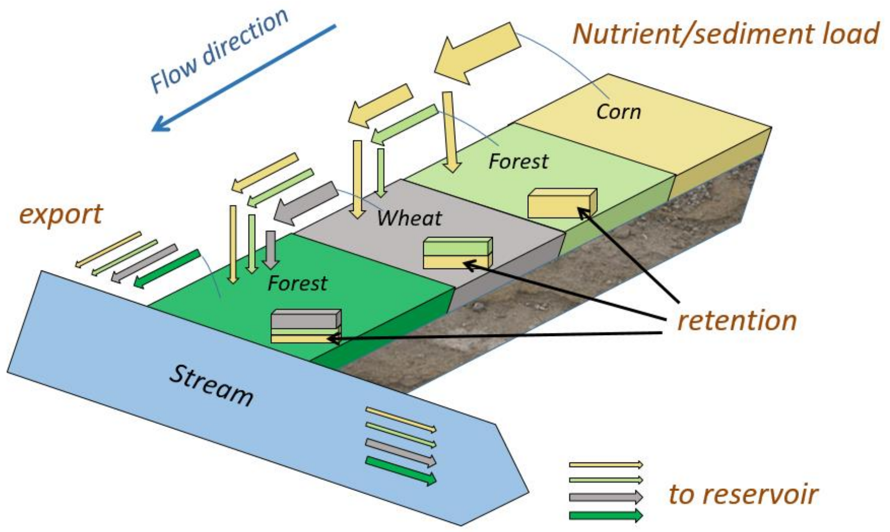
Economy

e.g., General Equilibrium



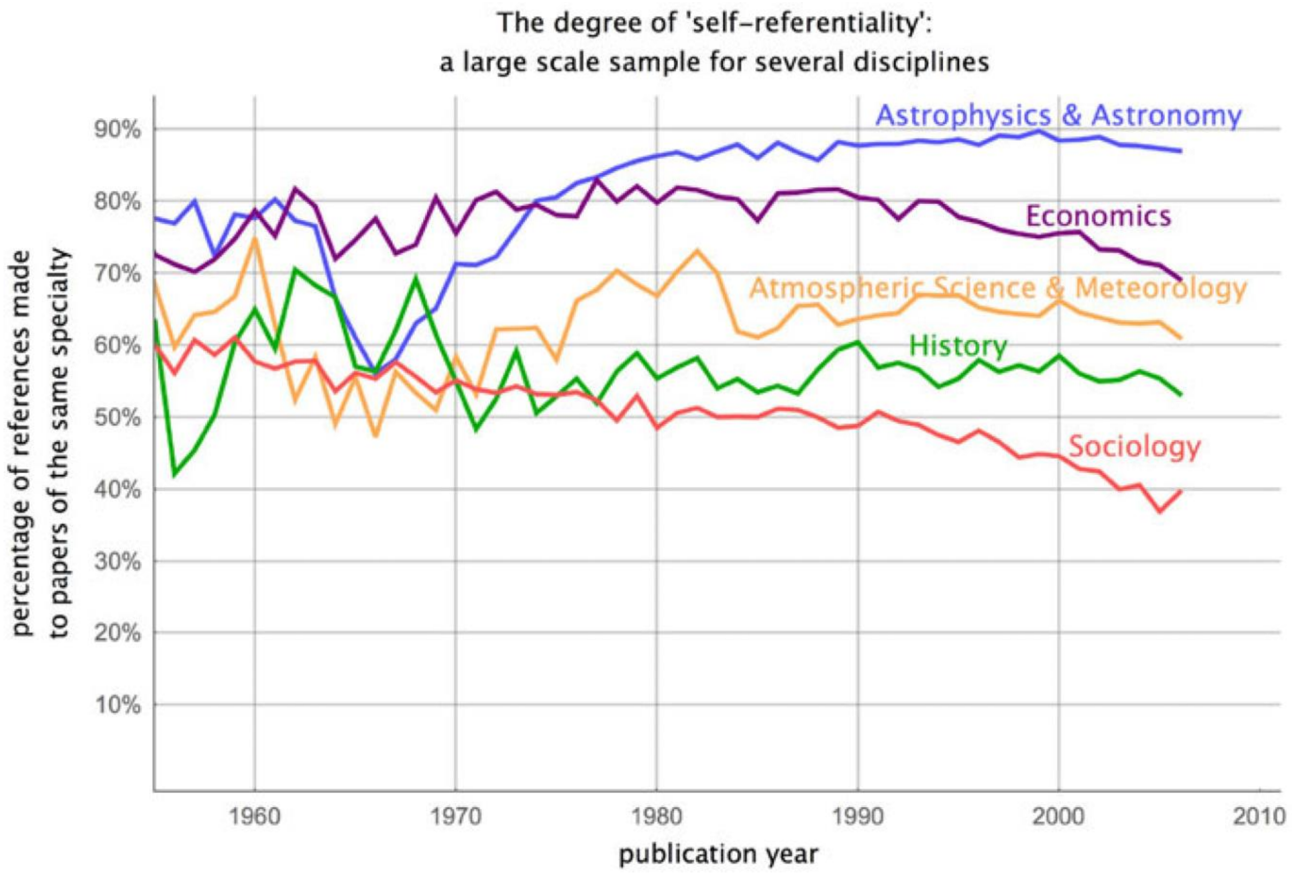
Environment

e.g., Hydrological Routing of Sediment Retention



Hard to combine

- Different, siloed disciplines
- Different assumptions (perfectly rational utility maximizers vs. complex individuals)
- Different purposes (understand the economy to make money vs. understand the world for the benefit of science)
- Different data (country-level statistics vs. data from satellites)
- Computational complexity



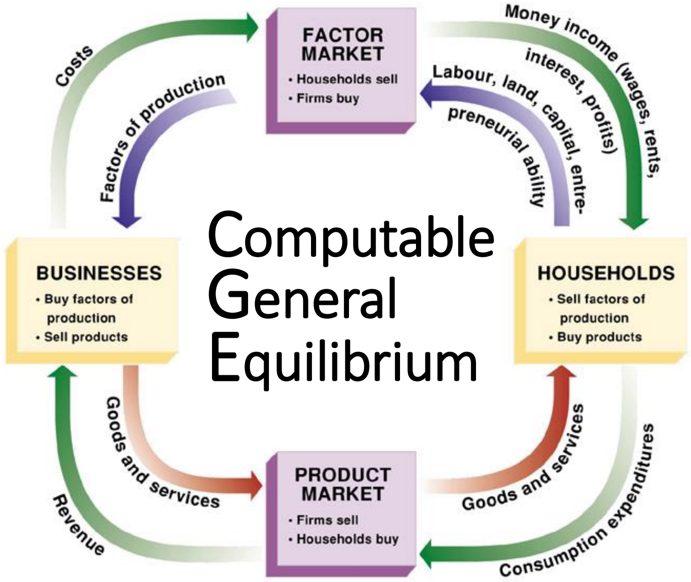
Linking models earth and economy models

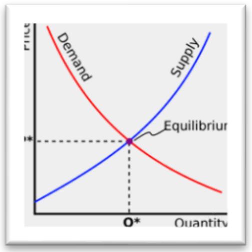
I have found it useful to refer to this type of work as Earth-Economy modeling.

Helps to distinguish it from the (very) broad array of other models that address global economic environmental issues.

What is Earth Economy modeling?

- A global model that combines:
    1. Computable general equilibrium economics
        - General here means ALL markets, prices, countries, etc. can affect each other.
    2. Very high-resolution depiction of the world
        - Detailed enough to model specific ecosystem services or specific land-owner decisions
    3. Embedded ecosystem service models
        - The economy impacts ES and ES impact the economy endogenously.
- Detailed enough to inform specific decisions





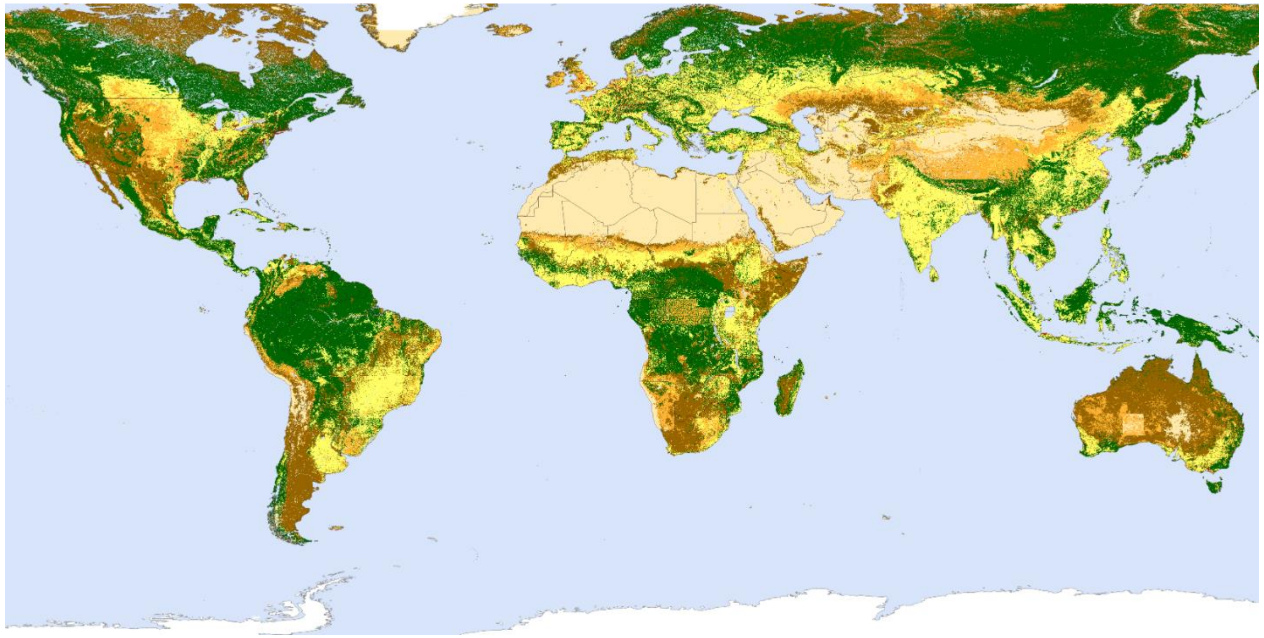
Households:

$$\underset{c,\,l}{maximize}\; Utility(c, l)$$

Firms:

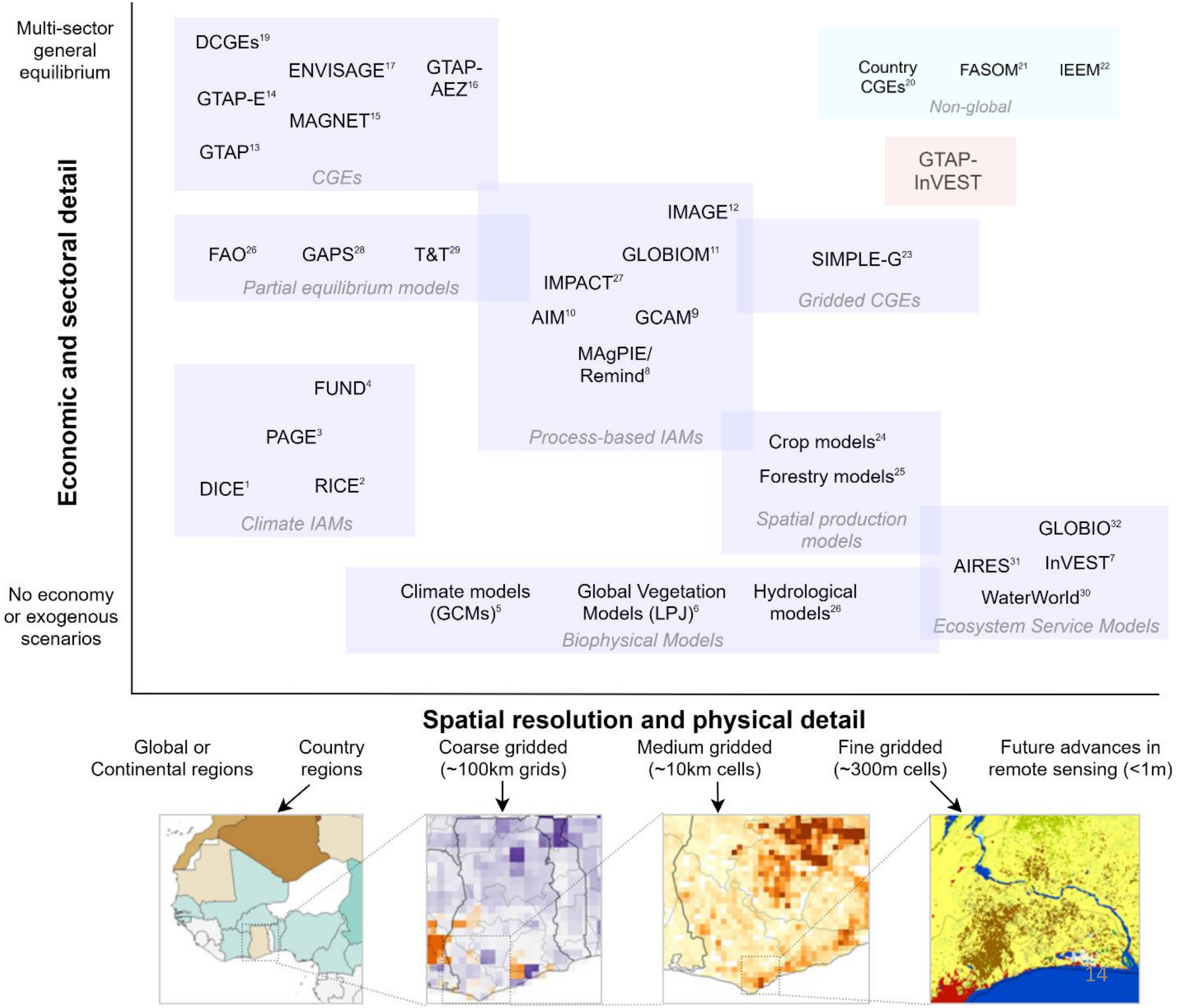
$$\underset{K,\,L,\,N}{maximize}\; Profit(K, L, N)$$

Land Cover maps (300m) used in to calculate InVEST globally



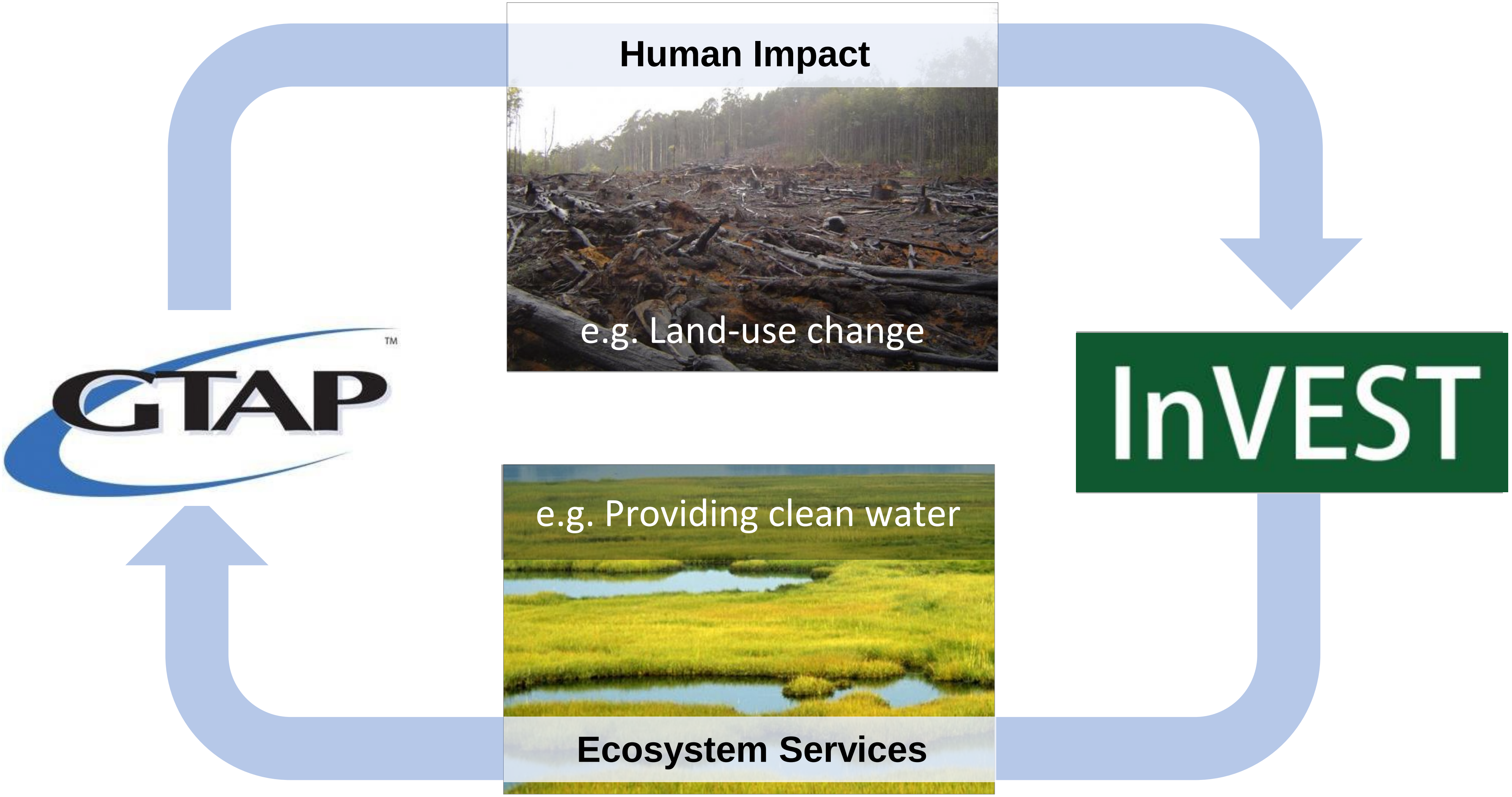
Context among global models

- Earth-Economy models aim to push the frontier (upwards and leftwards in this plot) on both spatial and economic detail
- Country models have pushed the furthest here
- IEEM is quickly increasing country inclusion towards global coverage
- GTAP-InVEST aims to improve detail on both dimensions



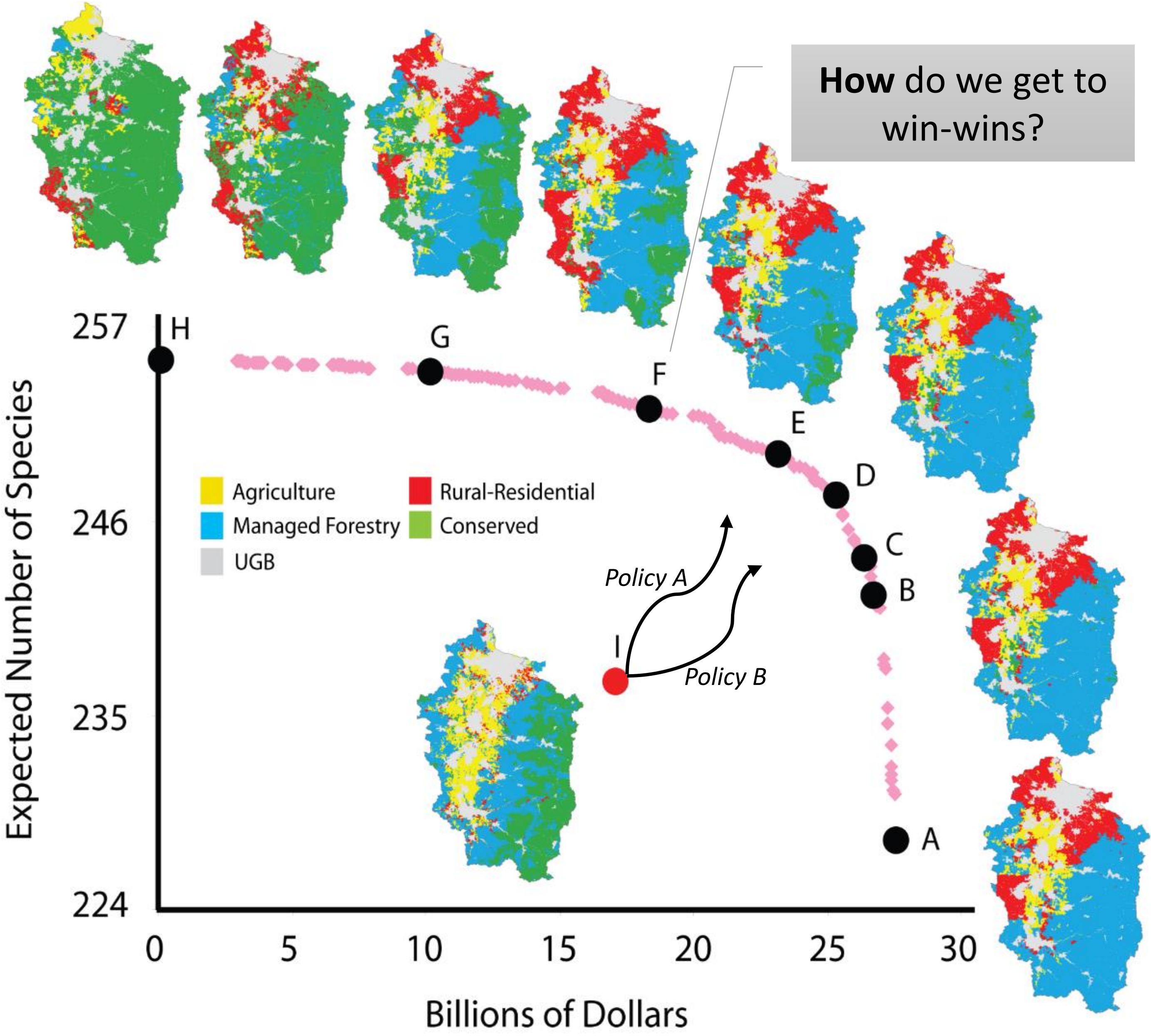
Summary of GTAP-InVEST

GTAP-InVEST integrates a detailed global model of the economy with spatially-explicit ecosystem services



Why link these two types of models?

- As I argued yesterday, optimization of land-use, land-cover (LULC) maps shows potential win-win changes
- Optimality does not say ***how*** to move from current landscape (point I) to something on the efficiency frontier
- Need to identify *policies* not landscapes.
  - This is where Earth Economy modeling aims.



InVEST and The Natural Capital Project

InVEST

integrated valuation of ecosystem services and tradeoffs

- Partnership of WWF, The Nature Conservancy, Stanford University, University of Minnesota and Chinese Academy of sciences
- InVEST is an open-source software tool to estimate ~20 ecosystem services
- Spatially-explicit, high-resolution, processed-based production functions, global extent

Calculating ecosystem services at the global scale is newly possible!

Chaplin-Kramer et al. 2019, Science

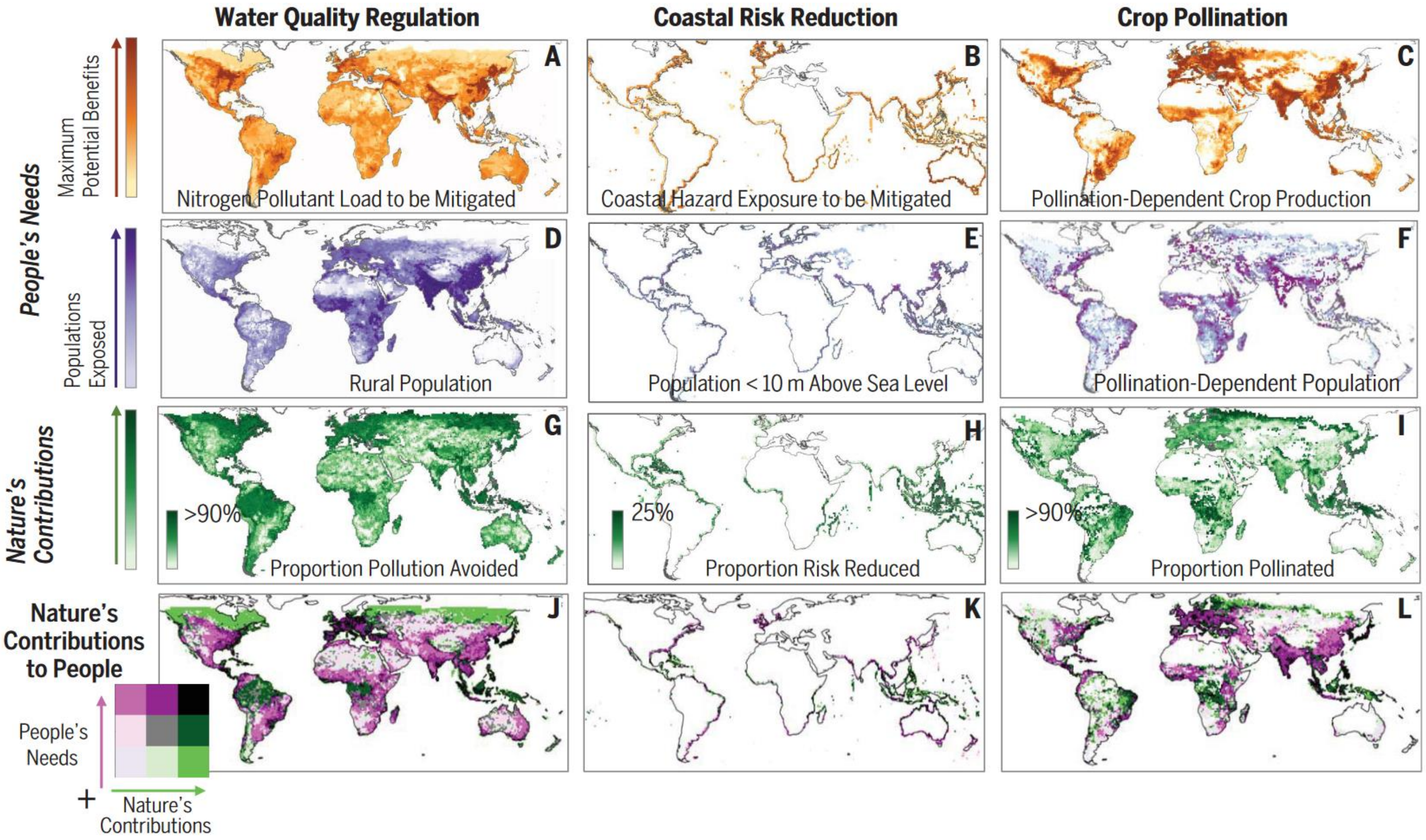
Two more recent publications:

- Chaplin-Kramer et al. 2023
- Neugarten et al. 2023

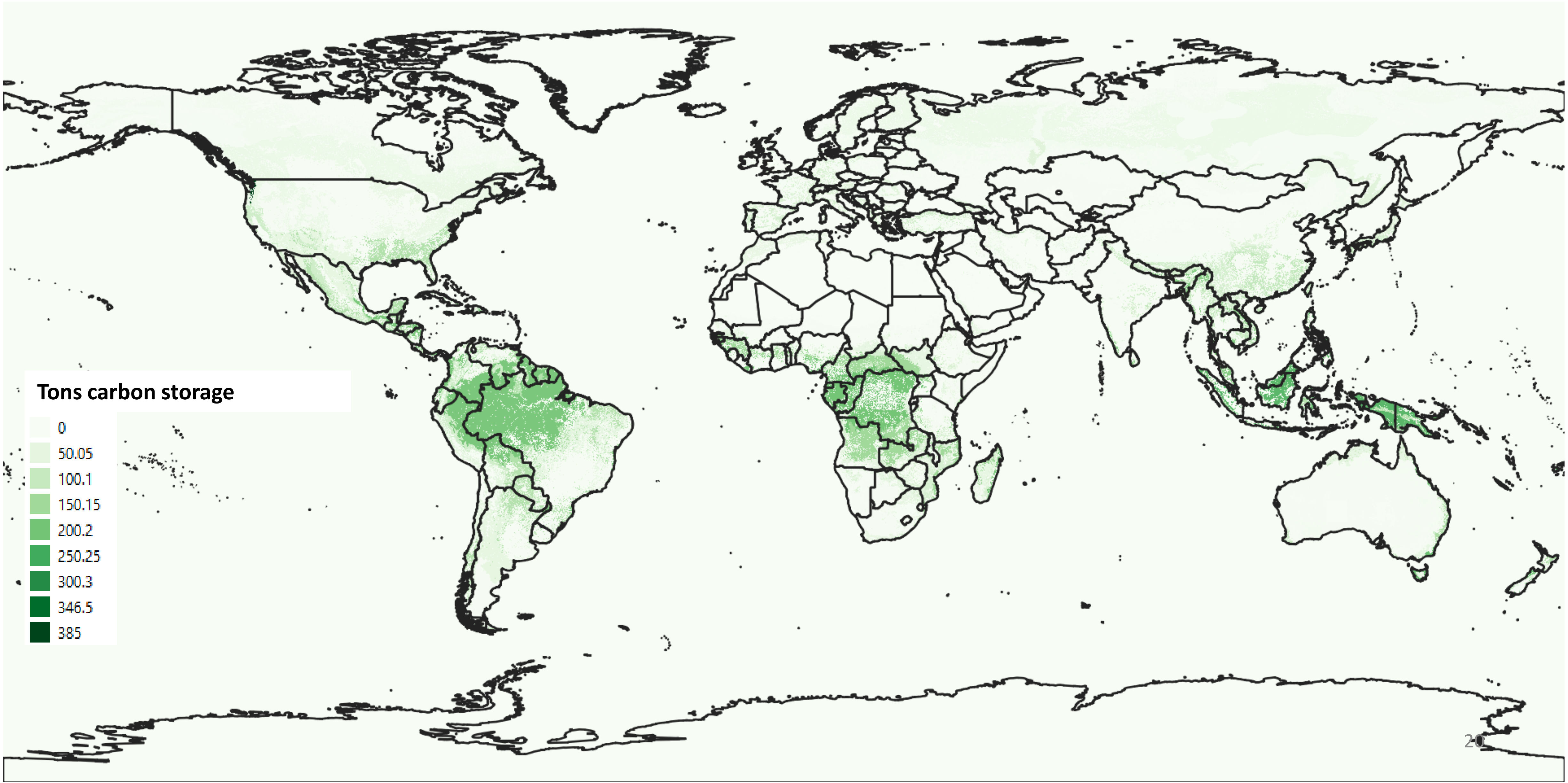
Science

Global modeling of nature's contributions to people

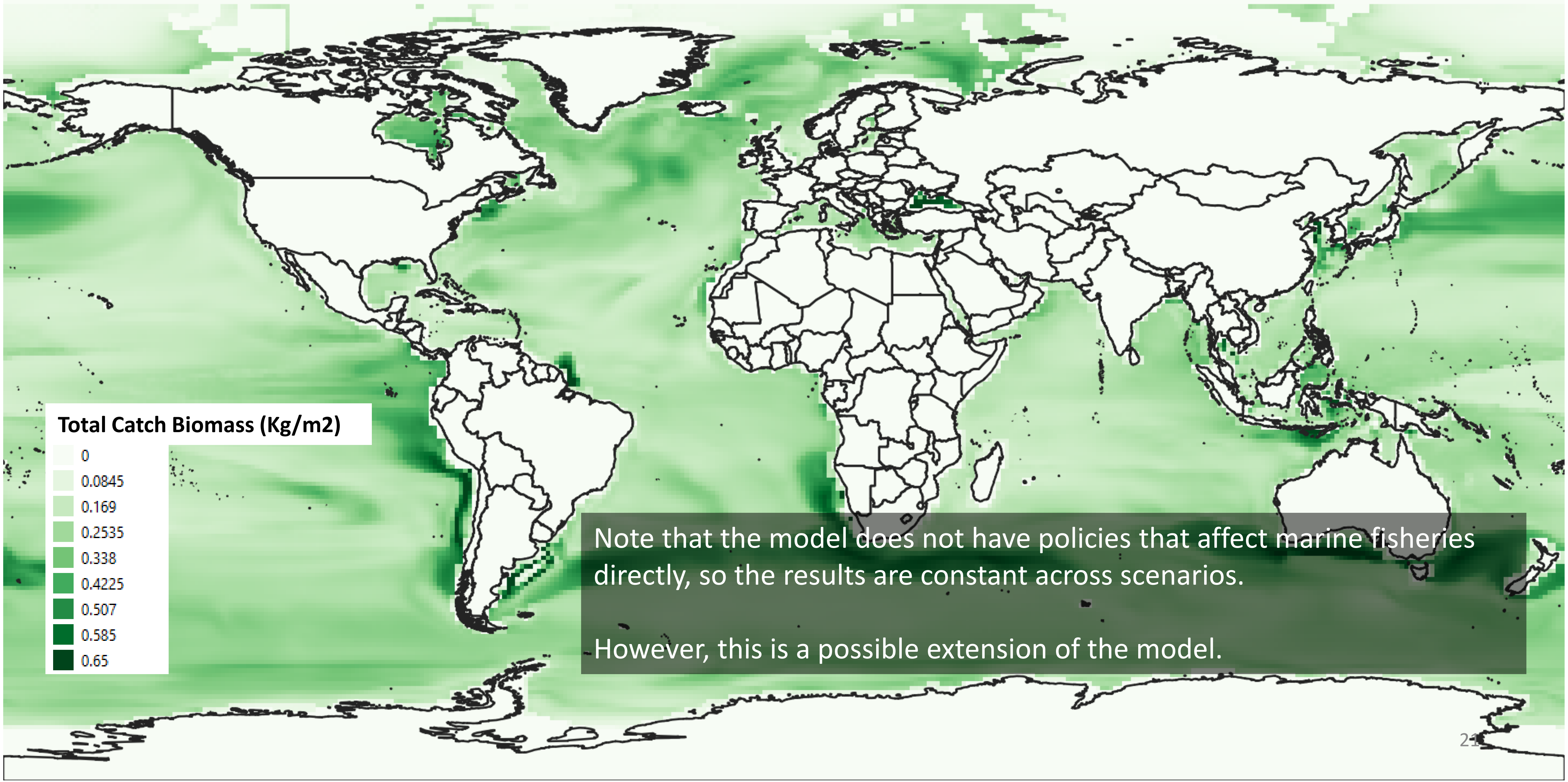
Rebecca Chaplin-Kramer, Richard P. Sharp, Charlotte Weil, Elena M. Bennett, Unai Pascual, Katie K. Arkema, Kate A. Brauman, Benjamin P. Bryant, Anne D. Guerry, Nick M. Haddad, Maike Hamann, Perrine Hamel, Justin A. Johnson, Lisa Mandle, Henrique M. Pereira, Stephen Polasky, Mary Ruckelshaus, M. Rebecca Shaw, Jessica M. Silver, Adrian L. Vogl and Gretchen C. Daily



Carbon storage and timber ecosystem service provision



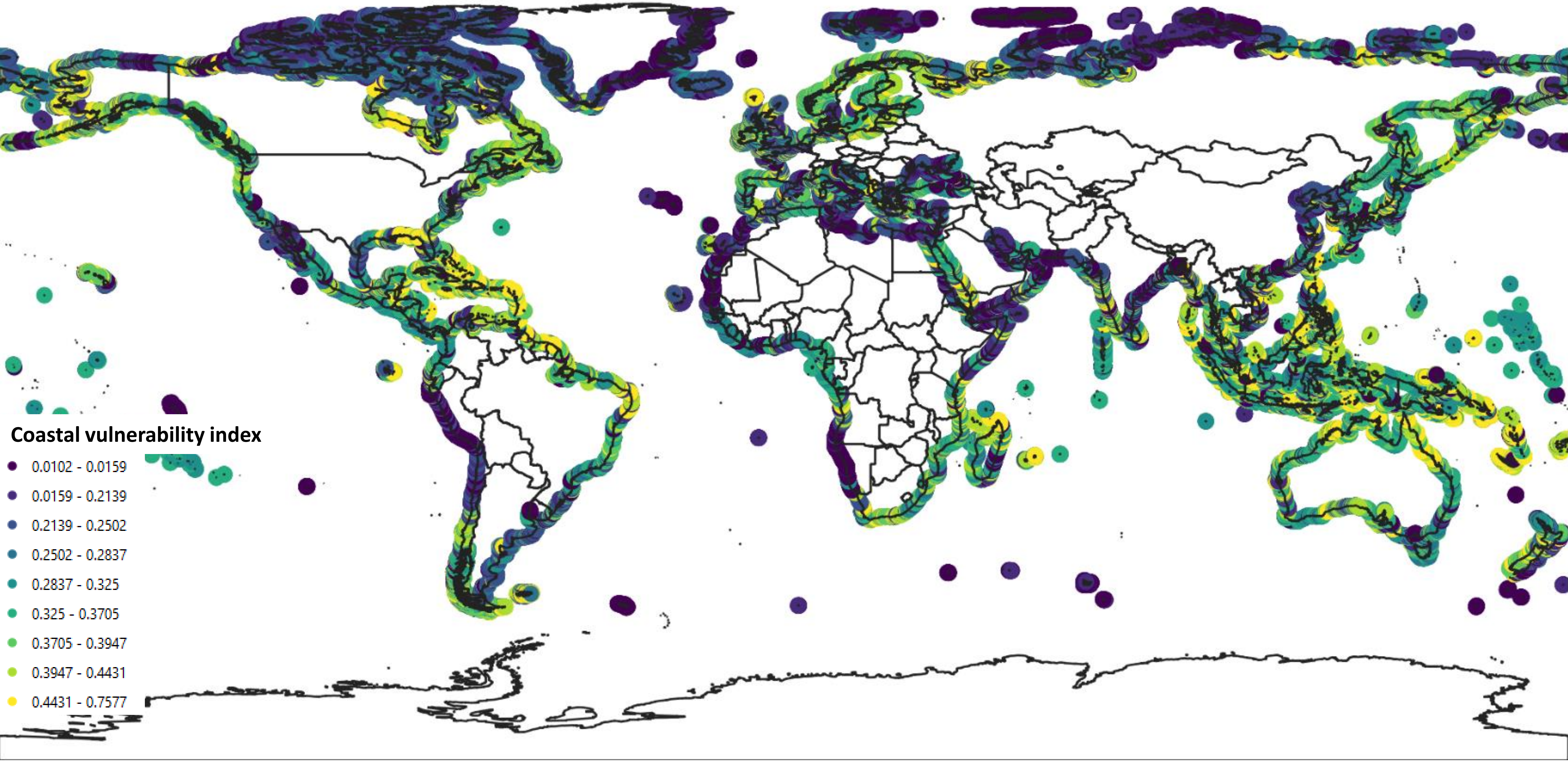
Marine fisheries ecosystem service provision



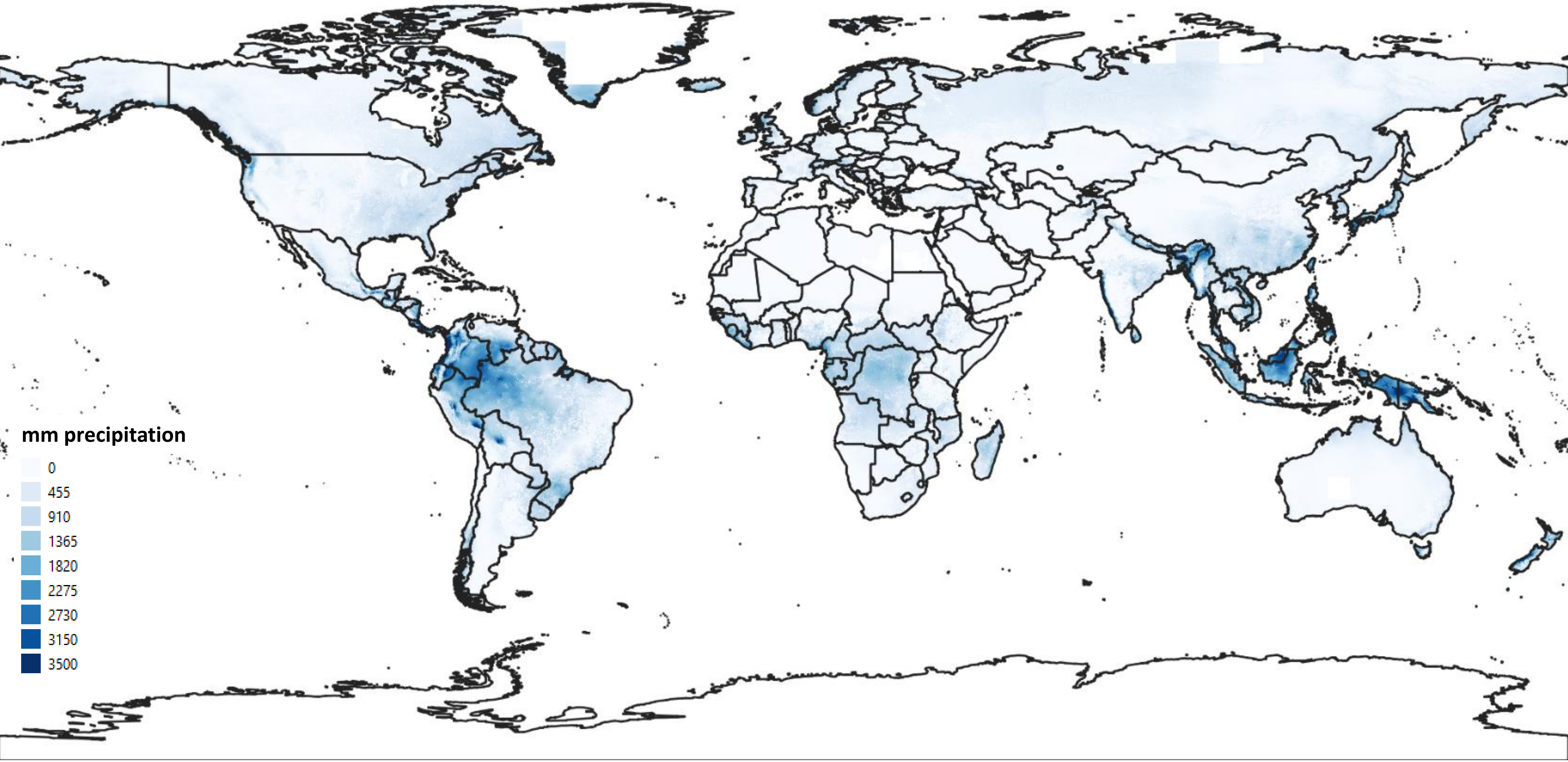
Note that the model does not have policies that affect marine fisheries directly, so the results are constant across scenarios.

However, this is a possible extension of the model.

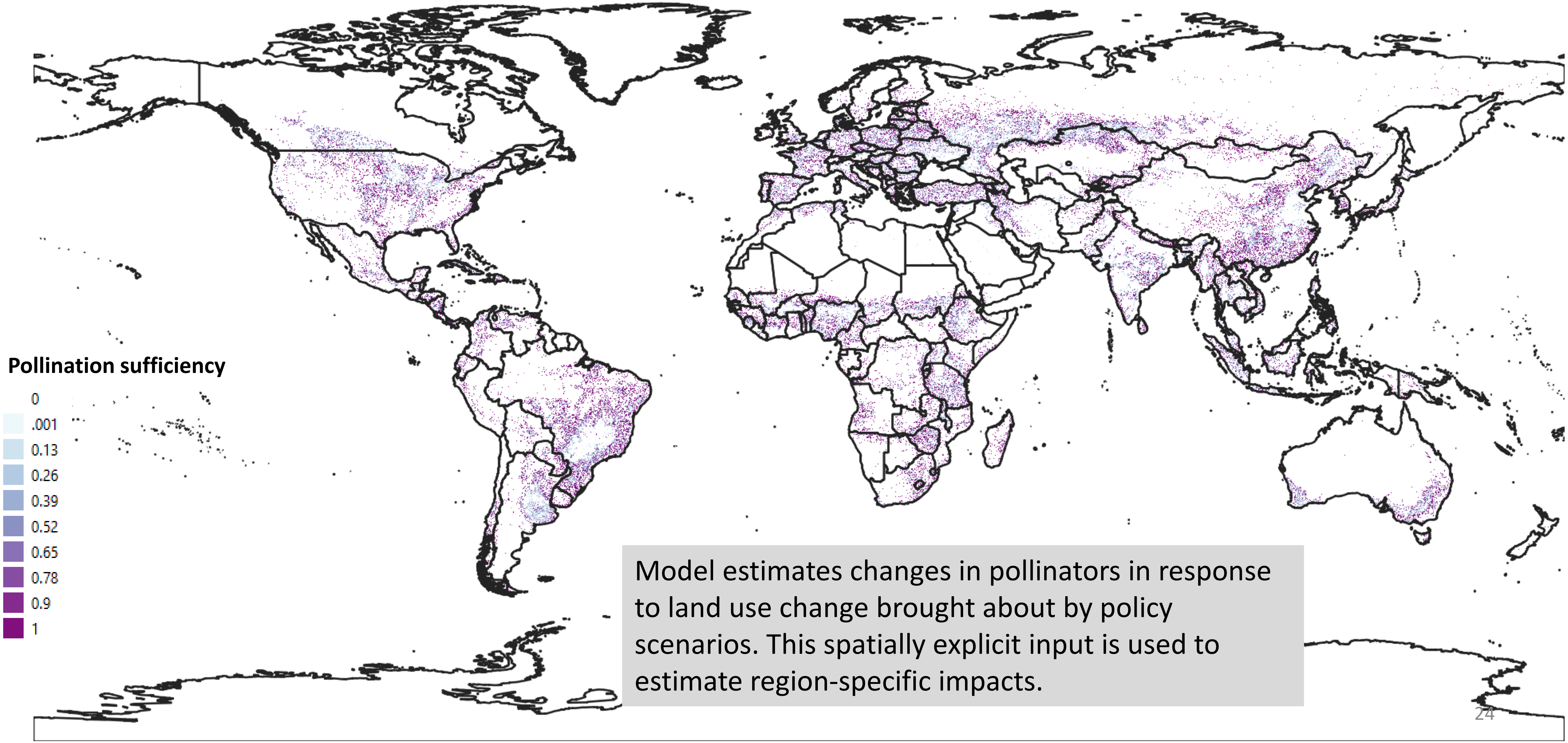
Coastal protection ecosystem service provision



Water yield ecosystem service provision

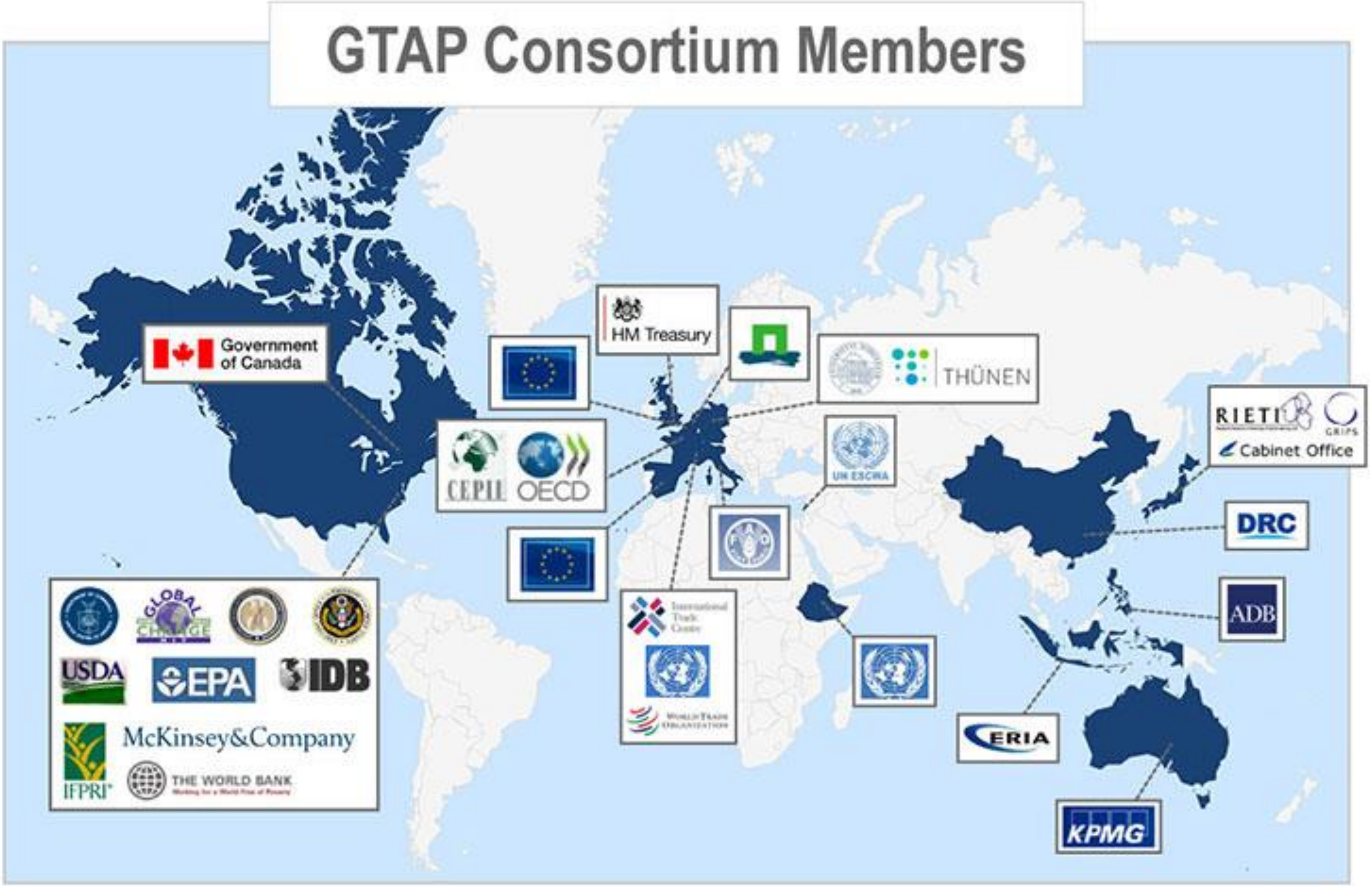


Wild pollinator ecosystem service provision



Model estimates changes in pollinators in response to land use change brought about by policy scenarios. This spatially explicit input is used to estimate region-specific impacts.

Global Trade Analysis Project (GTAP)



- GTAP was founded in 1992 one of our team members, Tom Hertel
- Publicly funded with core support from GTAP Consortium (33 members)
  - International: World Bank, ADB, IDB, OECD, UNECA, UNESCWA, UNCTAD, WTO, IFPRI, FAO, IFPRI, EU Commission, etc.
  - National: Canada, Japan, Germany, Netherlands, UK, United States, China
- 17,000+ members from 174 countries

• GTAP has two distinct components:

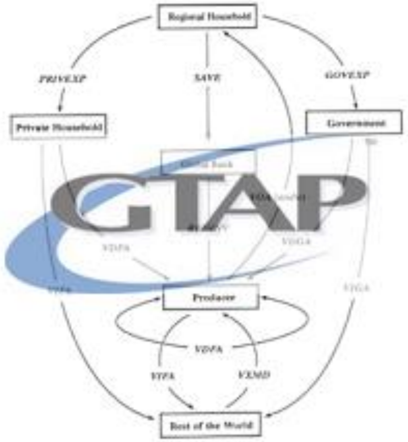
GTAP

Global Trade
Analysis Project

GTAP database

- Standardized, harmonized, curated and comparable database of key economic indicators.
- 141 regions, 57 sectors, four years (n v.11): 2004, 2007, 2011, 2014, 2017

GTAP computable general equilibrium (CGE) model



Preview: To link these models, three advances were necessary

GTAP

SEALS

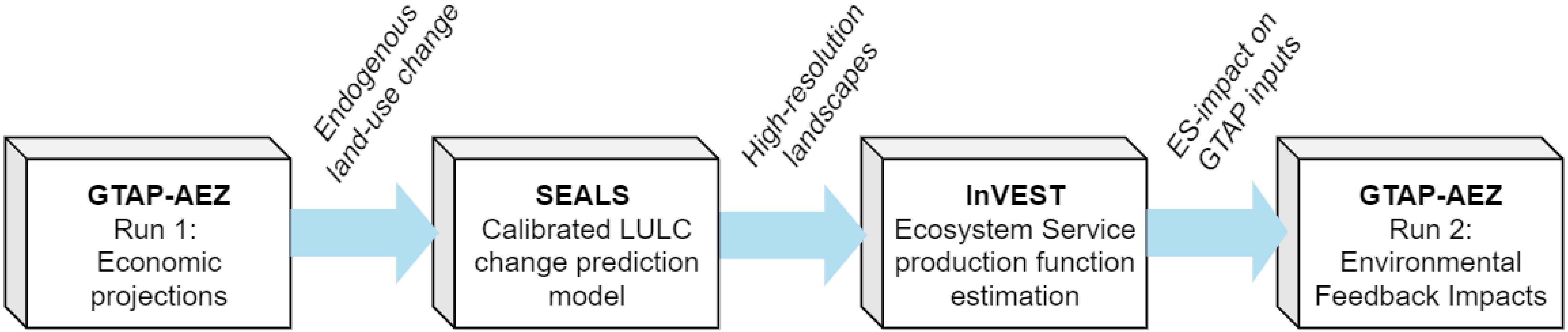
Advance 2: Spatial Economic Allocation Landscape Simulator. Downscales land-use change..

InVEST

Advance 1: Endogenizing the expansion of cropland, pasture, managed forests into natural lands.

Advance 3: Expression of changed ES as shocks to the economy

Model linkage in the GTAP-InVEST model



1. First GTAP run projects economic growth and endogenously calculates land-use change
2. Downscale endogenous change to 300m globally with the Spatial Economic Allocation Landscape Simulator (SEALS)
3. Calculate ecosystem service results with InVEST
4. Second run of GTAP calculates impact of changed ecosystem services on economic performance

Three quick methods points

Research task 1: Endogenizing land-use change

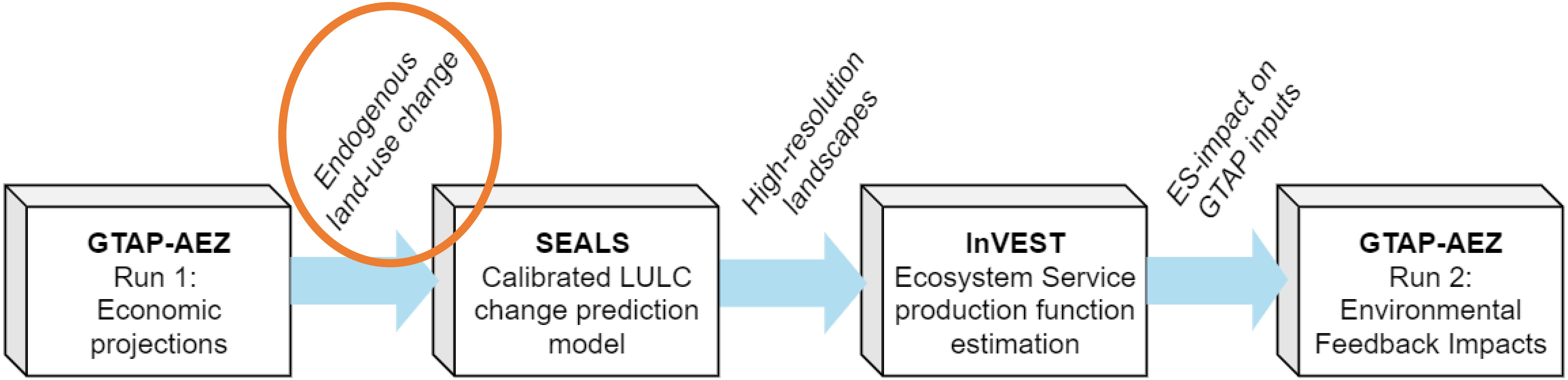
Determine how agriculture, pasture and plantation forests expand into natural areas with endogenous allocation among sectors and versus yield increases.

GTAP extensions

- GTAP by default only includes the monetary value of land as an input to production
- GTAP-AEZ (Agroecological Zone) is a frequently used extension that improves representation of land.
  - Land is now in physical (hectarage) terms rather than just as value
- However, GTAP-AEZ only considers how different sectors compete for a fixed amount of land.
  - This rules out expansion of cultivated land.
- We created a new version of GTAP-AEZ that adds expansion into natural areas

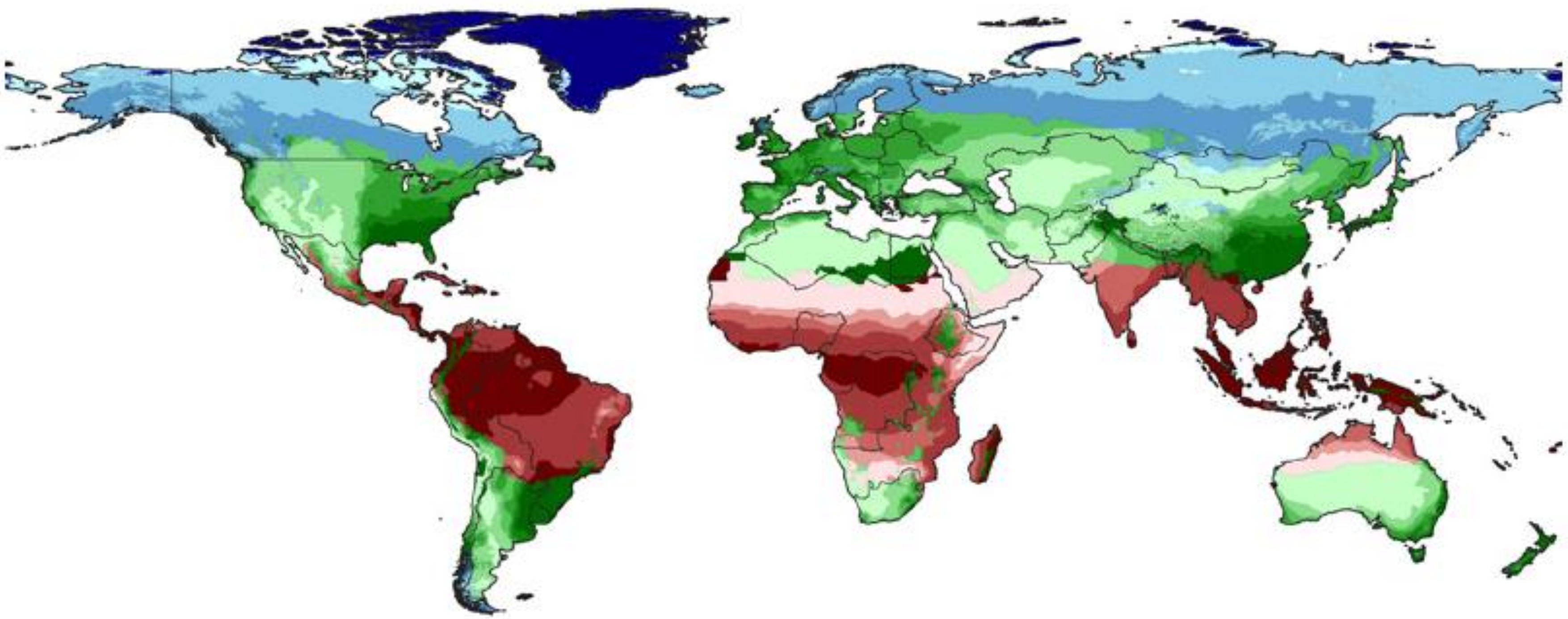
Calculate endogenous land-use change at the regional level

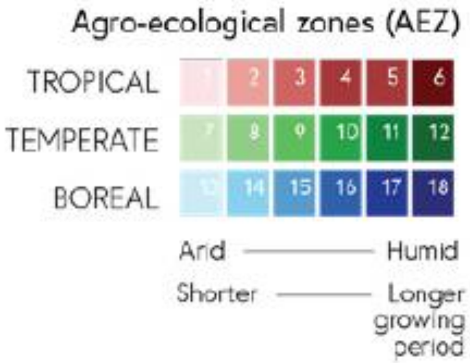
- Base on land-supply curves calibrated for each AEZ



Definition of AEZ-Regions

- The 18 AEZs (shown in different colors) are combined with the 37 aggregated GTAP regions (black boundaries)
- Creates 337 unique AEZ-Region zones
- This version of GTAP-AEZ increases the regional specificity over the original (see Baldos and Corong 2021 for details)

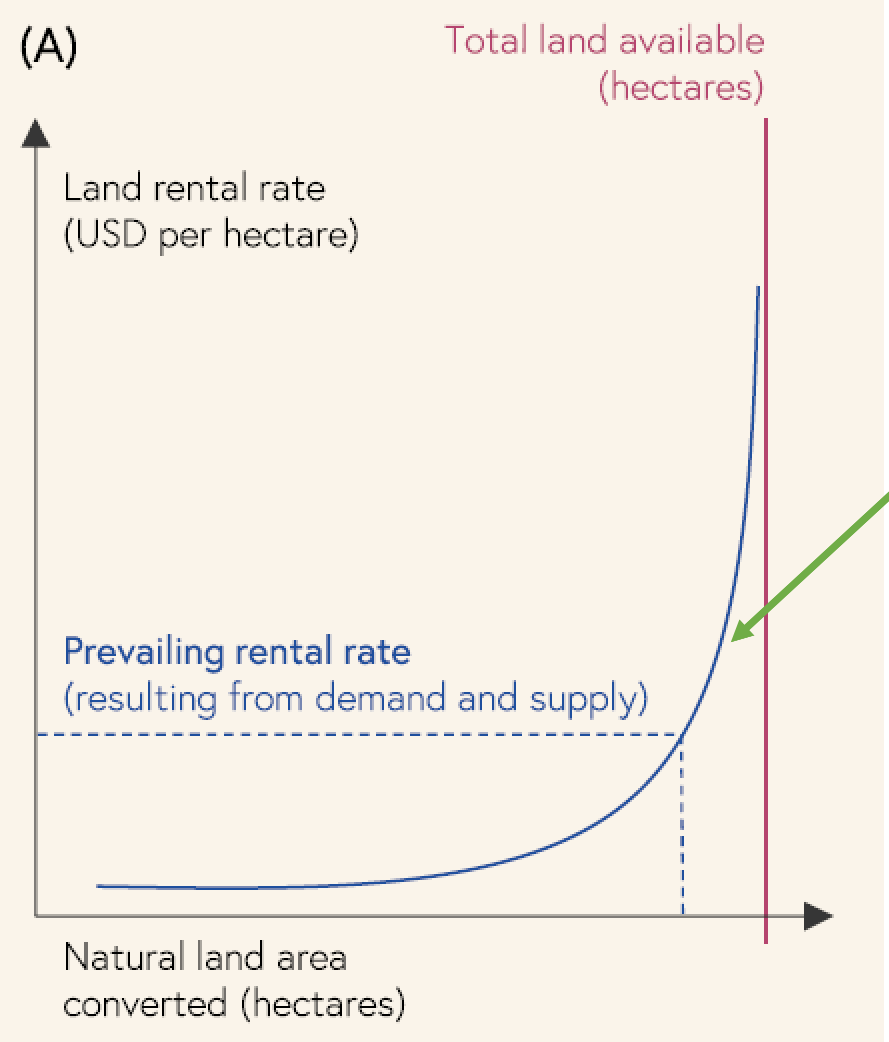


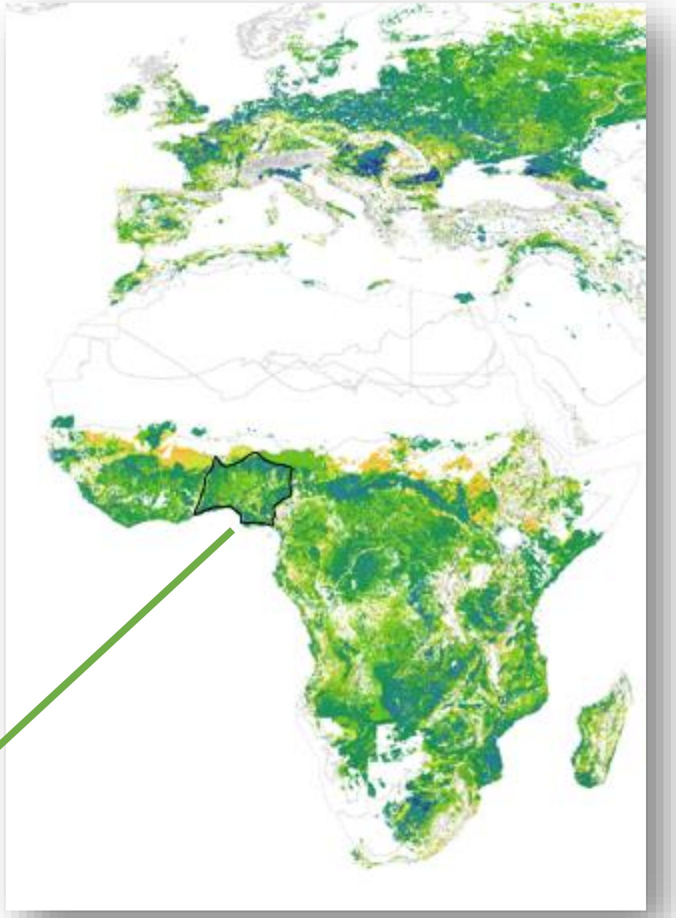


Note: The 18 agro-ecological zones are defined in Hertel et al. (2019). The GTAP country units cover 226 countries and territories, including Sub-Saharan Africa (44), Rest of South Asia (5), Rest of Southeast Asia (7), Central America (32), South America (11), Central Asia (21), Middle East and North Africa (17), Other Europe (4), Rest of East Asia (3), Oceania (24), and the European Union (29). The 226 countries and territories are aggregated to the 37 regions. When overlaid on the agro-ecological zones, this produced the 341 unique AEZ-Region zones shown above. In the figure, each agro-ecological zone is represented with a unique color.

Endogenized land-use change via land-supply curves

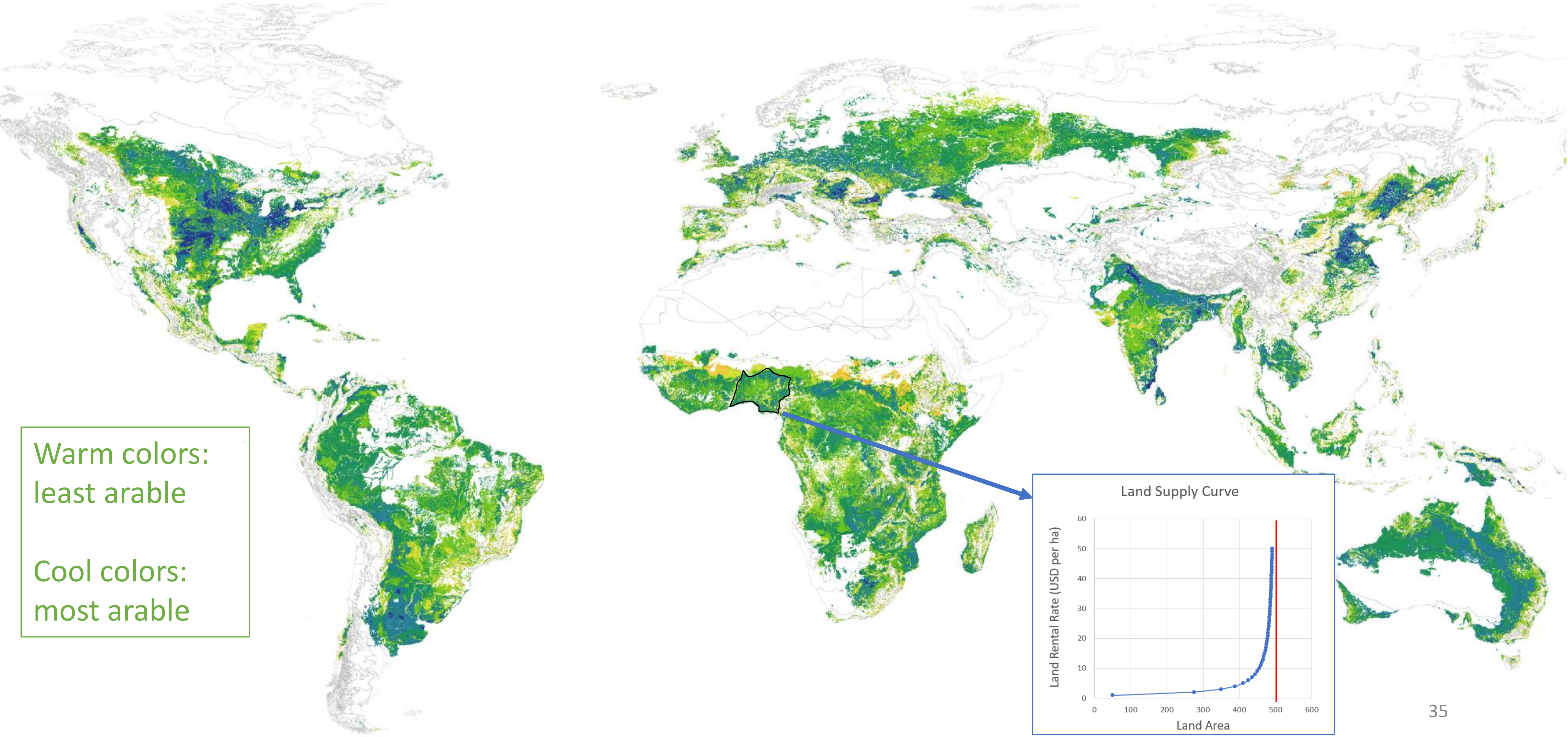
- For each region, we calibrated a land-supply curve
- Bringing more land into the economy requires a higher price, rising asymptotically with the limit





- Shape of the curve determined by high-res suitability data.
- Unique for each AEZ.

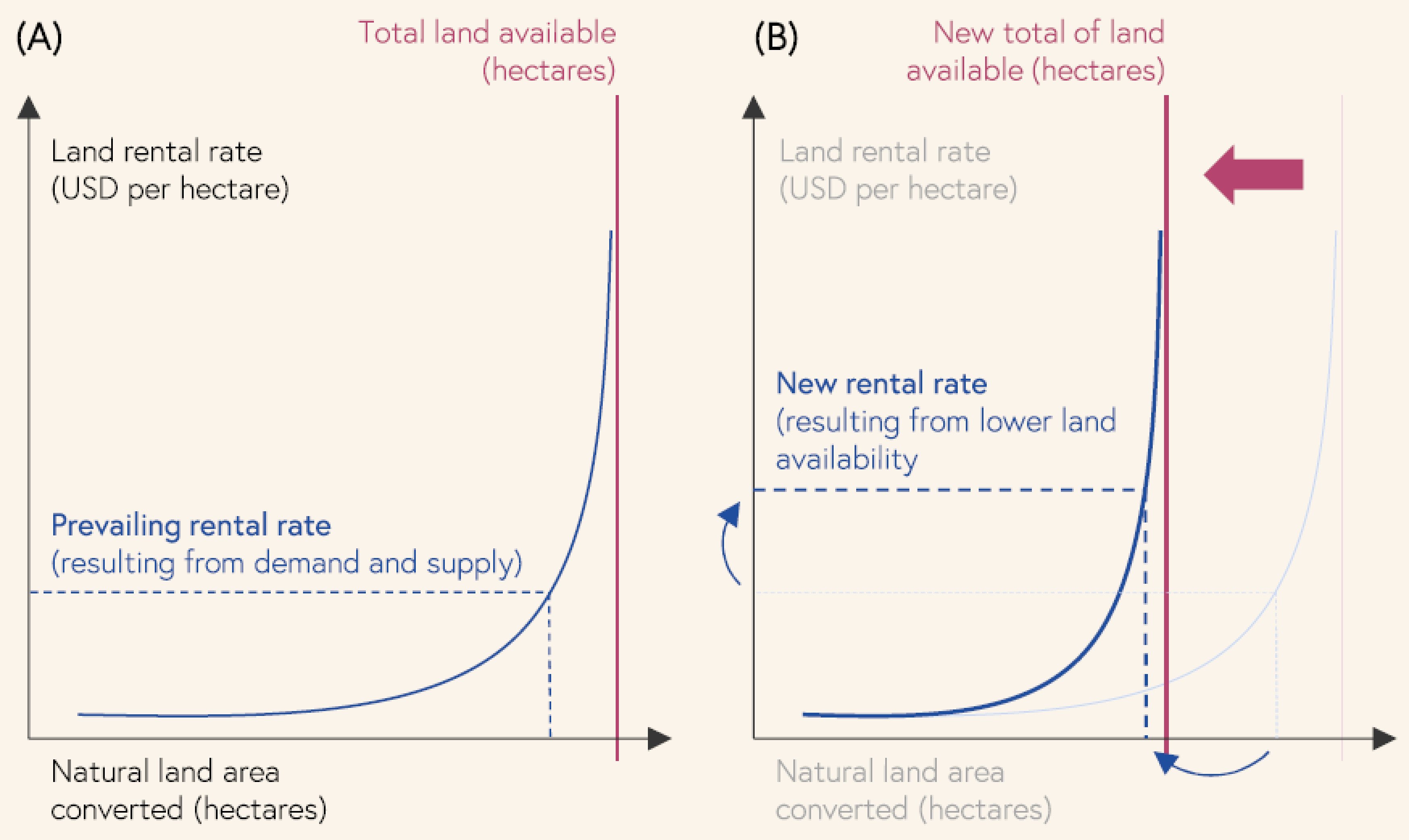
Shape of Land Supply Curve based on soil, topographic, land-use, adjacency, and cultivation constraints (e.g. salinity) present in each AEZ-Region



Necessary to calculate opportunity cost of protecting land

- Protecting land (removing it from economic use) shifts the asymptote left
  - Drives up the price and reduces land conversion

- Critical methodological point: this means that removing land from production is not "free"

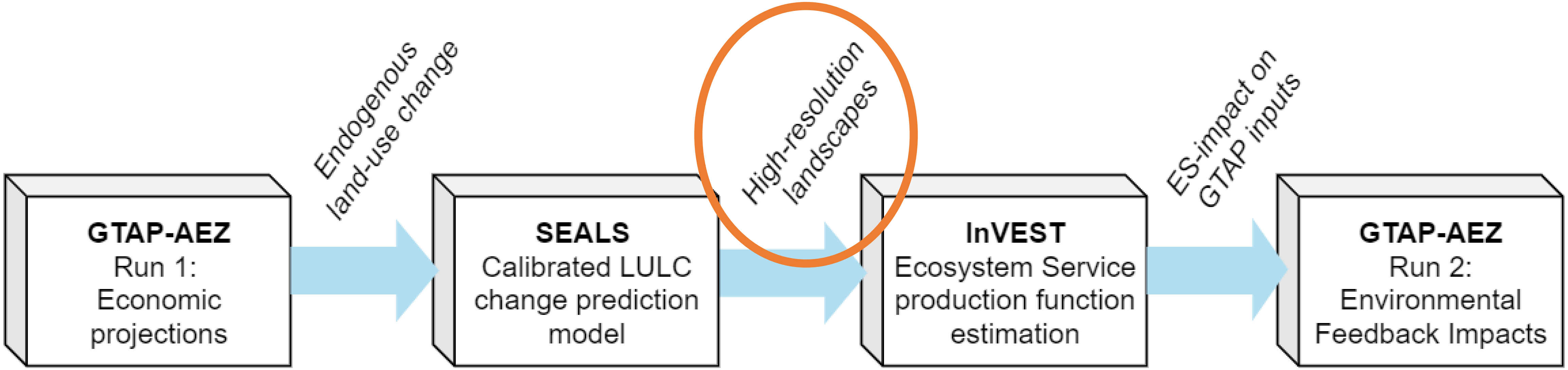


Research task 2: Downscale land-use change

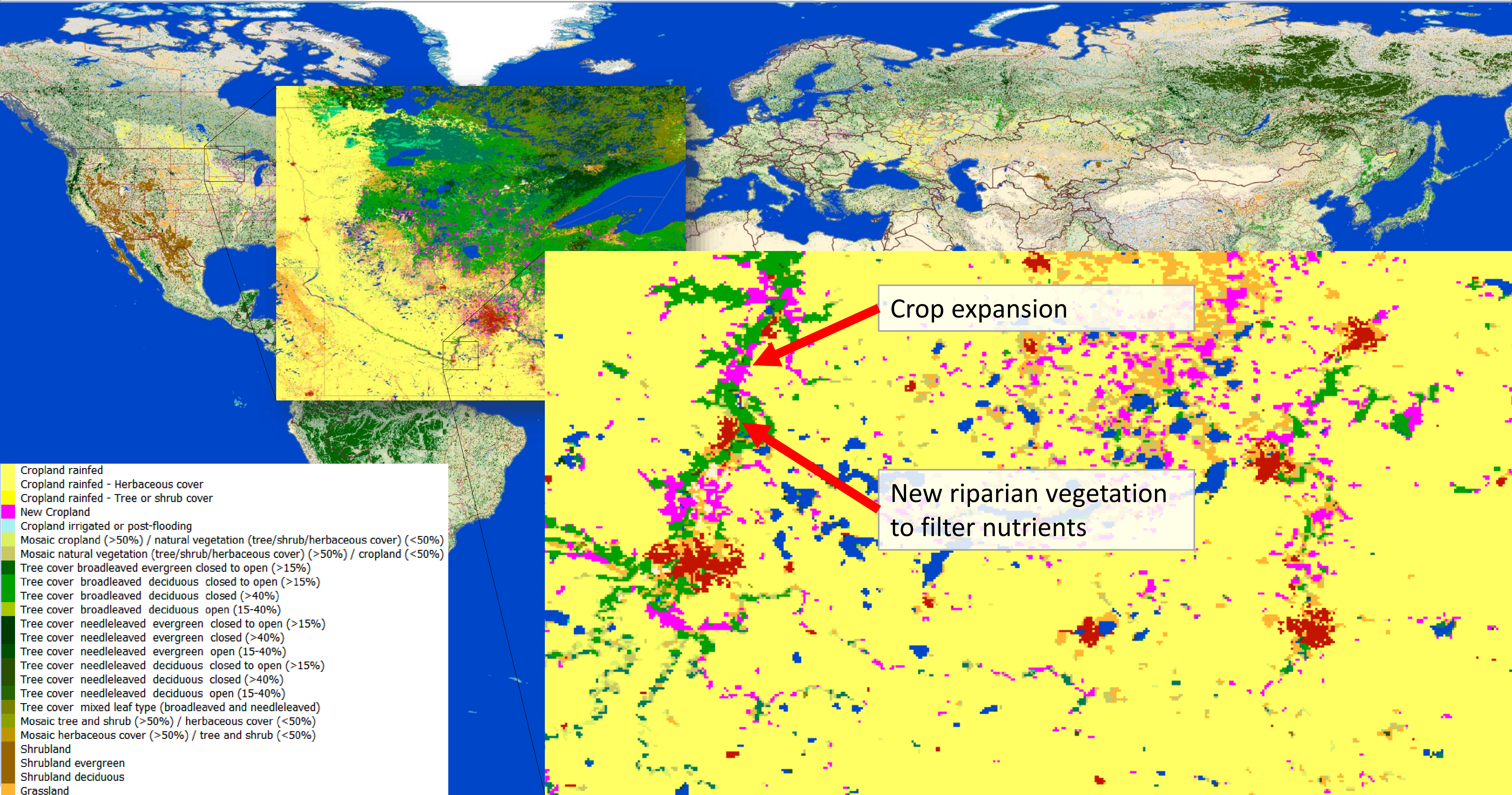
Downscale GTAP outputs on land-use change from ~100 regions to 8.4 billion grid-cells.

After GTAP-AEZ runs for the first step, we have per-region land-use change

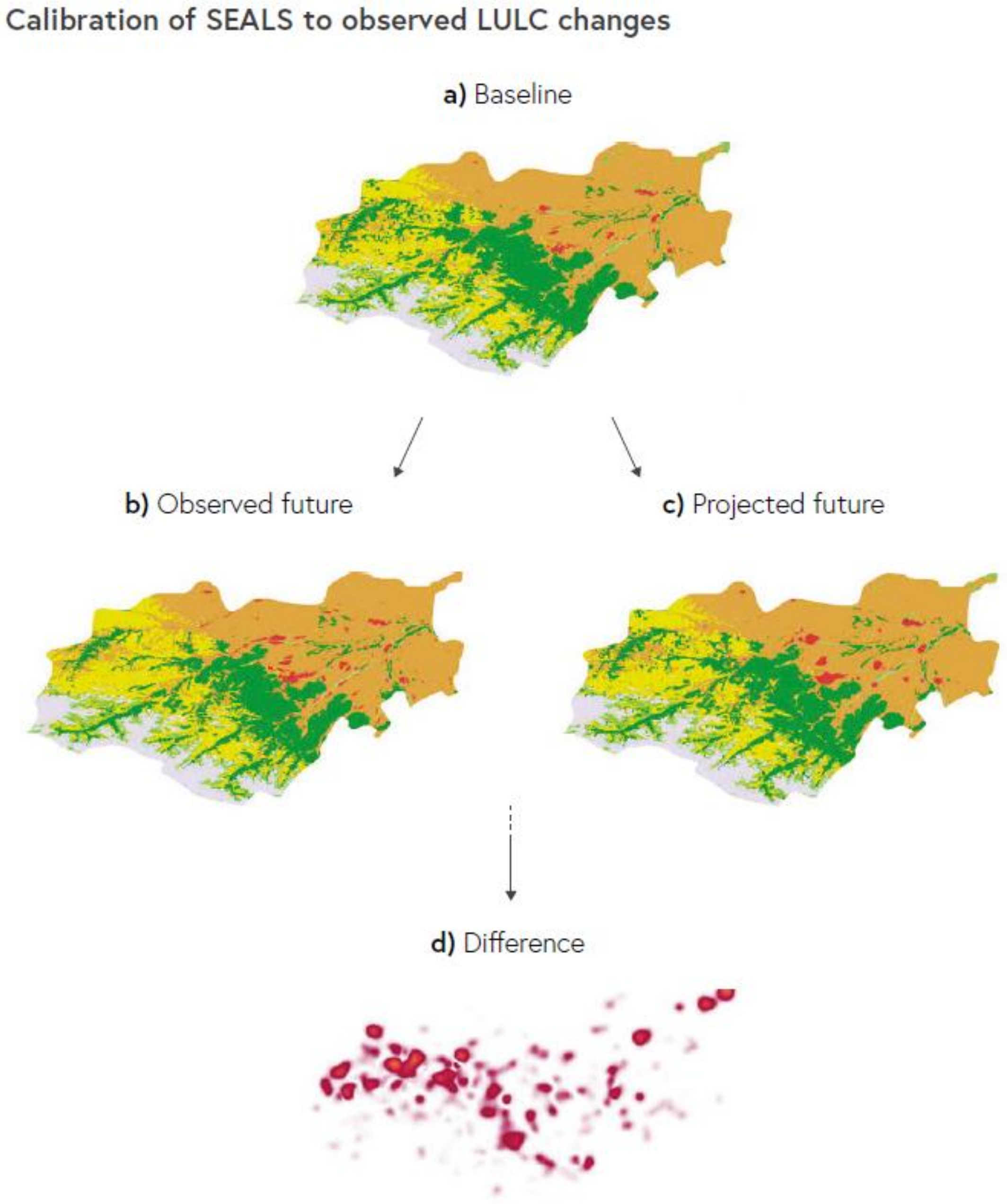
- Even with 341 regions, this is still very coarse compared to the resolution we need for ecosystem service calculation
- Thus, we have to downscale these regional projections of land-use change to a high-resolution land-use, land-cover map

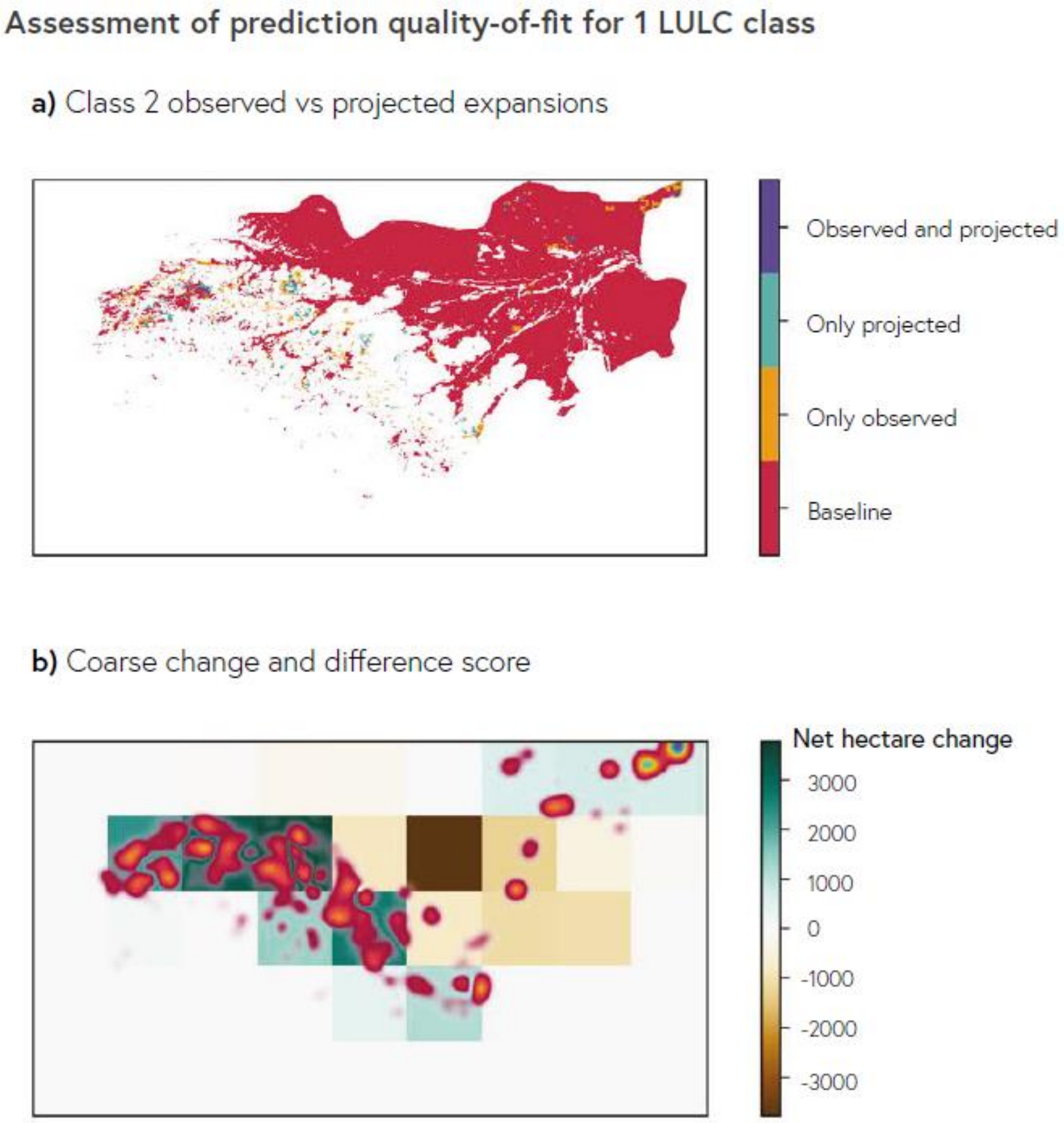


Need to be able to downscales while also implementing spatially-explicit conservation actions



SEALS methods

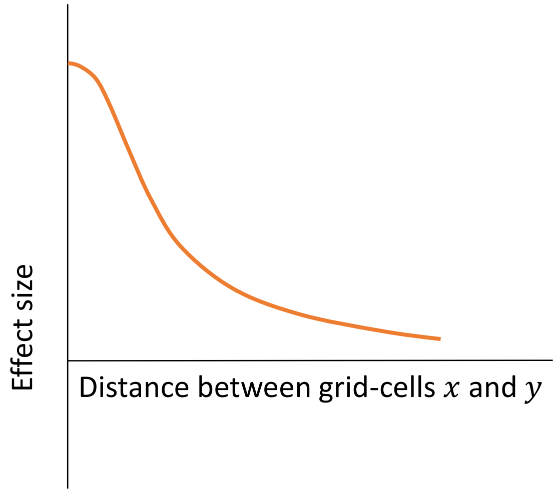




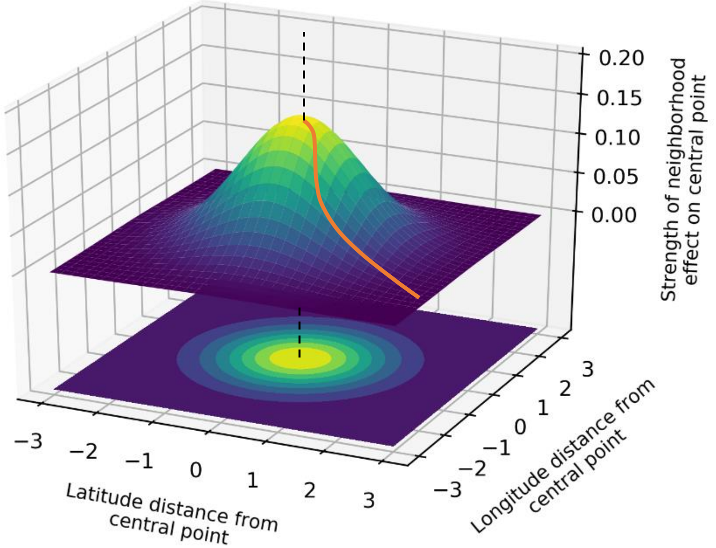
Key component in these regressions is the adjacency or “neighborhood effect”

- Gridded data preserve spatial structure
  - Nearby cells are highly correlated
  - The actual pattern may be a good predictor
- Can use 2-dimensional convolutions to express this structure
  - E.g., identify what is the relationship between two variables as their distance increases via a flexible parametric form

A. Example 1-dimensional adjacency relationships

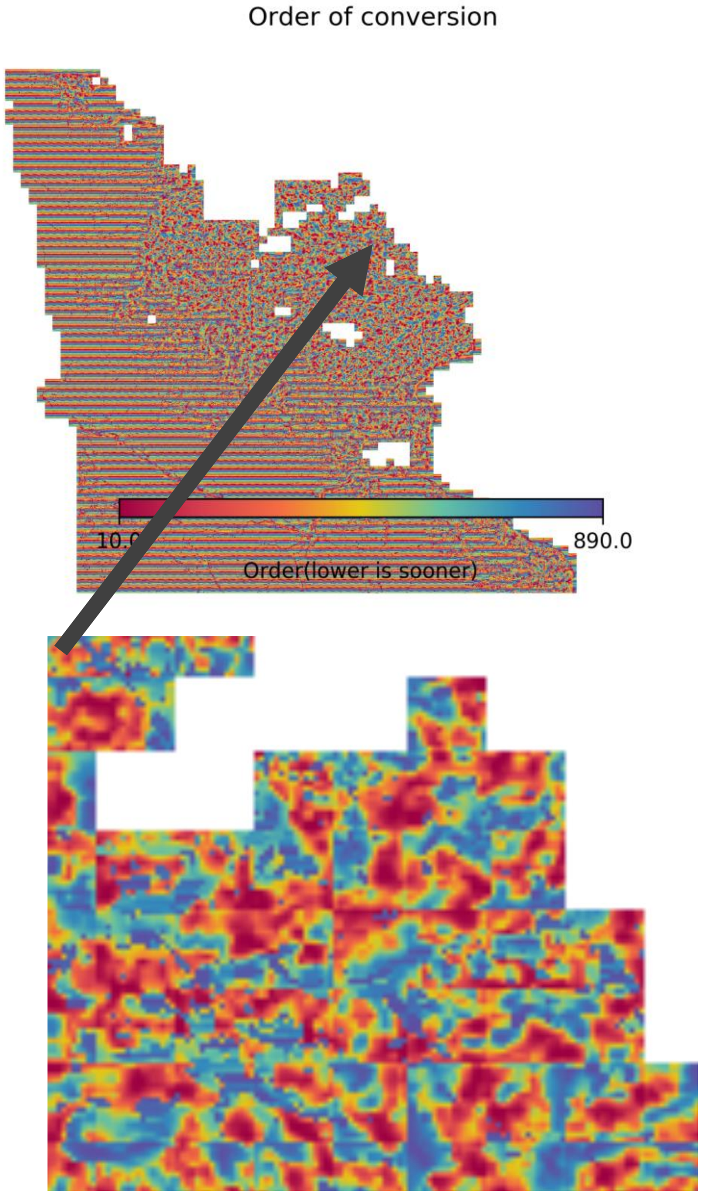


B. Expression in 2- and 3-dimensions



Behind the curtains

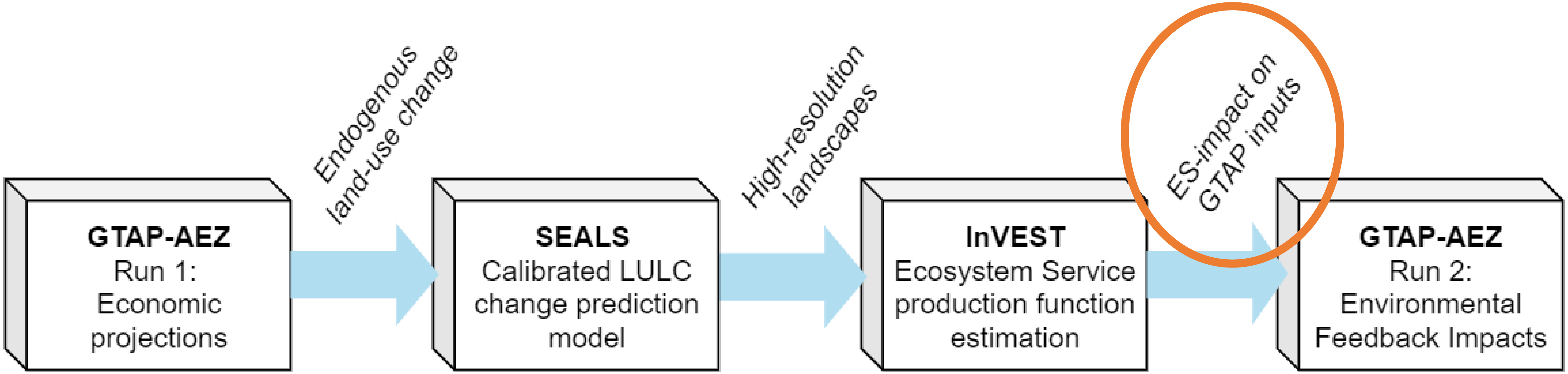
- For each of 30+ correlates, rank each grid-cell based on its suitability given some initial parameters
  - Allocate each land-use transition based on these rankings.
  - Calculate how similar this new landscape is to the observed landscape.
  - Adjust parameters and search for the parameters that minimize the difference.



Research advance 3: expressing degraded ecosystem services as economic “shocks”

InVEST produces gridded biophysical and valuation impacts

- How do we convert these huge raster maps into something that affects production decisions in GTAP?



Pollinator Connection to GTAP

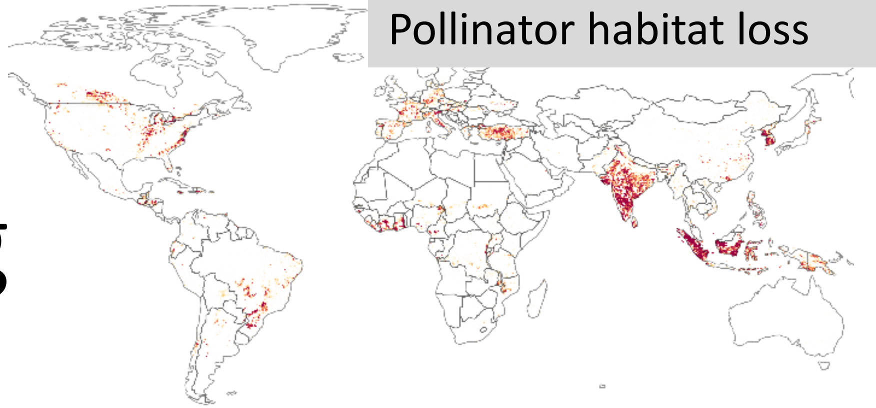
- In the literature, there are three frequently-used ways that environmental shocks have been modelled in CGEs
  1. Shifting the land supply curve directly to reflect a change in production
  2. Implementing a land-augmenting technological change
  3. Shifting the production function via a factor-neutral productivity shock
- For pollination, focused on the factor-neutral productivity shock

Connections to GTAP equations

- Aggregated the grid-cell level sufficiency change for each country and for each crop
  - Defined the a_0 parameter for each based on the zonal average

- Updated equations change throughout the GTAP code

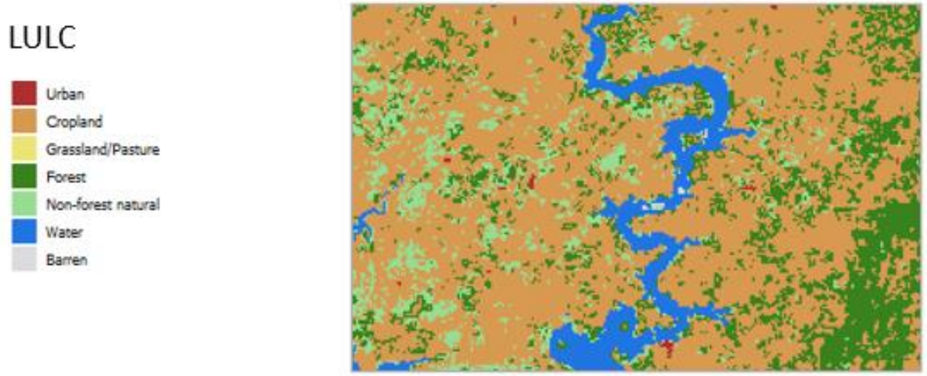
```
Equation E_qo
# industry zero pure profits condition #
(all,a,ACTS)(all,r,REG)
    po(a,r) + ao(a,r)
        = sum{e,ENDW, STC(e,a,r) * [pfe(e,a,r) - afe(e,a,r) - ava(a,r)]}
        + sum{c,COMM, STC(c,a,r) * [pfa(c,a,r) - afa(c,a,r) - aint(a,r)]}
        + profitslack(a,r);
```



Pollinator Biophysical Modelling

- Models the extent to which pollinator habitat is provided adjacent to areas of pollinator dependent cropland production
  1. Calculated proportional area of natural land around all agricultural grid-cells within 2km flight-distance (Kennedy 2013) to calculate sufficiency (Kremen 2005)
  2. Multiplied sufficiency by that crops pollination dependency function (Klein et al. 2013)
  3. Generated grid-cell and crop-specific outputs on changed productivity

Pollination example of linking land-use change to economic performance



- Used a global land-use change model (SEALS) to create 300m global LULC maps from GTAP-derived regional land-use change predictions.
- Then used these as inputs into InVEST.
- Then used these as inputs (shocks) to GTAP specific to each crop and region.
- Calculates macroeconomic impact from lost ecosystem services.

Results

For tomorrow!