Global-Local-Global Analysis of Systems Sustainability

GLASSNET

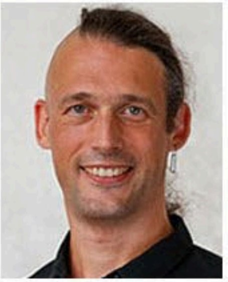
An International Network of Networks

GLASSNET Use Case Workshop

Spillover effects play key role in maintaining planetary boundaries

September 14, 2023 · 9:00-11:00 AM EDT (UTC-4)

Catherine Kling
Cornell University



Christoph Müller
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Dieter Gerten
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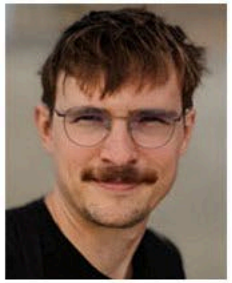

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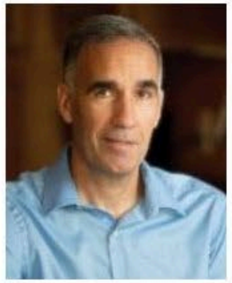

Chris Kucharik
University of Wisconsin-Madison

Monika Zurek
University of Oxford

Register

https://purdue-edu.zoom.us/

GLASSNET: An International Network of Networks designed to tackle GLG challenges

https://mygeohub.org/groups/glassnet

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Spillover Effects Play Key Role in Maintaining Planetary Boundaries

Iman Haqiqi, Jannes Breier, Dieter Gerten, Christoph Müller

September 14, 2023

GLASSNET Use Case Workshop

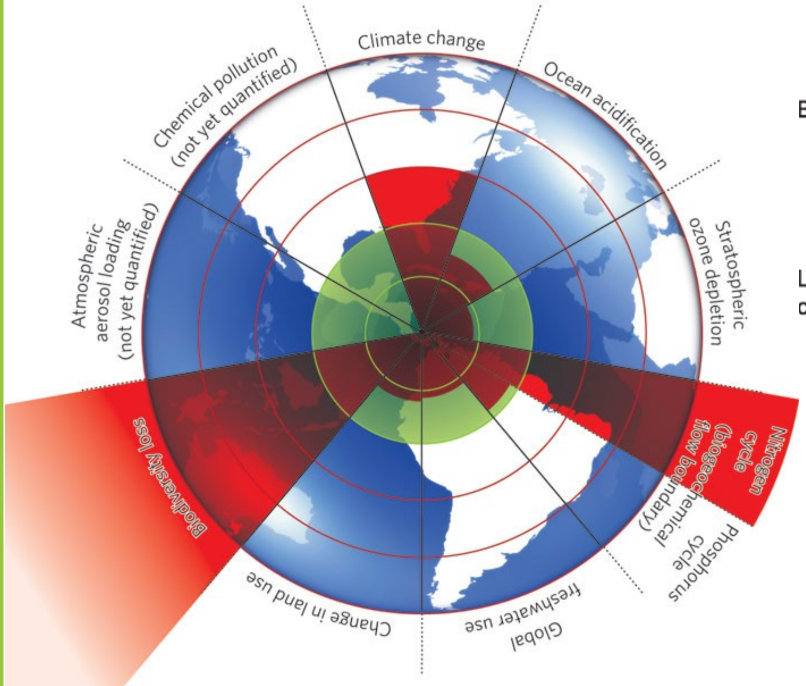
Introduction

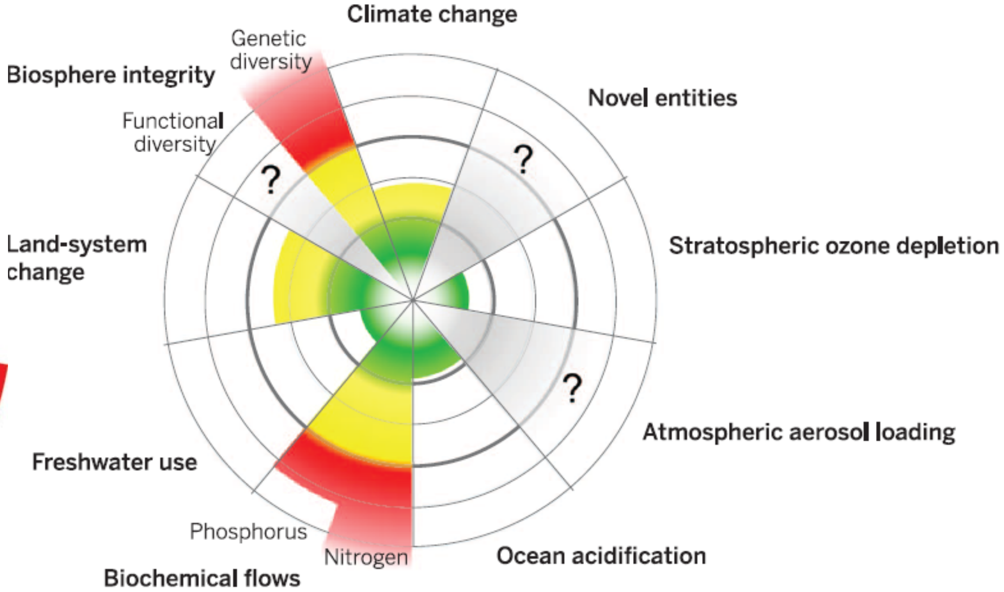
Planetary Boundaries (PBs) framework

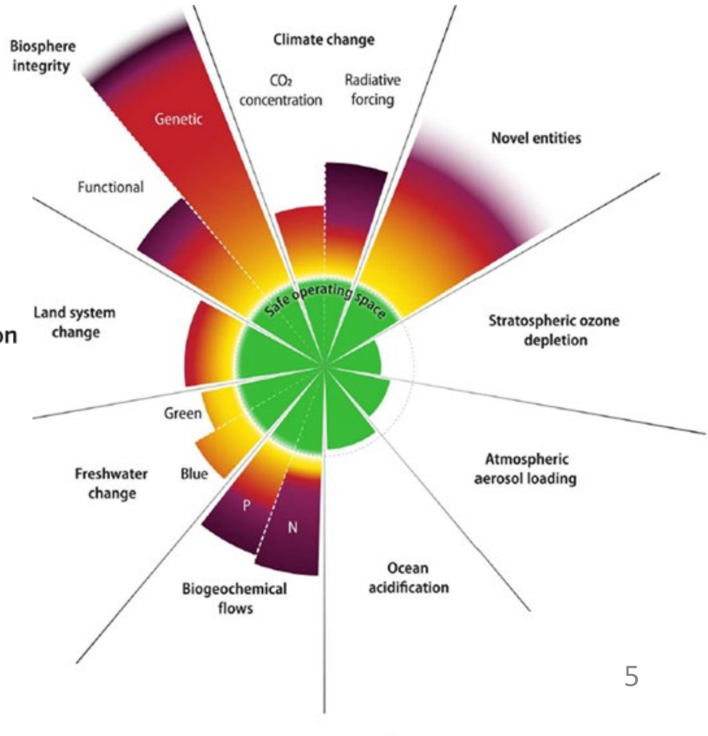
Rockström et al.,
Nature 2009

Steffen et al.,
Science 2015

Richardson et al.,
Science Advances 2023
(yesterday!)







Planetary Boundaries (PBs) framework

- For **nine** interacting Earth system processes PBs are identified, which **together** demarcate the **Holocene state** of our planet:

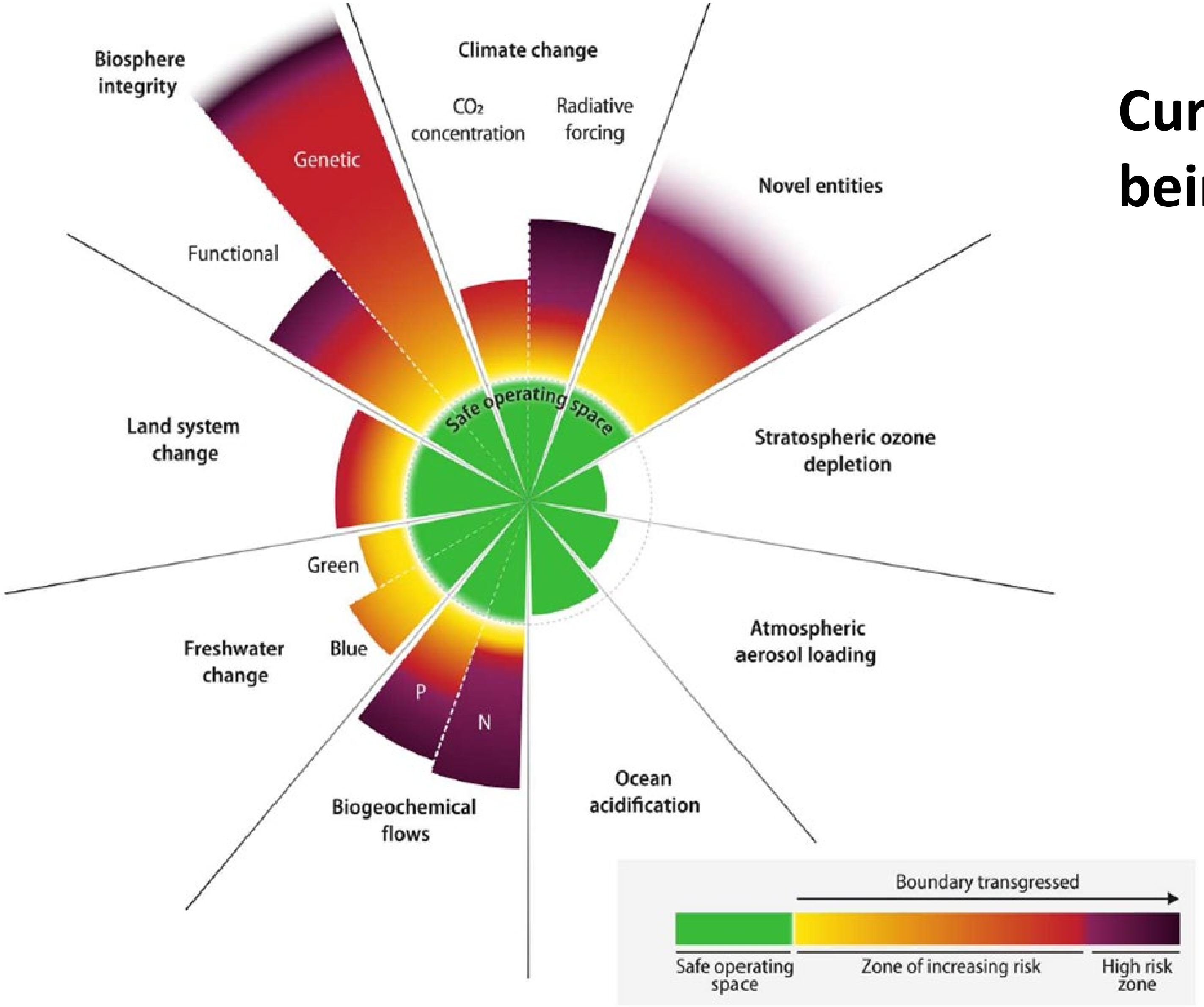
  Climate change | Stratospheric ozone depletion | Atmospheric aerosols | Ocean acidification | Biogeochemical flows | Novel entities | Land-system change | Biosphere integrity | Freshwater use

- The **Holocene** is considered a **safe operating space**, which enabled human civilization to develop – and which thus should not be left.

- **Transgression** of (multiple) PBs may alter the Earth system with **dangerous consequences**.

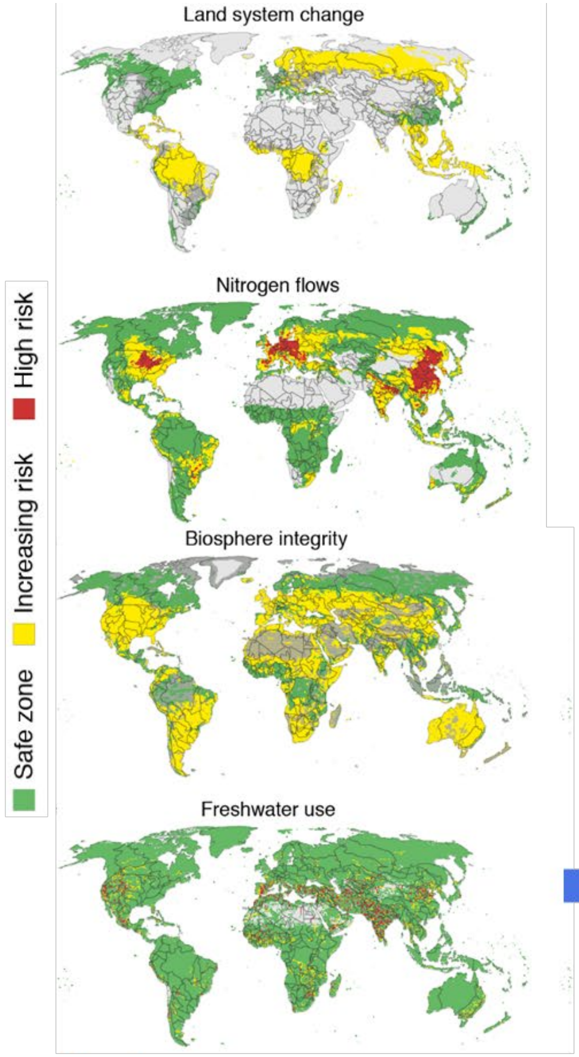
- A **precautionary principle** is applied – as unkown abrupt changes and reinforcing feedbacks are likely, and societies react with delay.

6 out of 9 PBs already transgressed

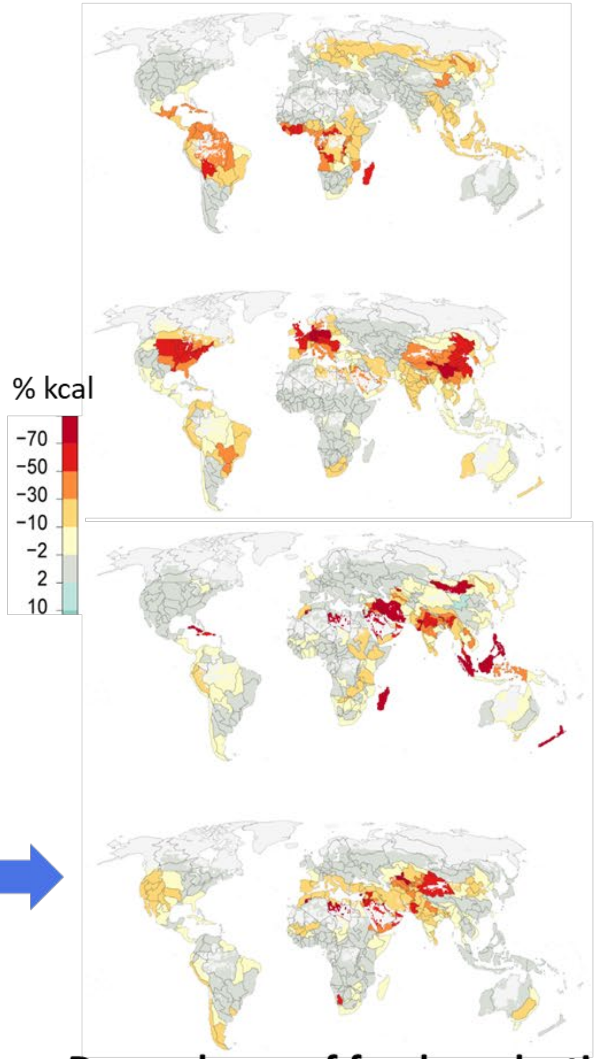


Current world agriculture being a main driver

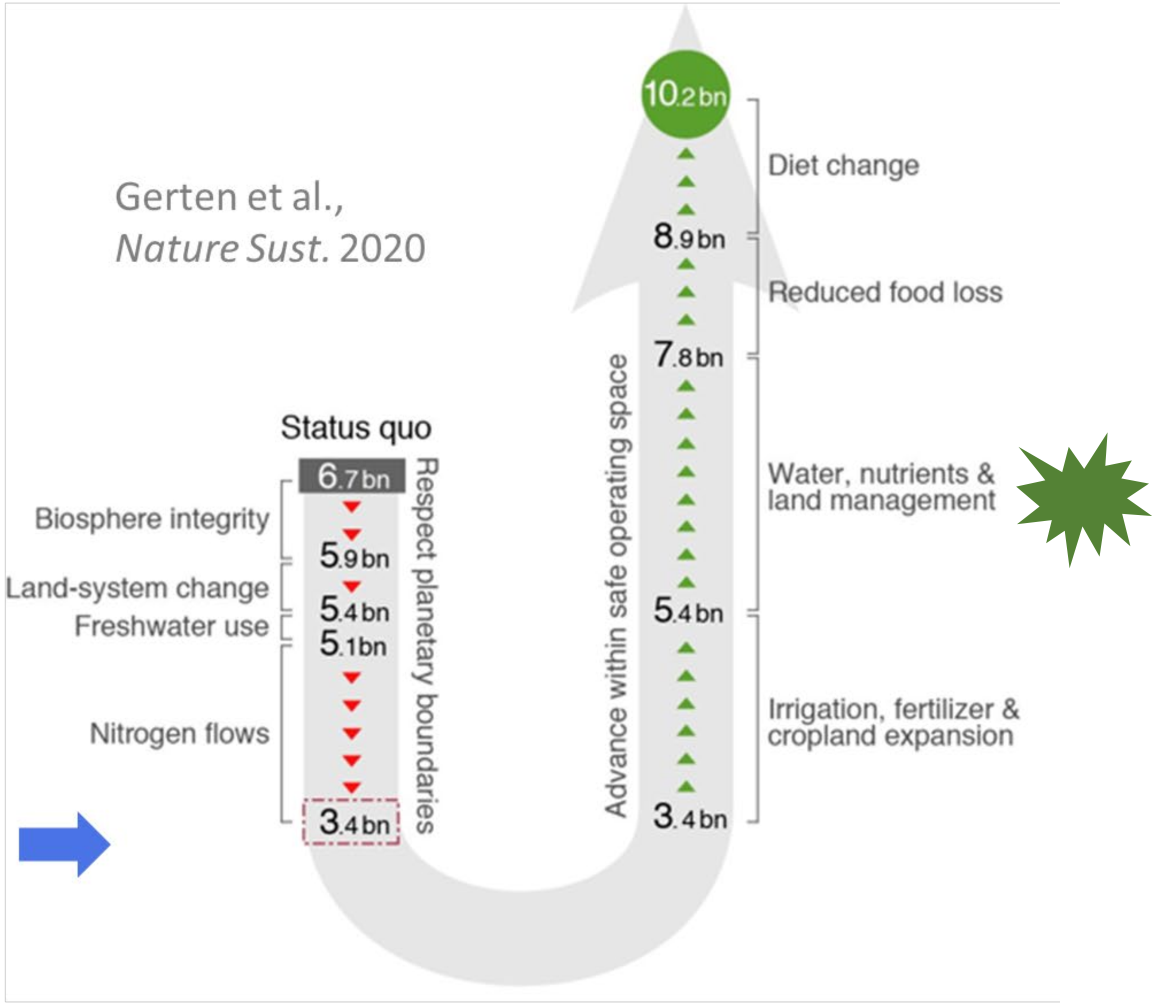
Transform the food system within PBs



LPJmL: dynamic, process-based, spatial simulation of terrestrial PBs



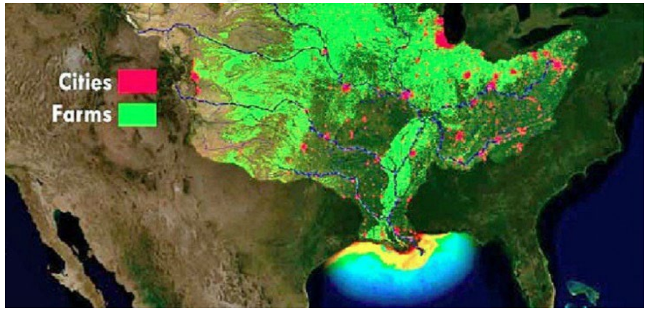
Dependence of food production on current PB transgressions



Option space exists to provide food for 10 bn people within the PBs

A focus on nitrogen

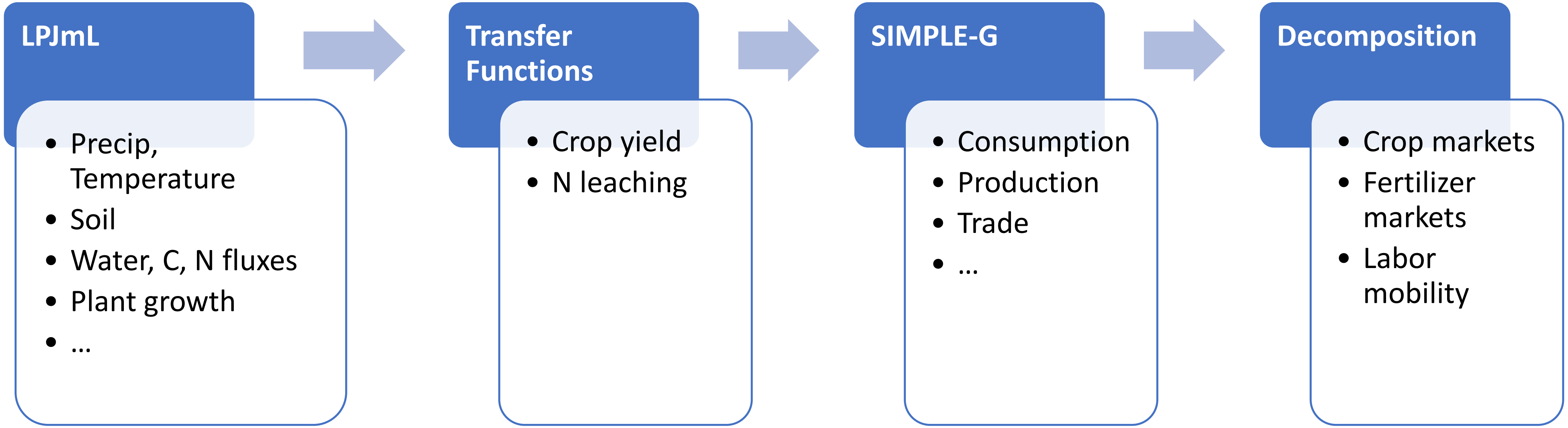
- N application largest driver of terrestrial PB transgression
- Serious impacts of N leaching on freshwater ecosystems
  - e.g. N fertilizer application in the Corn Belt => water quality => health system
  - Transfer through Mississippi => dead zone in ecosystem
    - >2 million acres of habitat potentially unavailable to fish and bottom species
    - hypoxic zone in 2017: 5.6 million acres
- Global–local and telecoupled impacts



Research objective

- Study selected socioeconomic implications of required transformations
- Specifically, quantify spillover effects (market-mediated impacts) of policies towards maintaining the nitrogen PB
- Multi-scale analysis required of policies as well
  - Local substitution with other inputs: more stress on local land and water
  - Regional relocation (+ global trade change): new stress on land and water elsewhere
- Develop a framework for coupling LPJmL and SIMPLEG models

The need for multidisciplinary setting



- LPJmL:
  - Global gridded vegetation model
- Transfer Functions:
  - Estimated N application, Yield response, and leaching
- SIMPLE-G-Global:
  - Developed a new N fertilizer trade module based on FAO data
- Decomposition the spillover effect

Methods (1): LPJmL

Introduction to LPJmL

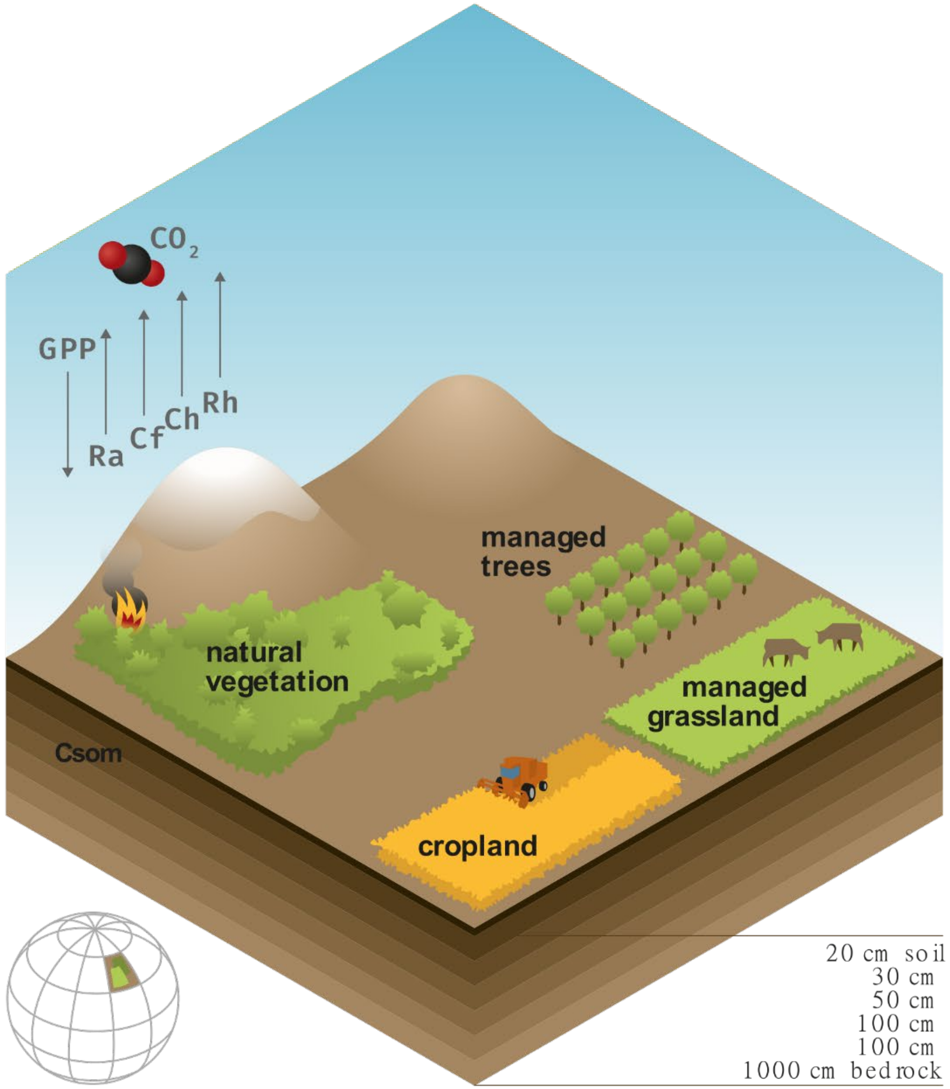
LPJmL

Lund-Potsdam-Jena
managed Land Model

Introduction to LPJmL

Carbon

GPP	gross primary production
Ra	autotrophic respiration
Rh	heterotrophic respiration
Ch	harvested carbon
Cf	fire carbon fluxes
Csom	soil organic matter C



Introduction to LPJmL

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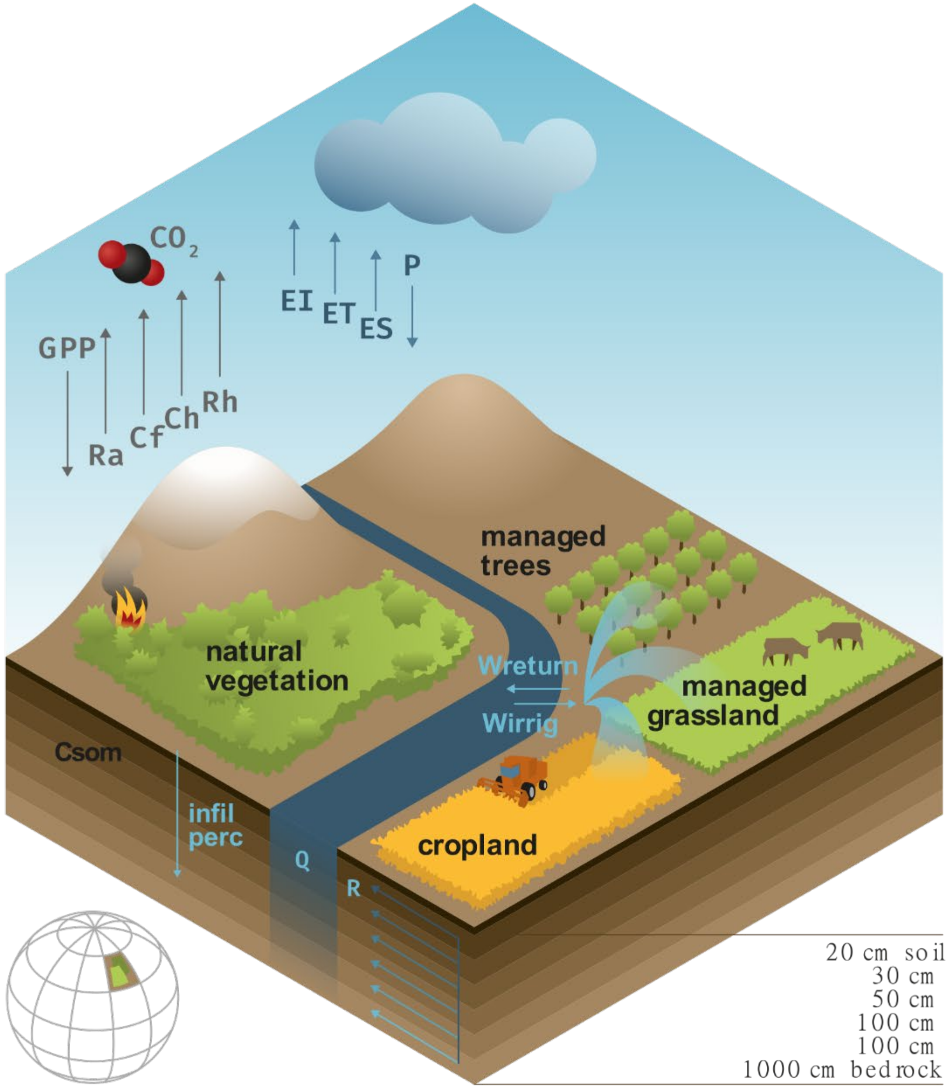
Water

EI	interception
ET	transpiration
ES	evaporation
P	precipitation
perc	percolation
infil	infiltration
R	runoff
Wreturn	return flow of irrigation
Wirrig	irrigation water
Q	discharge



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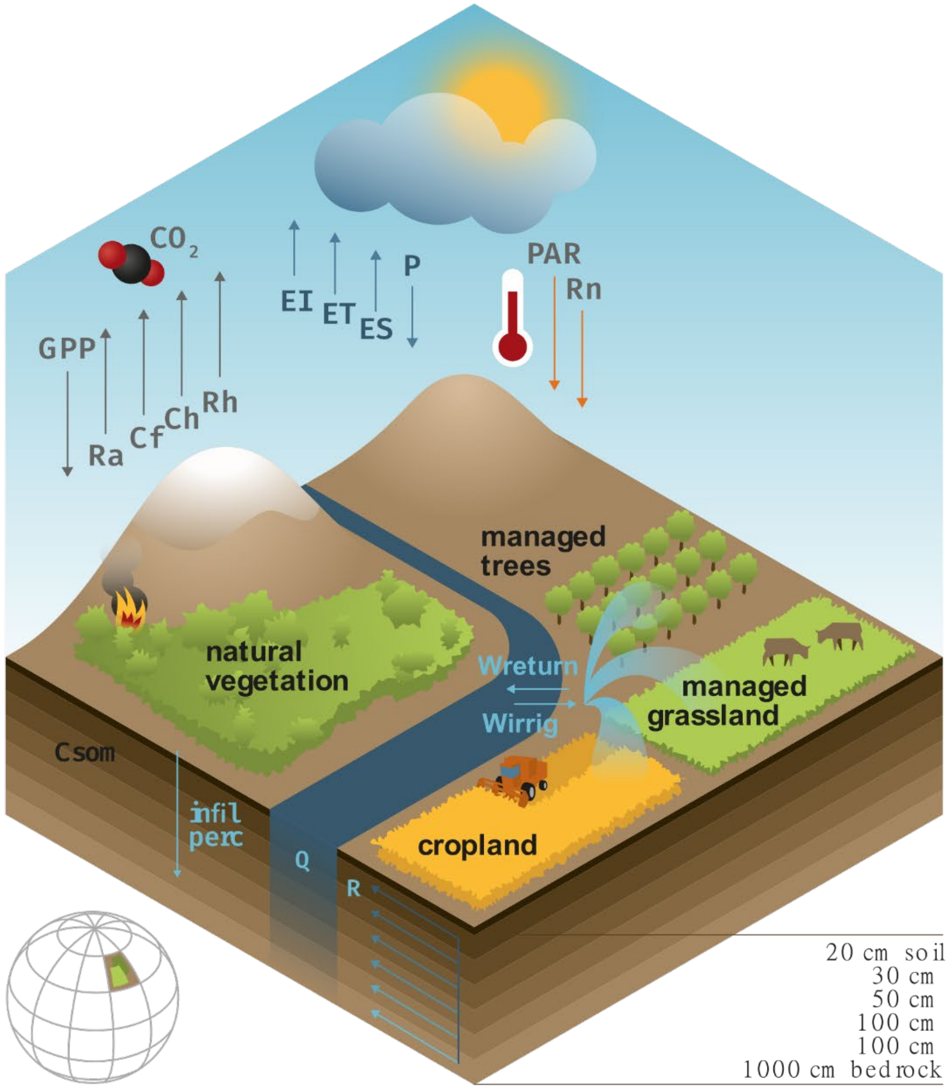
Energy

PAR	photosynthetic active radiation
Rn	net radiation



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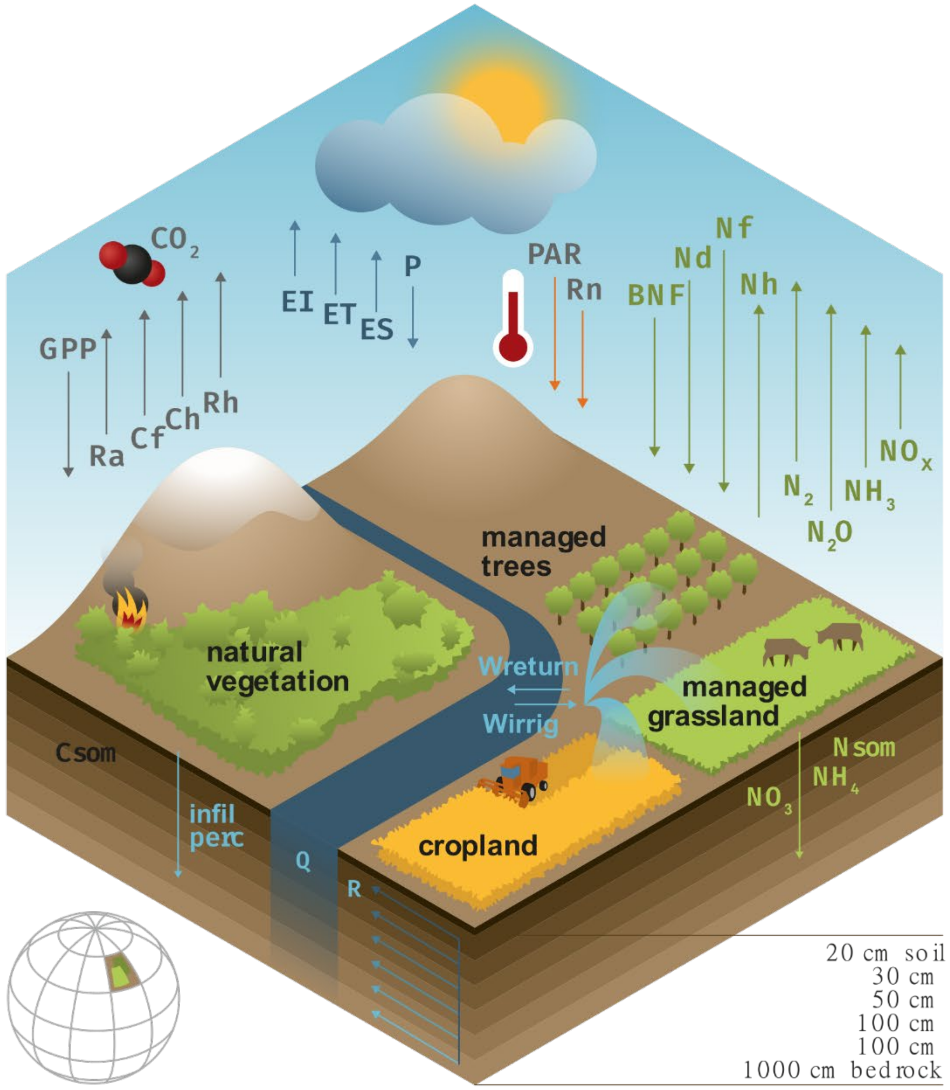
Energy

PAR	photosynthetic active radiation
Rn	net radiation

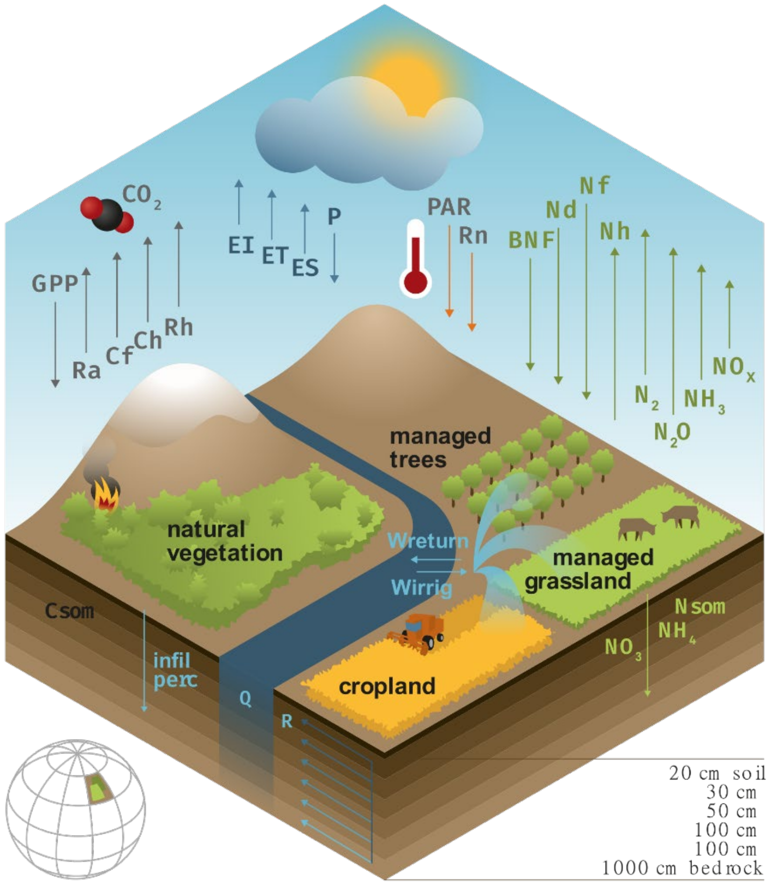
Nitrogen

BNF	biological N fixation
Nf	fertilizer/manure input
Nd	atmospheric deposition
Nh	harvested nitrogen
N_2	molecular N emission
N_2O	nitrous oxide emissions
NH_3	ammonia volatilization
NO_x	nitrogen oxides emissions
Nsom	soil organic matter N



Input & Output

- **Soil**
- **Climate**
- **Water**
- **Management**
  - Land use
  - Tillage
  - Residue Management
  - Cover cropping
  - Fertilizer input
  - Irrigation type
  - Rainwater management
- **Other**
  - Population density
  - N deposition
  - ...

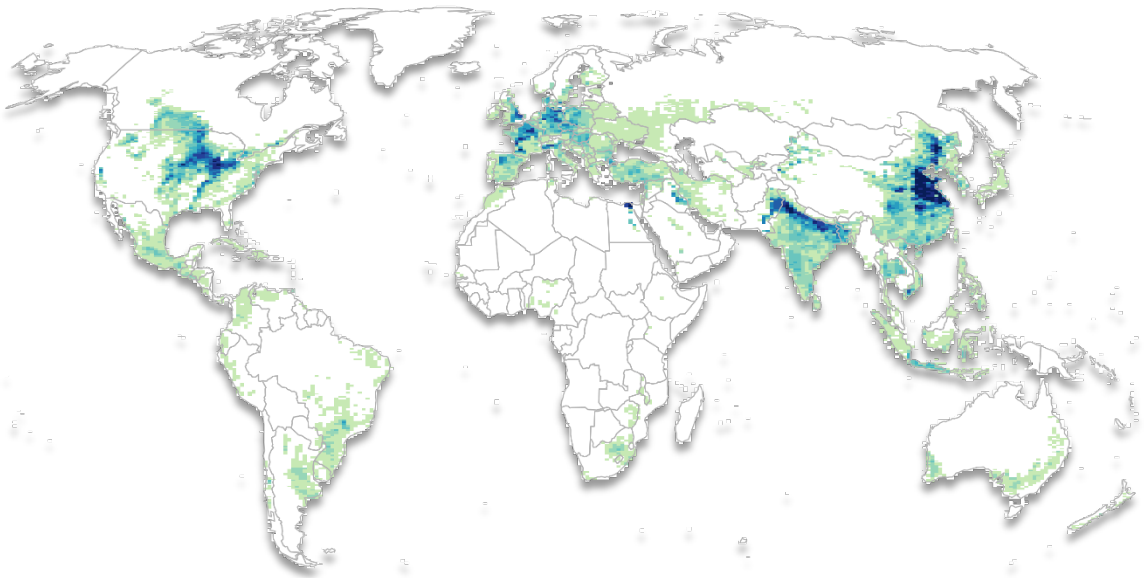


- **General**
  - Vegetation biomass
  - GPP/NPP
  - Litter carbon
  - Soil carbon
  - Runoff
  - Environmental Flow Requirements (EFRs)
  - N leaching
  - ...
- **Agriculture**
  - Crop yield
  - Sowing/Harvest dates
  - Residue yield
  - ...

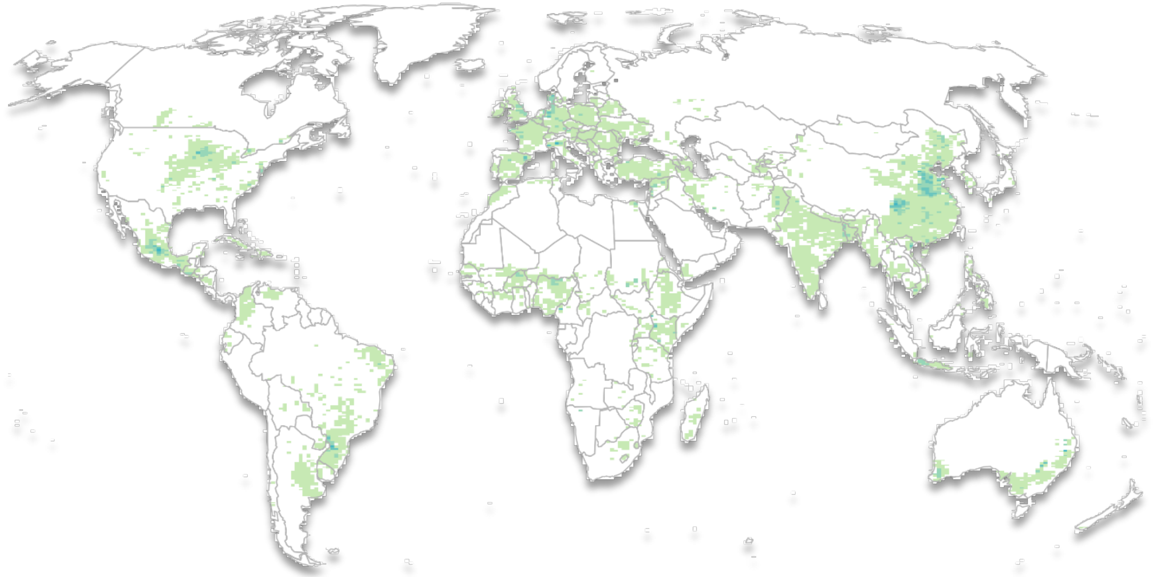
Planetary Boundary Status

Global fertilizer application

Fertilizer application 2018

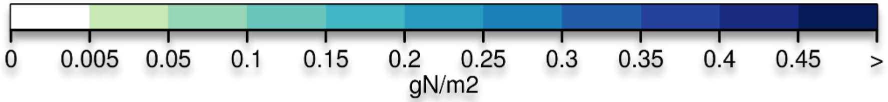


Manure application 2018

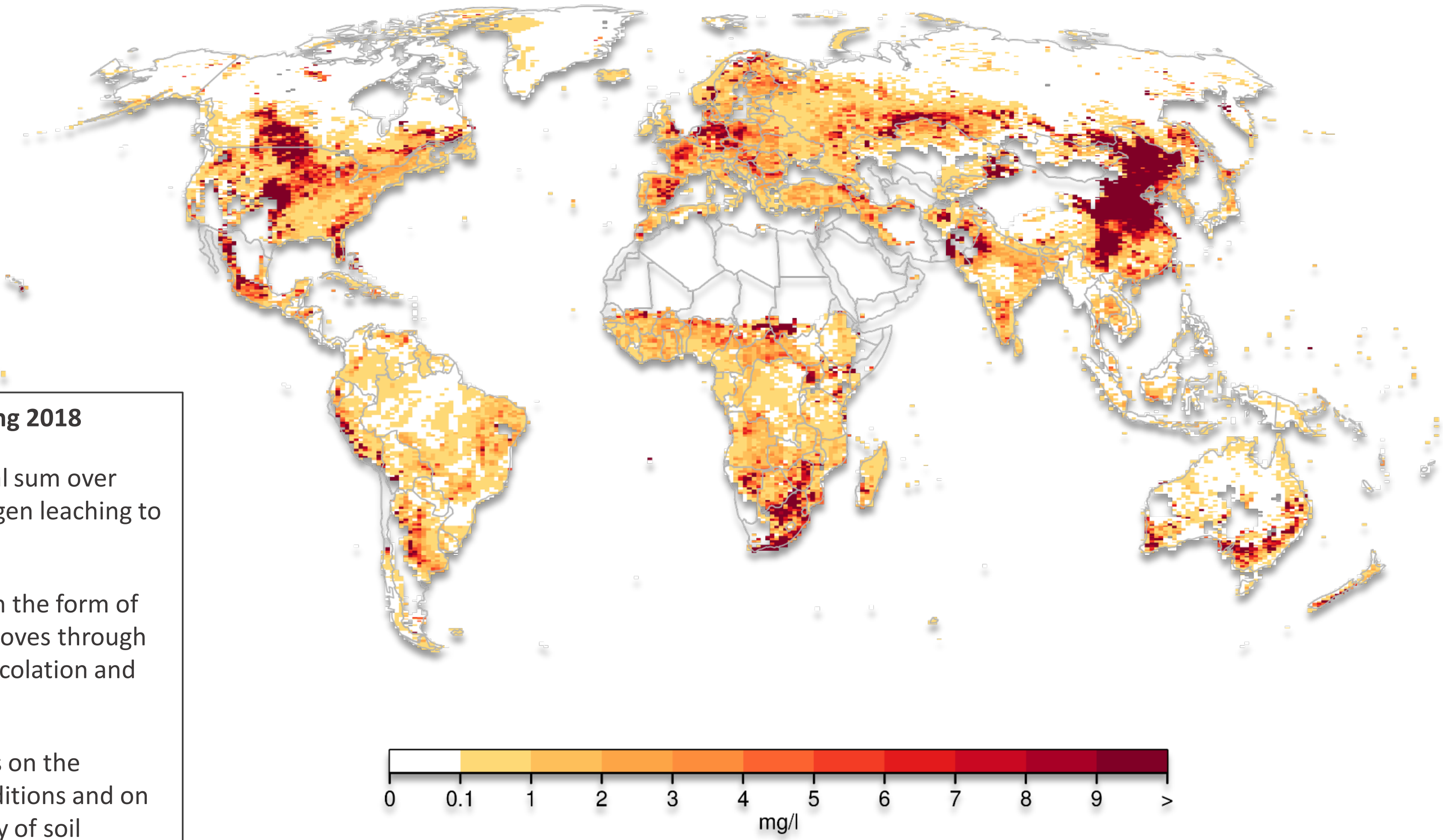


Annual fertilizer application year 2018

- Product by Ostberg et al. (2020)
- Model input of LPJmL
- 20% applied on sowing date, 80% at second event



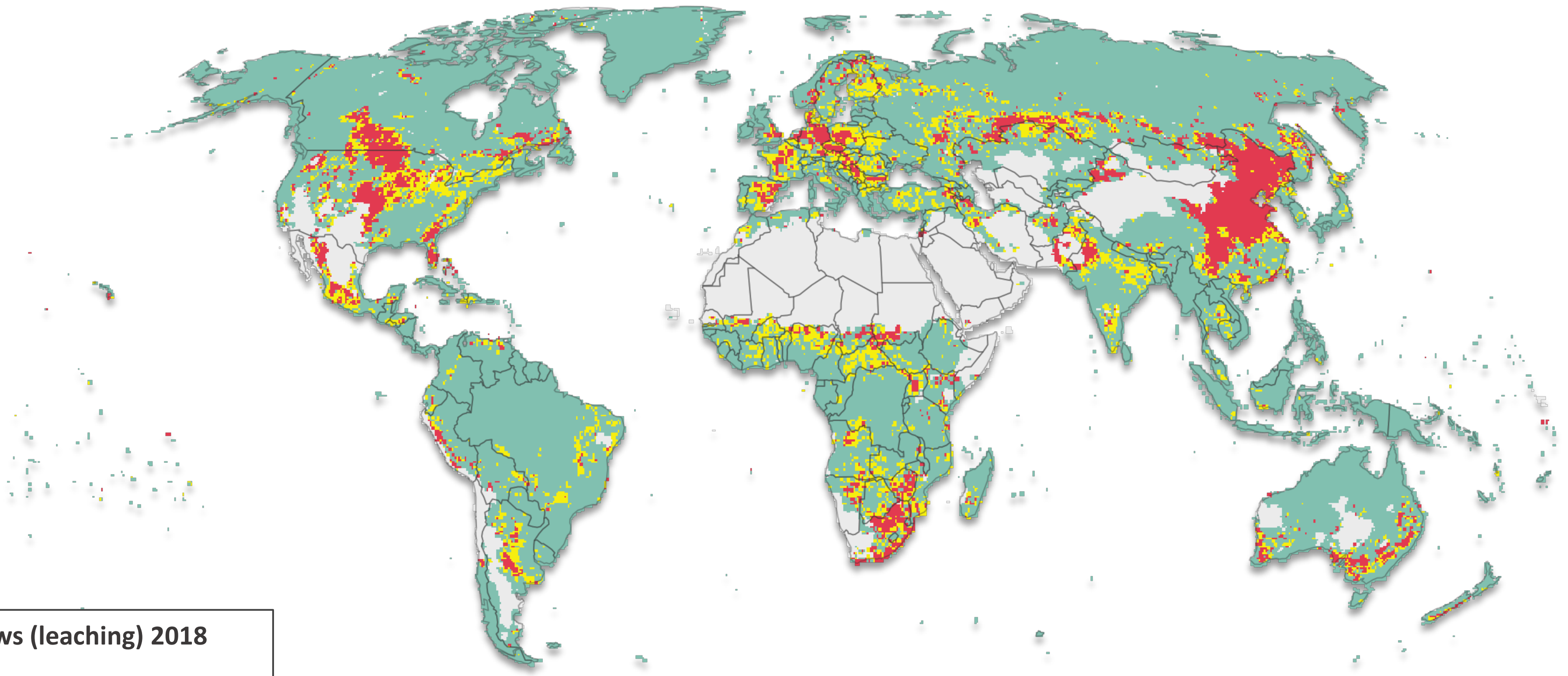
Global nitrogen leaching



Annual nitrogen leaching 2018

- Defined as the annual sum over daily simulated nitrogen leaching to the aquatic systems
- Nitrogen is leached in the form of nitrate (NO3-) that moves through the soil via water percolation and runoff
- The amount depends on the climatic and soil conditions and on the type and intensity of soil management (e.g. plant cover, soil treatment, fertilization).

The planetary boundary status



- safe zone
- increasing risk
- high risk

PB Nitrogen flows (leaching) 2018

Defined after Schulte-Uebbing et al. 2022 and de Vries et al (2021):

› Safe Zone: < 2 mgN/l

› Increasing risk: 2-5 mgN/l

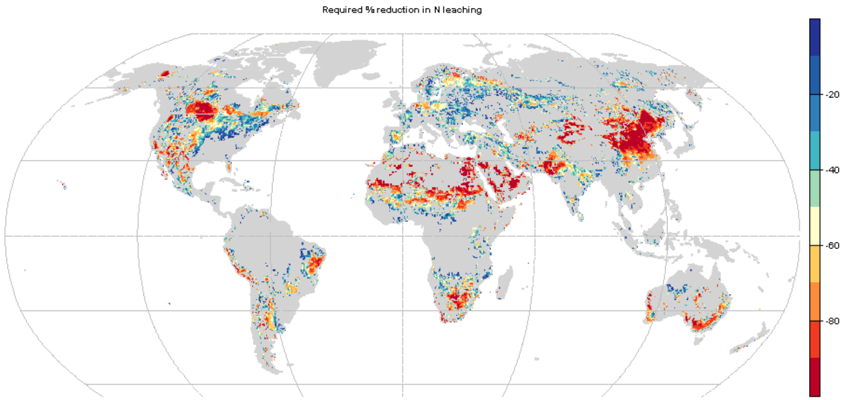
› High risk: > 5 mgN/

Methods (2): Emulators and transfer functions

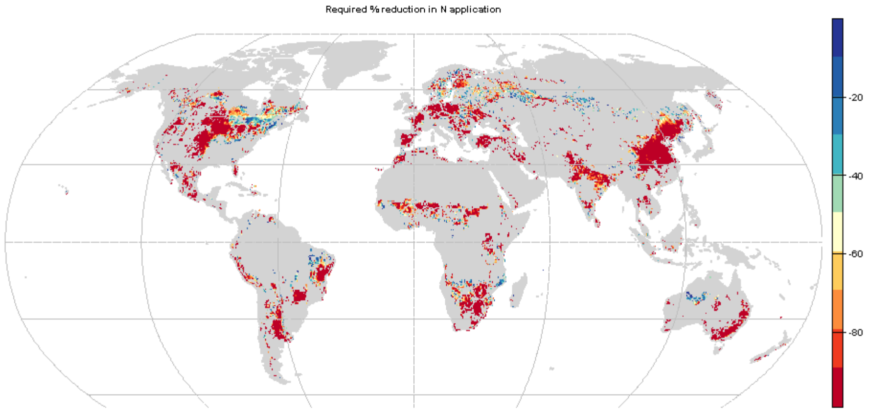
Following: Liu, Jing, et al. (2023).Tackling policy leakage and targeting hotspots could be key to addressing the" Wicked" challenge of nutrient pollution from corn production in the US. *Environmental Research Letters*. **DOI** 10.1088/1748-9326/acf727

How much reduction in N is required?

Required % change in leaching



Required % change in N



Scenario:

The change from current conditions needed to get to the boundary levels.

Boundary definition:

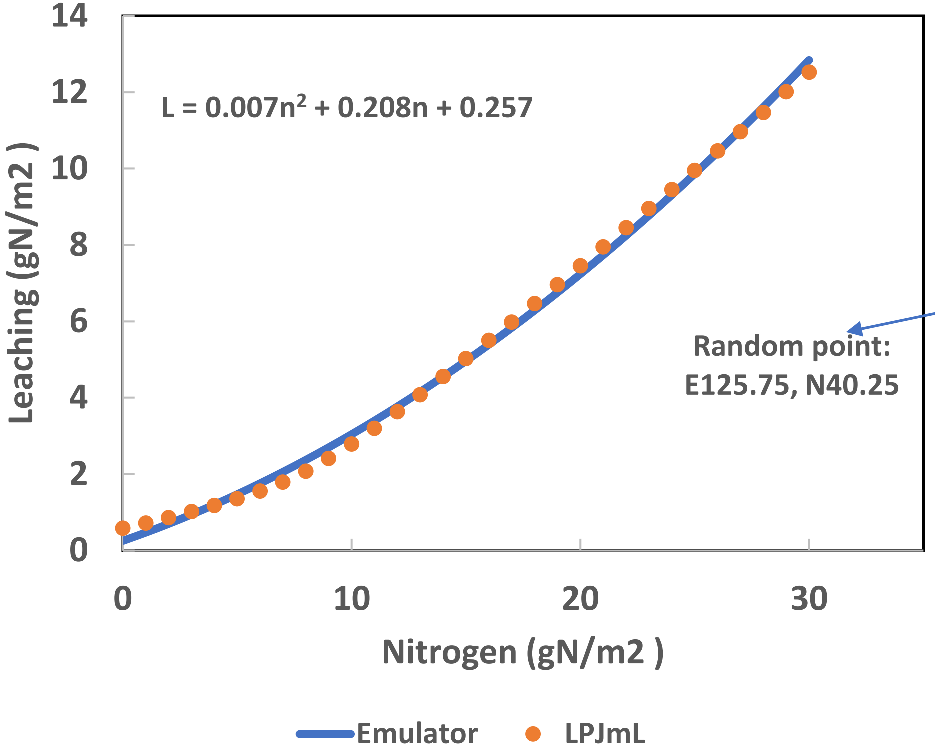
- **leaching/runoff should not be more than 2 mg/l to be in the safe space and not more than 5 mg/l to be in the zone of uncertainty**

- **Non-linear leaching functions**
- **Considering 2009-2018 LPJmL runs**

LPJmL: leaching emulator

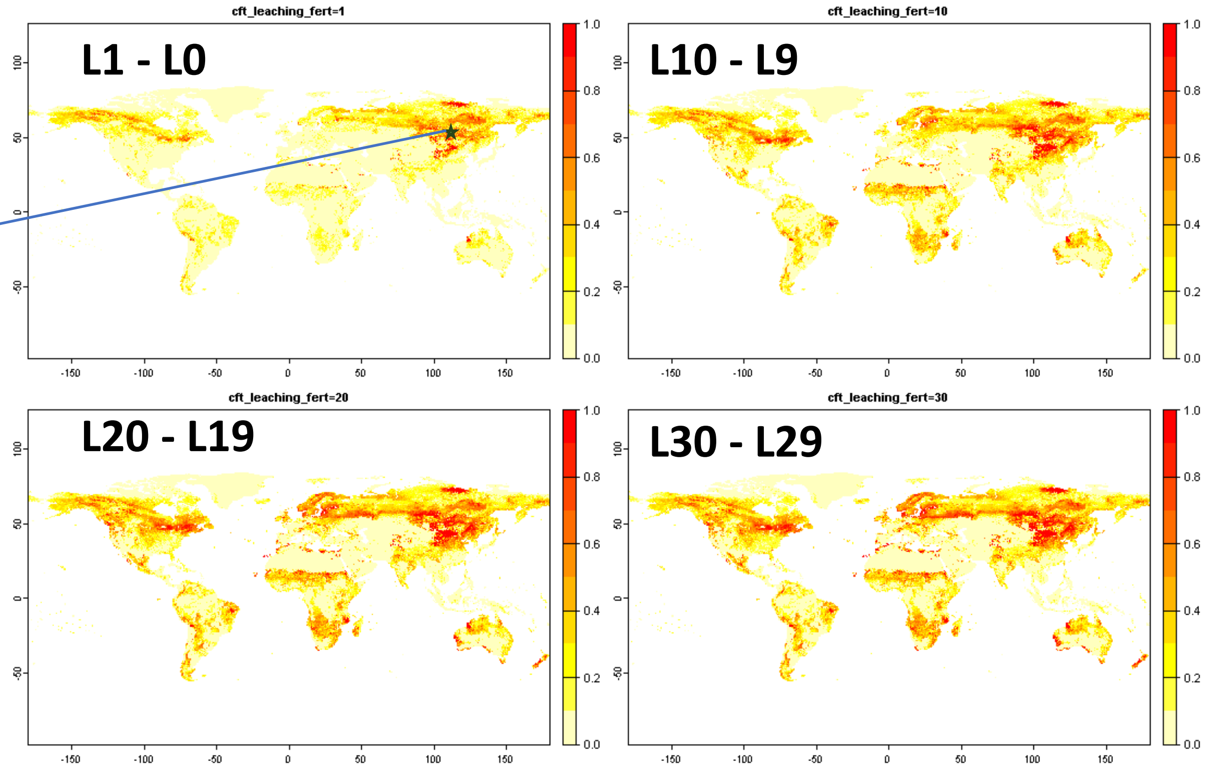
- We estimated the coefficients of a quadratic emulator based on LPJmL runs and 31 levels of N
- Coefficients are grid-cell specific
- Marginal N leaching rate: the change in leaching by adding one unit of N
  - Maps show that at higher N application rates, the bigger portion of is leaching

Leaching emulator

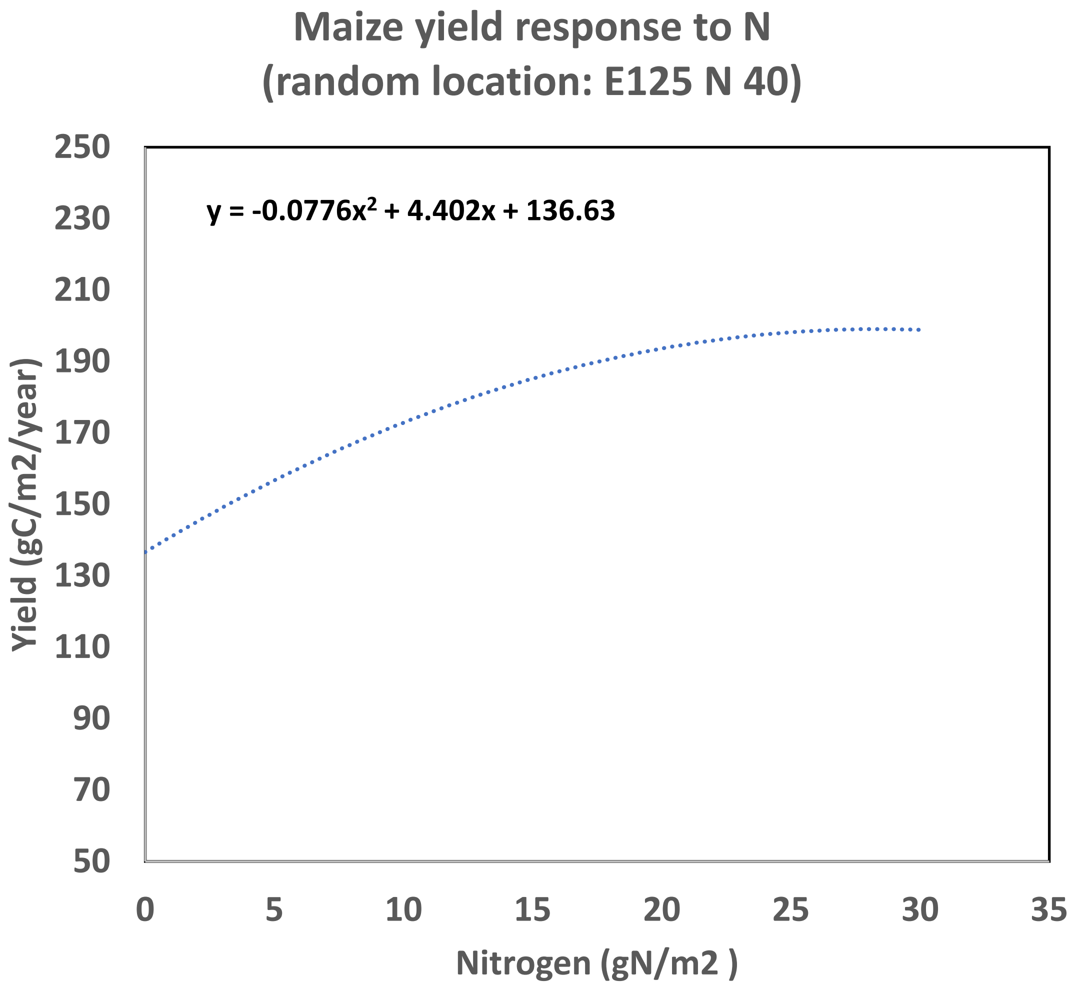


- NOTE: Figure is based on a random point

Increasing "marginal N leaching rate"



LPJmL: Yield emulator



$$Y_i = \alpha_i + \beta_i N + \theta_i N^2$$

$$V_i = P_i Q_i \xrightarrow{Q_i = L_i Y_i} V_i = P_i L_i Y_i$$

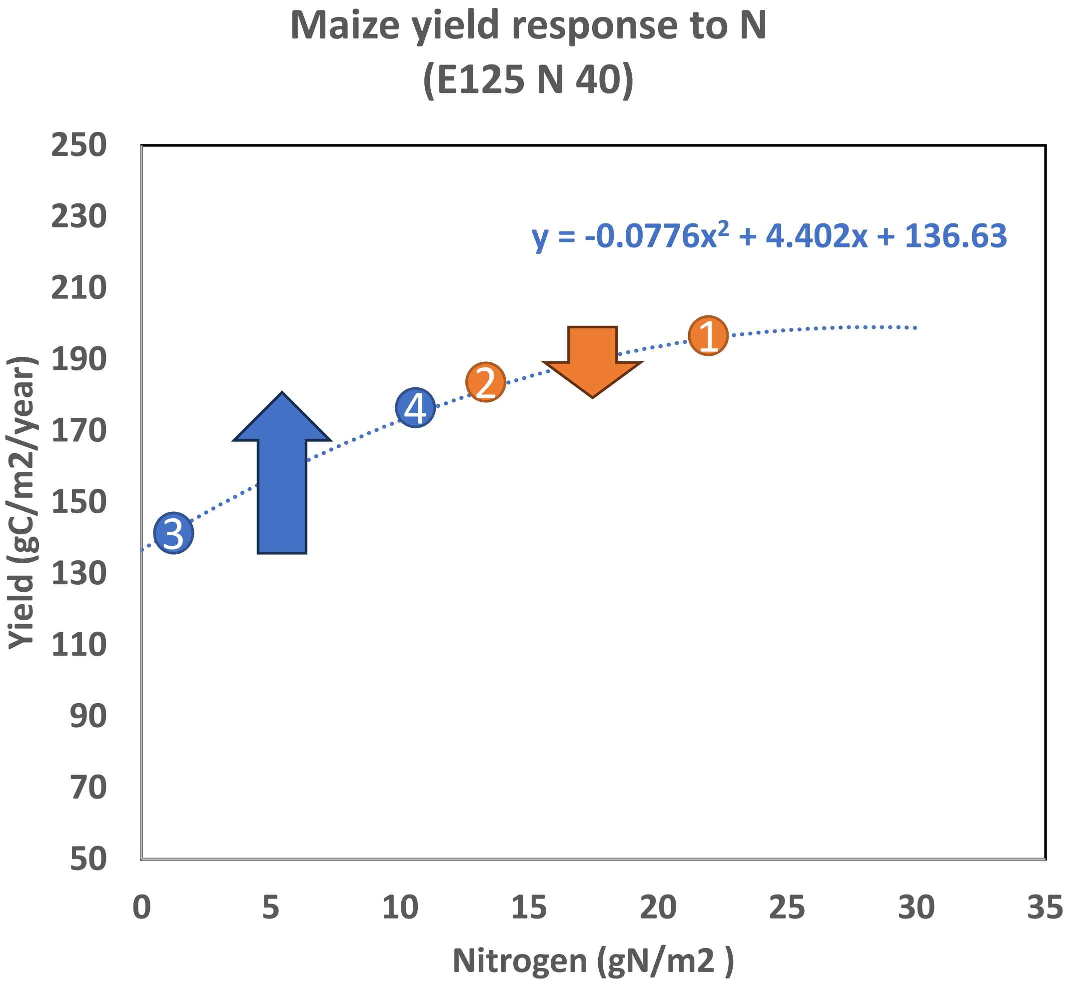
$$V_{all} = \sum_i V_i = \underbrace{\sum_i P_i L_i \alpha_i}_{\alpha_{all}} + N \underbrace{\sum_i P_i L_i \beta_i}_{\beta_{all}} + N^2 \underbrace{\sum_i P_i L_i \theta_i}_{\theta_{all}}$$

- We estimated the coefficients of the emulator based on LPJmL runs
- Coefficients are grid-cell specific
- We take 31 runs of LPJmL for different levels of N application
- All crops for 2009-2018

- NOTE: Figure is based on a random point.

To inform SIMPLE-G:

substitution elasticity



- NOTE: Figure is based on a random point

- **We compute the substitution elasticity between N and other inputs.**
- **Definition:**
  - **% change in ratio of input quantities in response to 1 % change in ratio of input prices**
- **Higher elasticity implies lower yield cost for reducing N**

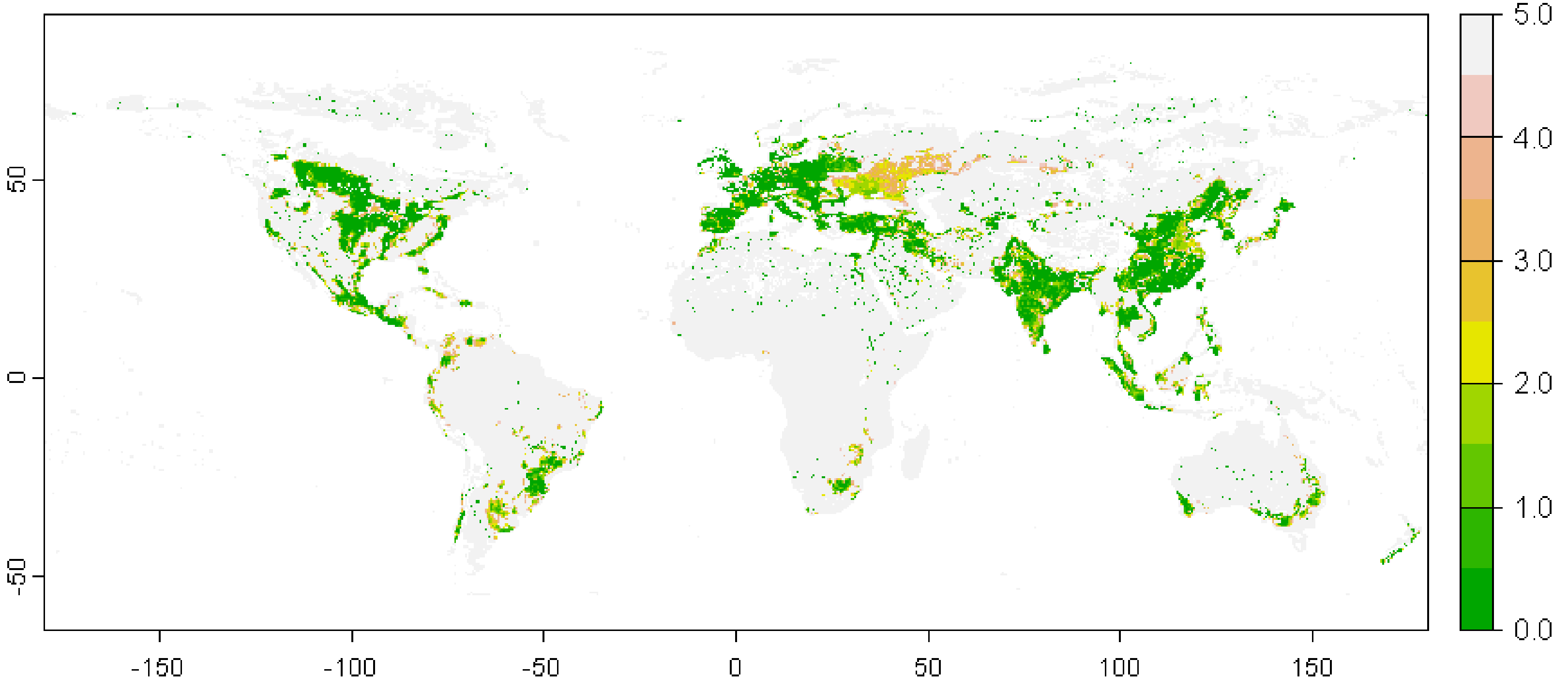
$$\sigma_{NL} = \frac{f'(n)\left[f(n) - nf'(n)\right]}{-nf''(n)f(n)}$$

$$f(n) = \alpha + \beta n + \theta n^2$$

$$f'(n) = \beta + 2\theta n$$

$$f''(n) = 2\theta$$

Map of estimated σ (substitution elasticity)



- The substitution elasticity is spatially heterogeneous
- It is relatively high in parts of China, US, East Europe, and Europe

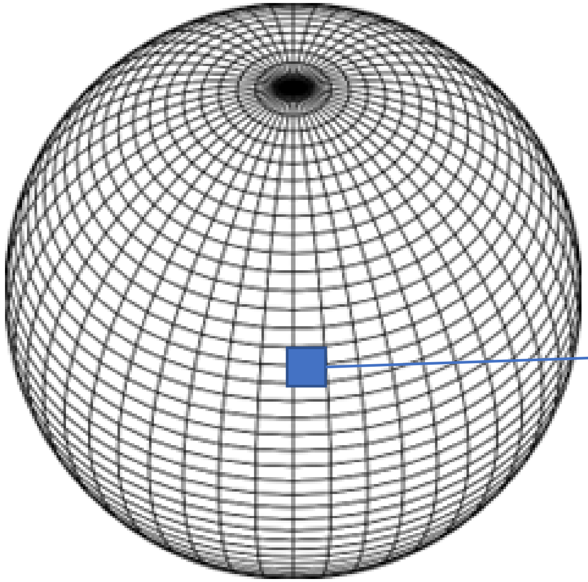
Methods (3): SIMPLE-G Global

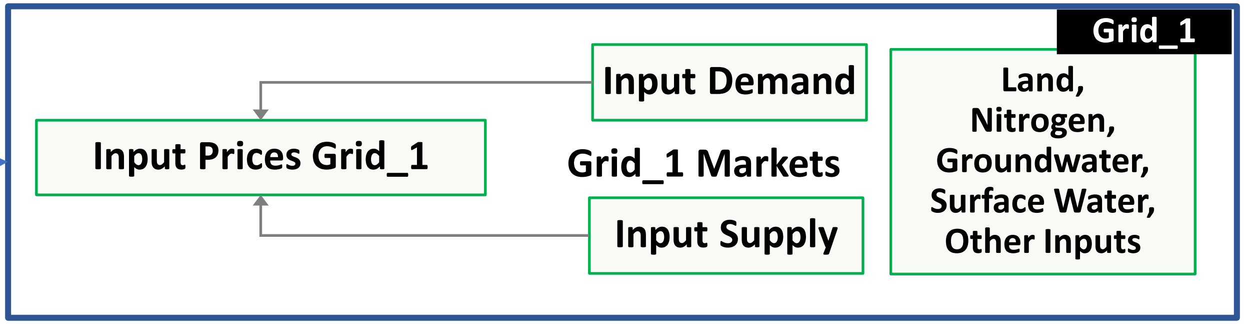
SIMPLE-G:

a **S**implified **I**nternational Model of **P**rices **L**and use and the **E**nvironment-**G**ridded version

Multiscale framework for **integration** of economic, hydrological and biophysical determinants of sustainability

Agricultural economic decisions in each location





Local markets with gridded supply and demand

depending on local economic and biophysical conditions (land)

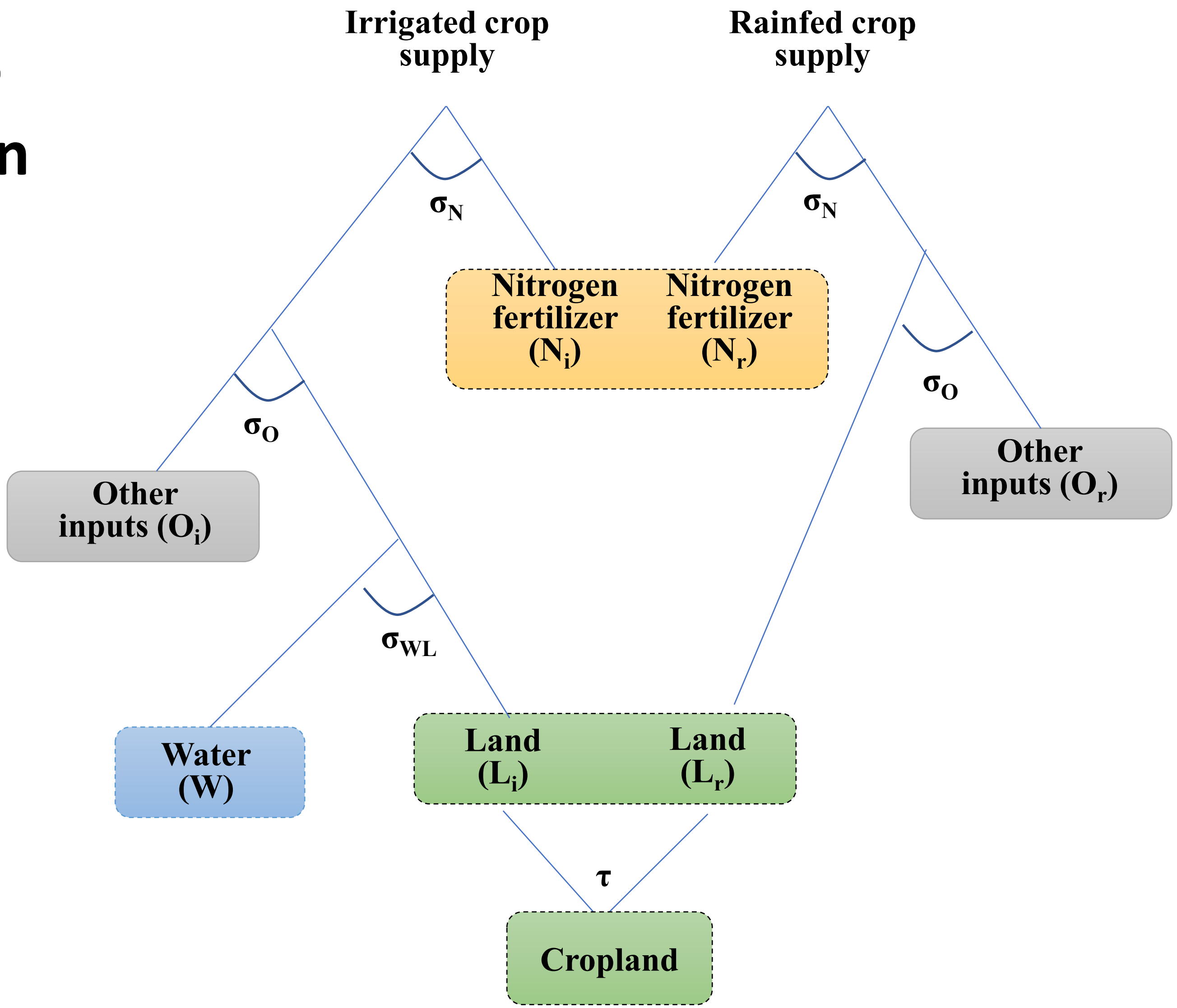
SIMPLE-G: Nested production function and demand for agricultural inputs

Economic demand for each input depends on

- Relative prices
- Production scale

Some biophysical features are reflected in parameters

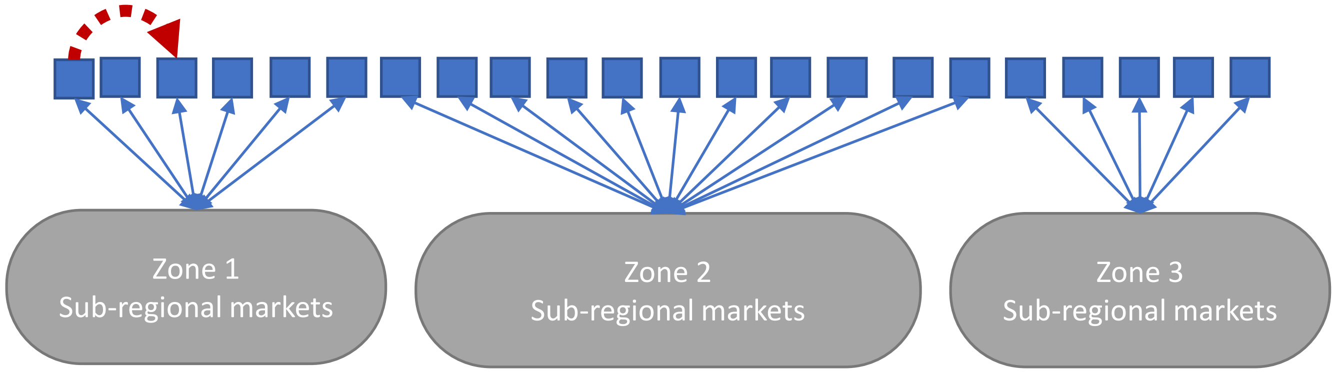
- Substitution elasticity
- Transformation elasticities



~1.4 million grid cells at 5 arc-min

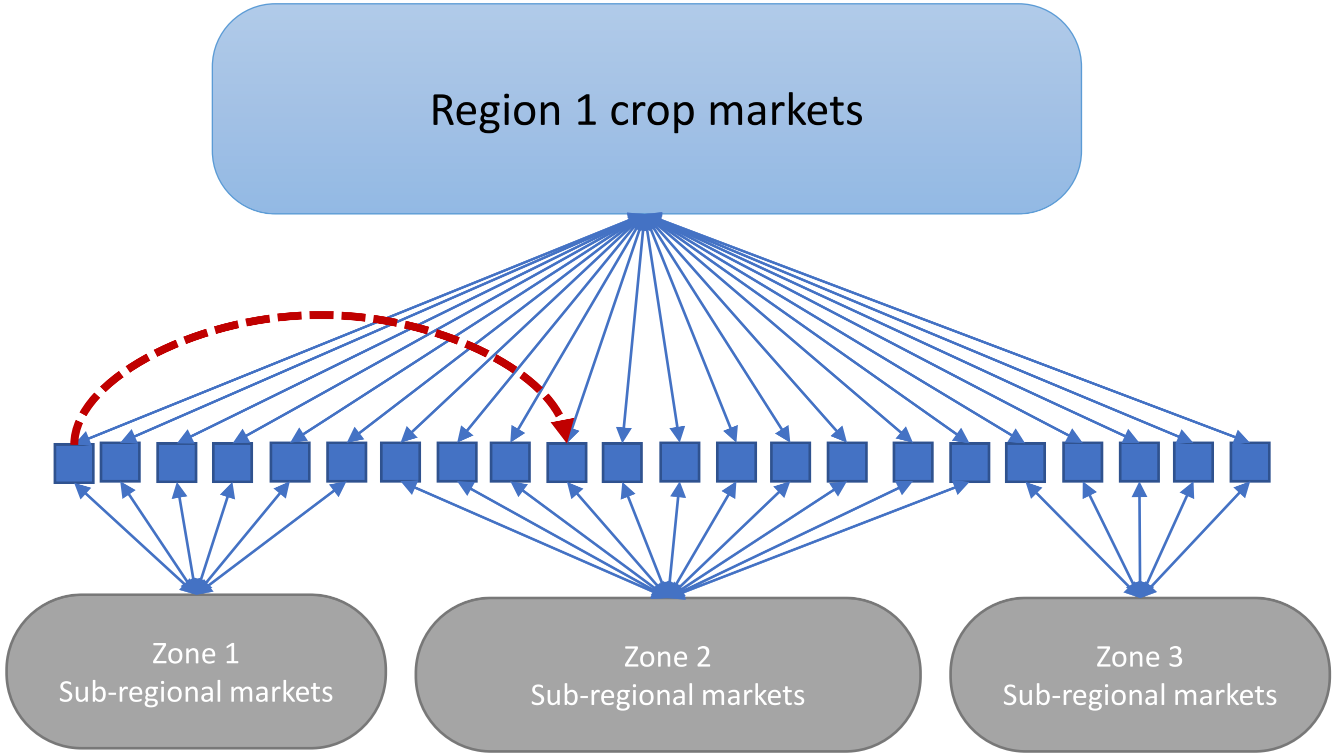
All grid cells are connected via sub-regional input markets and …

Sub-regional markets with imperfect mobility (labor)

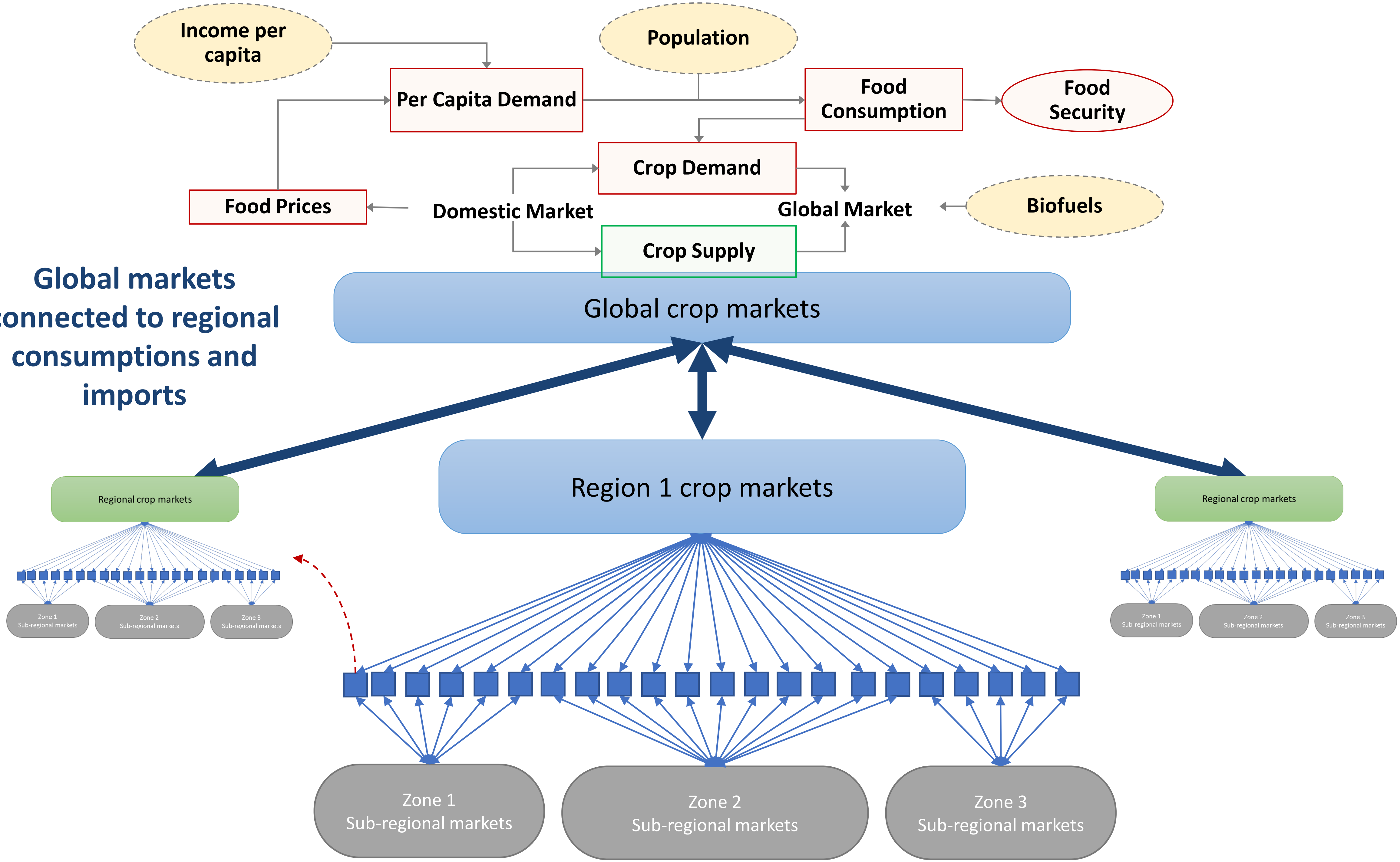


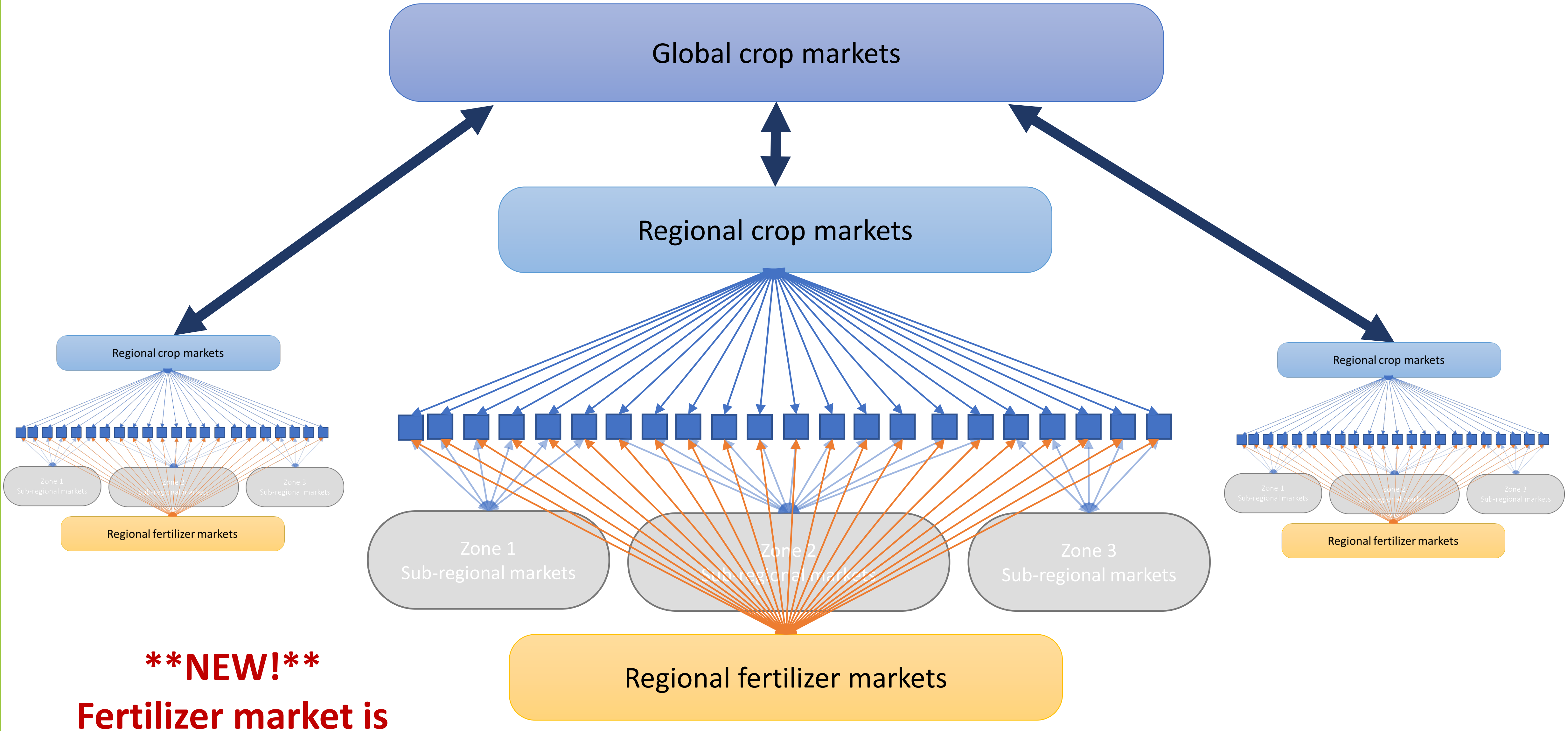
Also, grid cells are connected via regional crop markets and …

regional markets considering product similarity



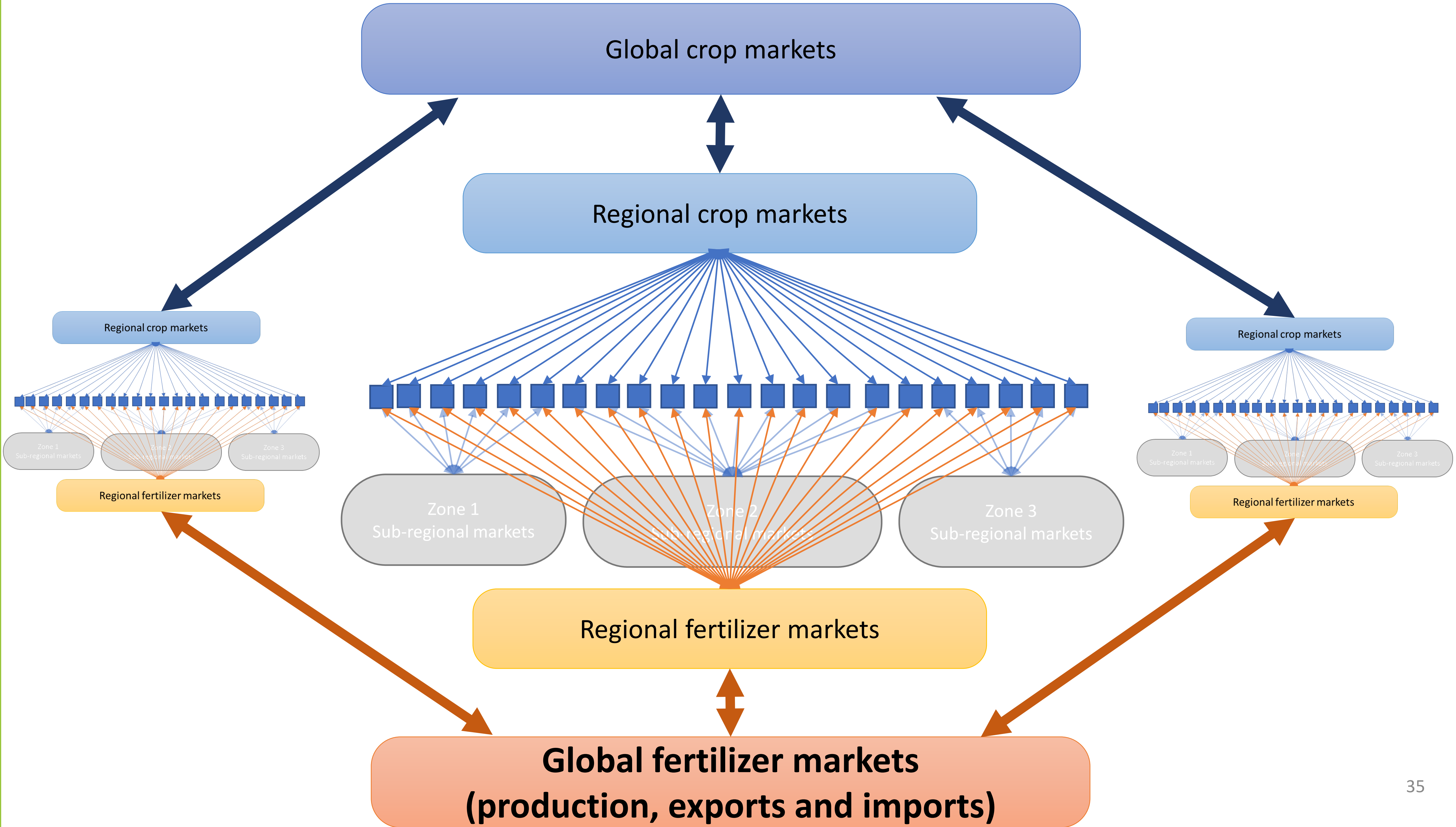
Global markets connected to regional consumptions and imports





****NEW!****

Fertilizer market is another channel for geospatial connections

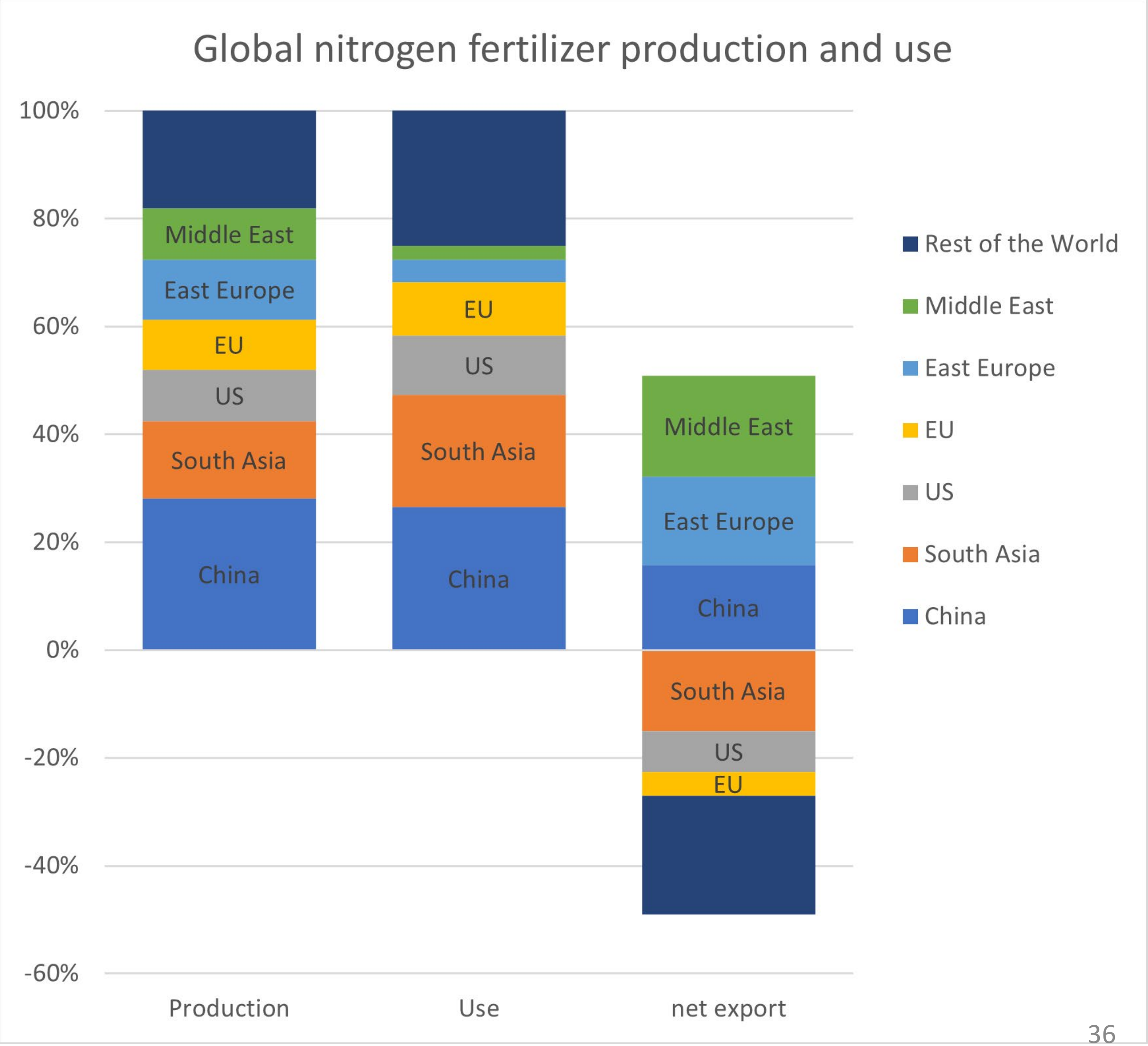


Global crop markets
Regional crop markets
Regional crop markets
Regional crop markets
Zone 1
Sub-regional markets
Zone 2
Sub-regional markets
Zone 3
Sub-regional markets
Regional fertilizer markets
Regional fertilizer markets
Regional fertilizer markets
Global fertilizer markets
(production, exports and imports)

Value of global agricultural markets

- **Nitrogen fertilizer has a small share in total agricultural expenditure**
- **Thus, There should not be a large price shock by limiting N**
- **Global cost share of fertilizer is around 4%**
- ***Simple calculation: Keeping everything else constant, a 100% increase in price of N could lead to ~4% increase in food price***

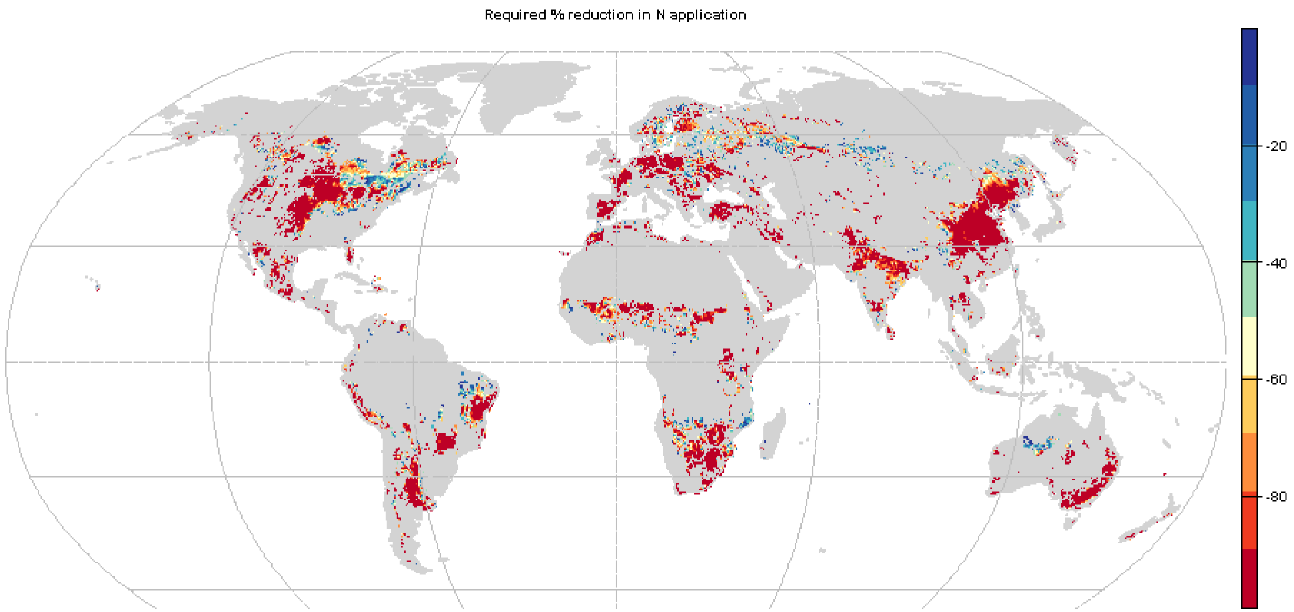
	Value
Value of global agricultural production	~ $5,000 Billion
Value of global fertilizer production	~ $200 Billion
Volume of inorganic N fertilizer	~ 100 Billion kg
Global cropland area	~ 1.4 – 1.9 Billion ha



Results (1)

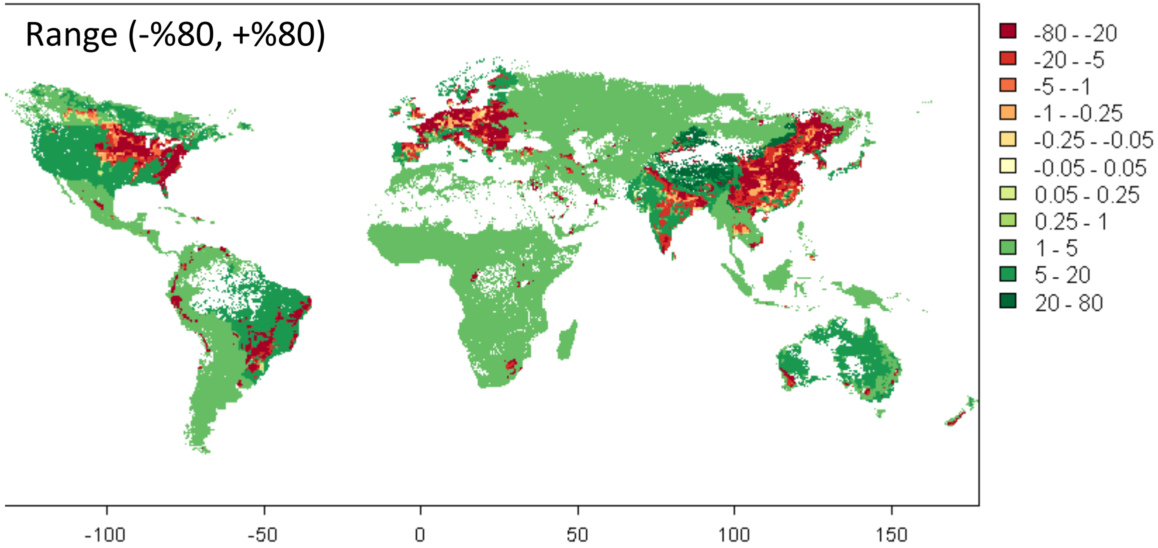
Look again at the scenario

- Policy:
  - Limiting N to the boundary value
- We expect to see
  - Changes in local production
  - Changes in prices
  - Changes in trade
  - Changes in the pattern of water and land use
- Note:
  - Results are preliminary as the scenario and the input data will be updated.

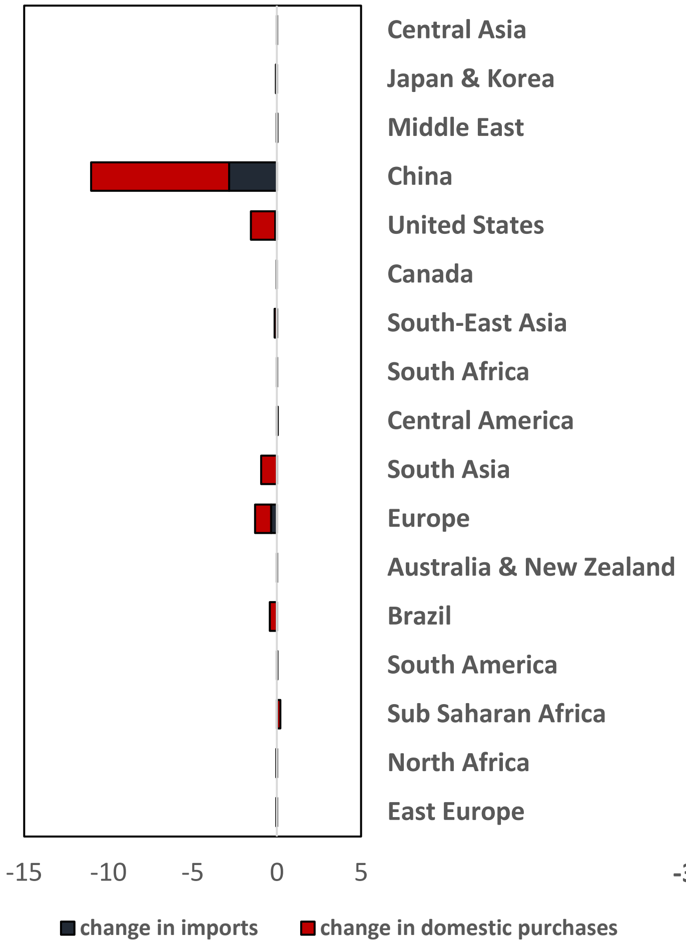


Results: Nitrogen

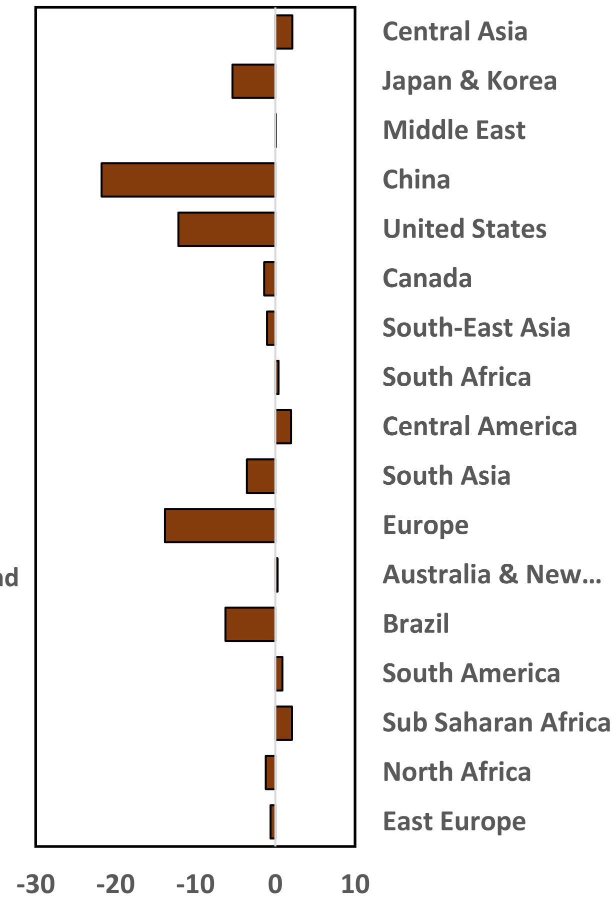
% change in gridded nitrogen fertilizer application



Change in regional nitrogen applications by source (Million ton)



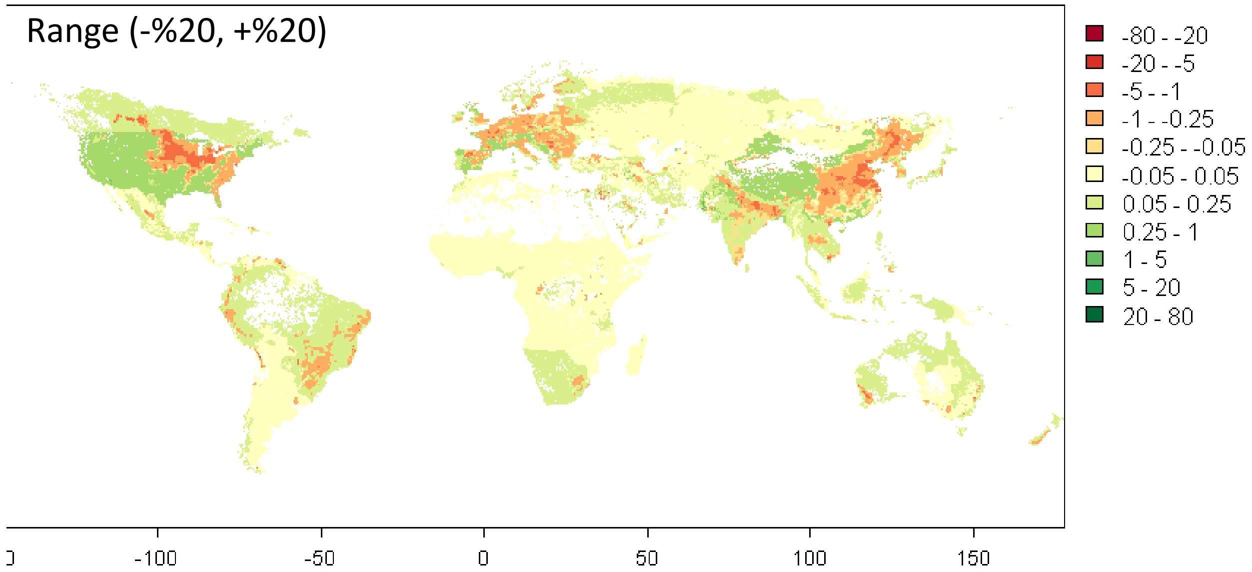
% change in regional nitrogen fertilizer applications



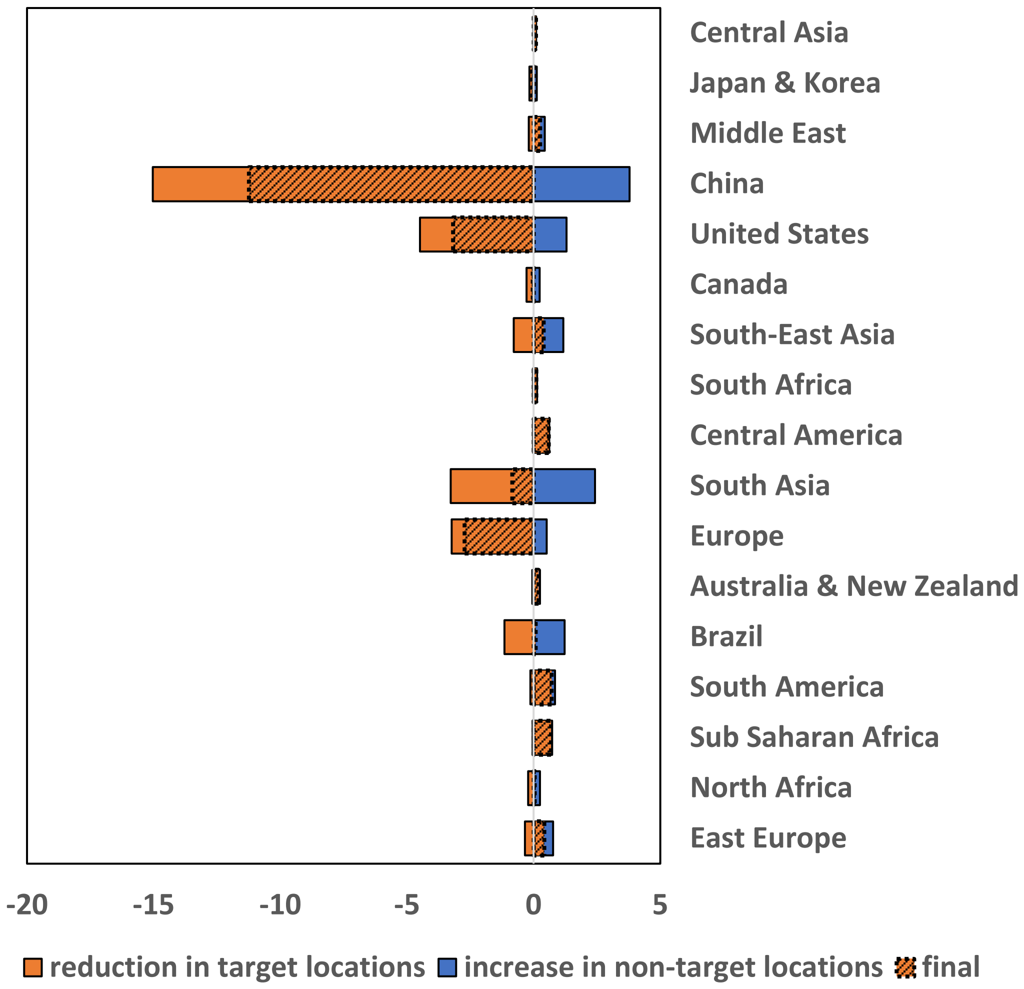
- N application declines in target locations
- N application increases in non-target locations
- The pattern of global fertilizer trade is changed

Results: crop production

% change in gridded crop production



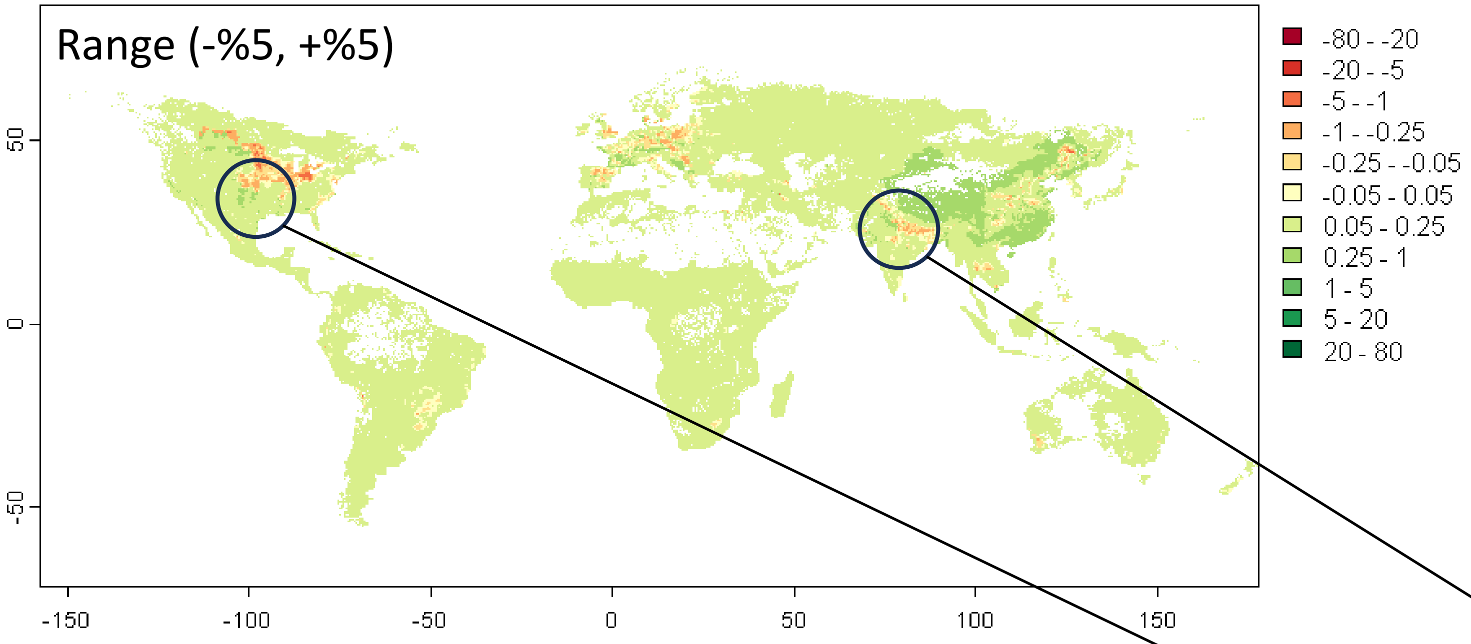
Change in regional crop production (million ton, price adjusted)



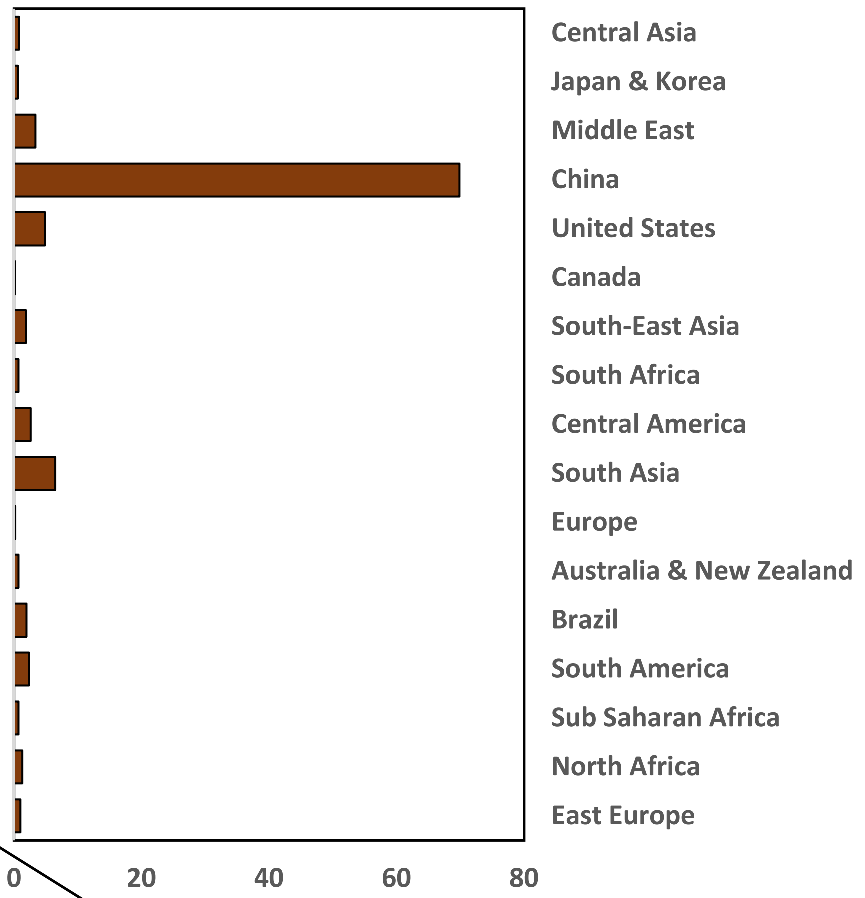
- Local production impact is smaller due to non-linear yield response to N
- Regional production is moderated through spillover to non-target locations
- Trade in crops is flexible but less than fertilizer due to product variations and perishability

Results: water

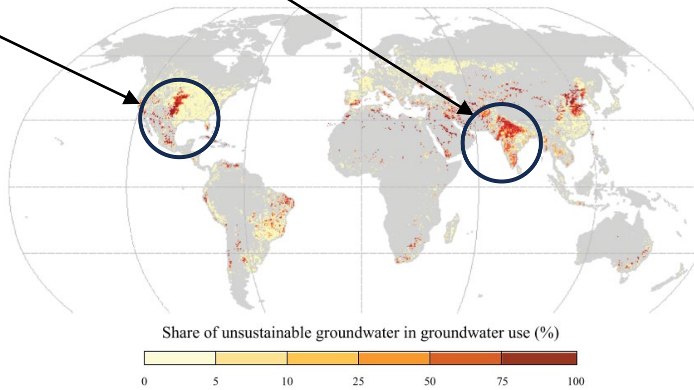
% change in gridded water withdrawals



Change in regional water withdrawals (million m3/year)



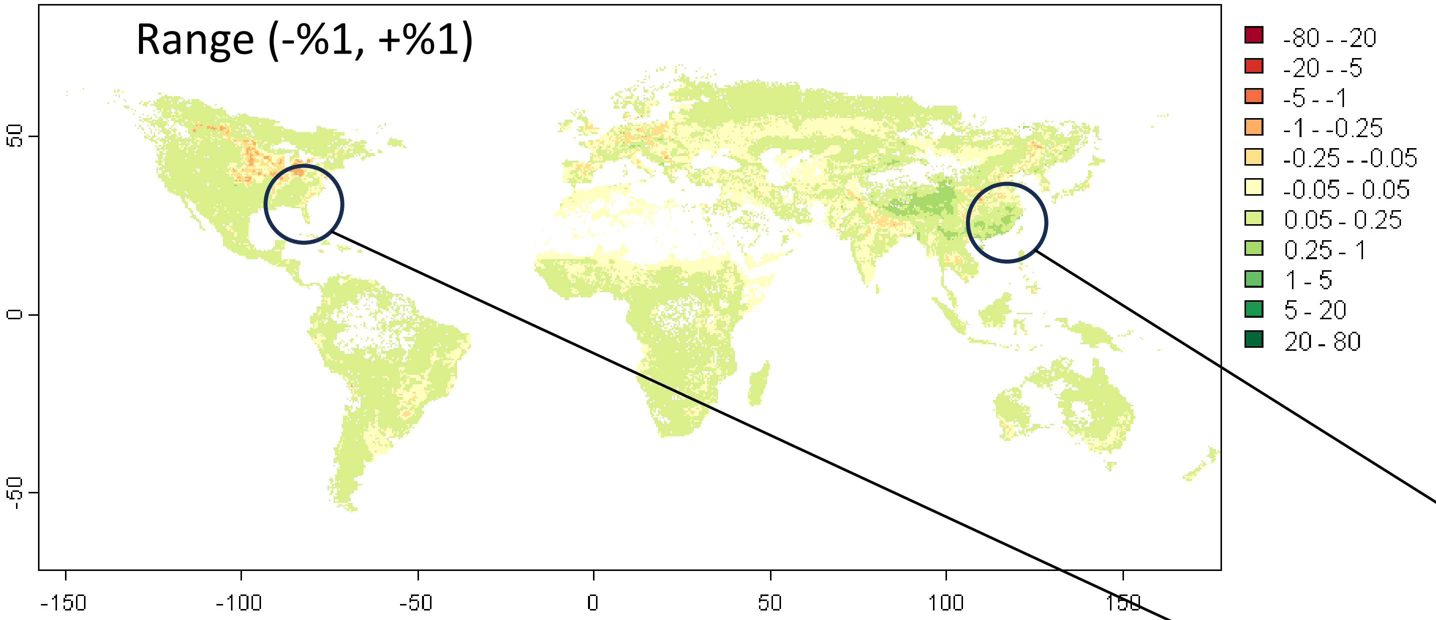
- Groundwater withdrawals declines in some locations, improving sustainability
- In general, water withdrawal increases and adding to the current stress



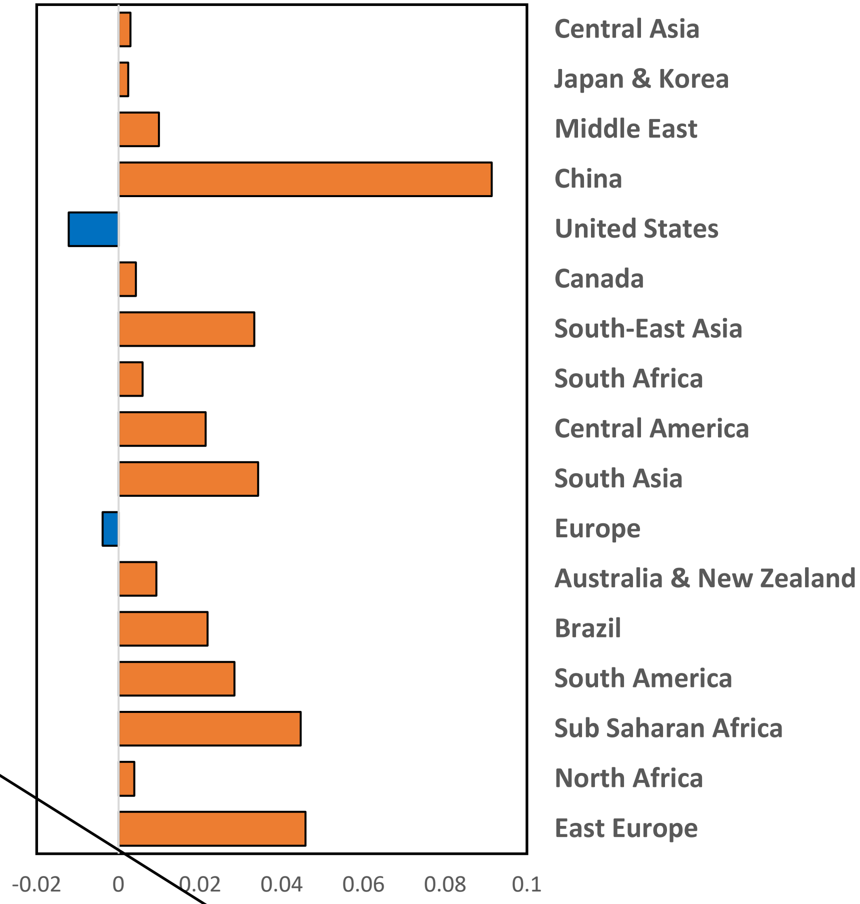
Currently stressed groundwater

Results: cropland

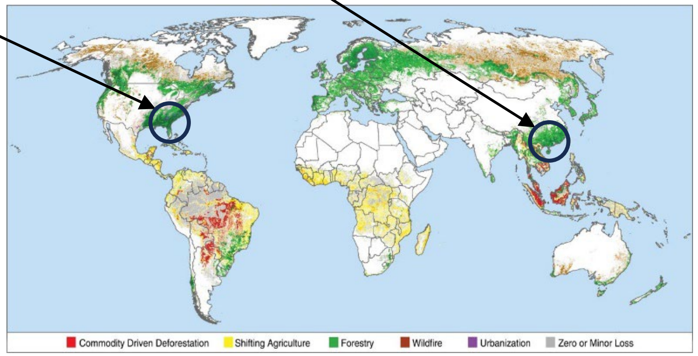
% change in gridded cropland areas



Change in regional cropland area (million ha)

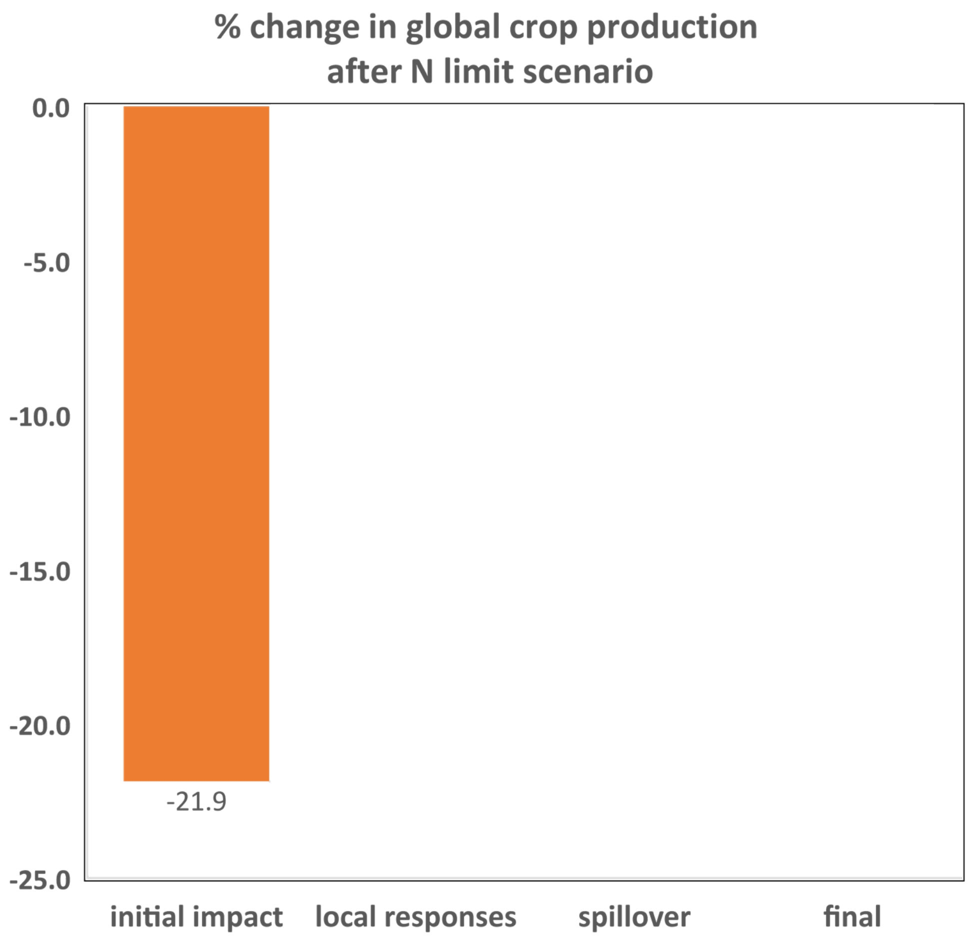


- **In general, cropland expands and adds to the current stress (biodiversity loss, deforestation)**

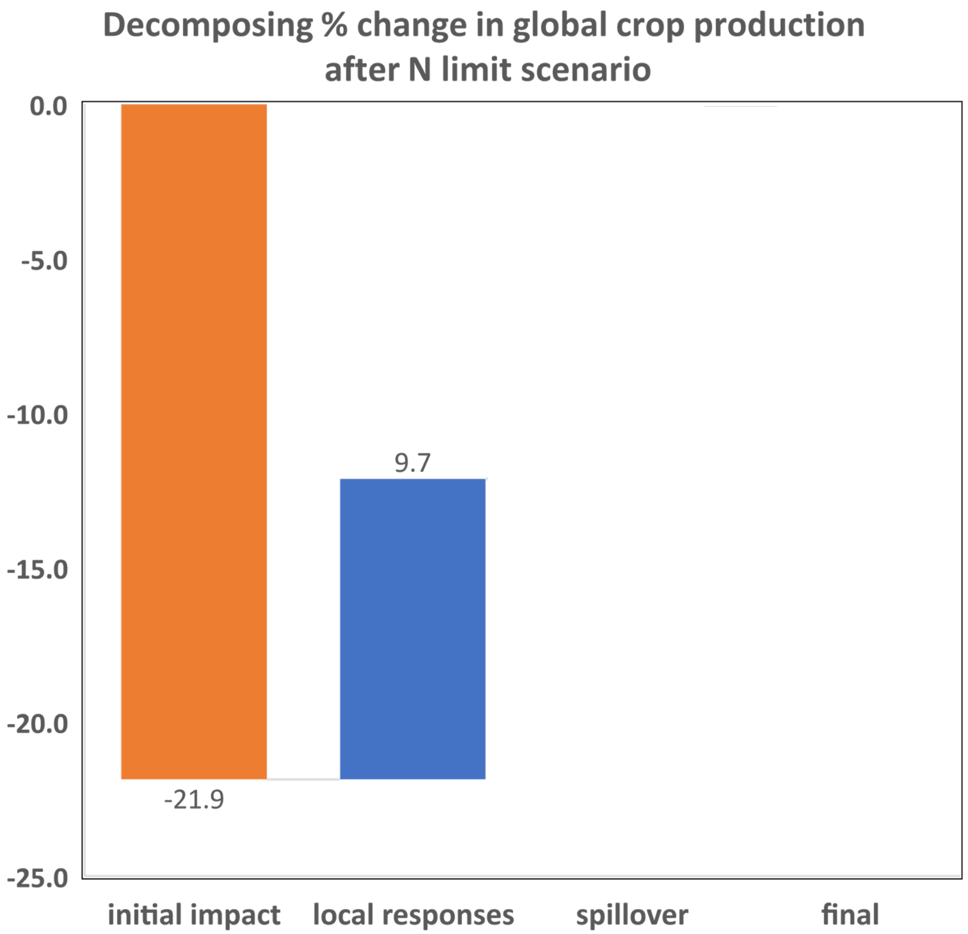


Results (2): decomposition

Absent adaptation, assuming a linear yield response: the reduction in global crop production is dramatic

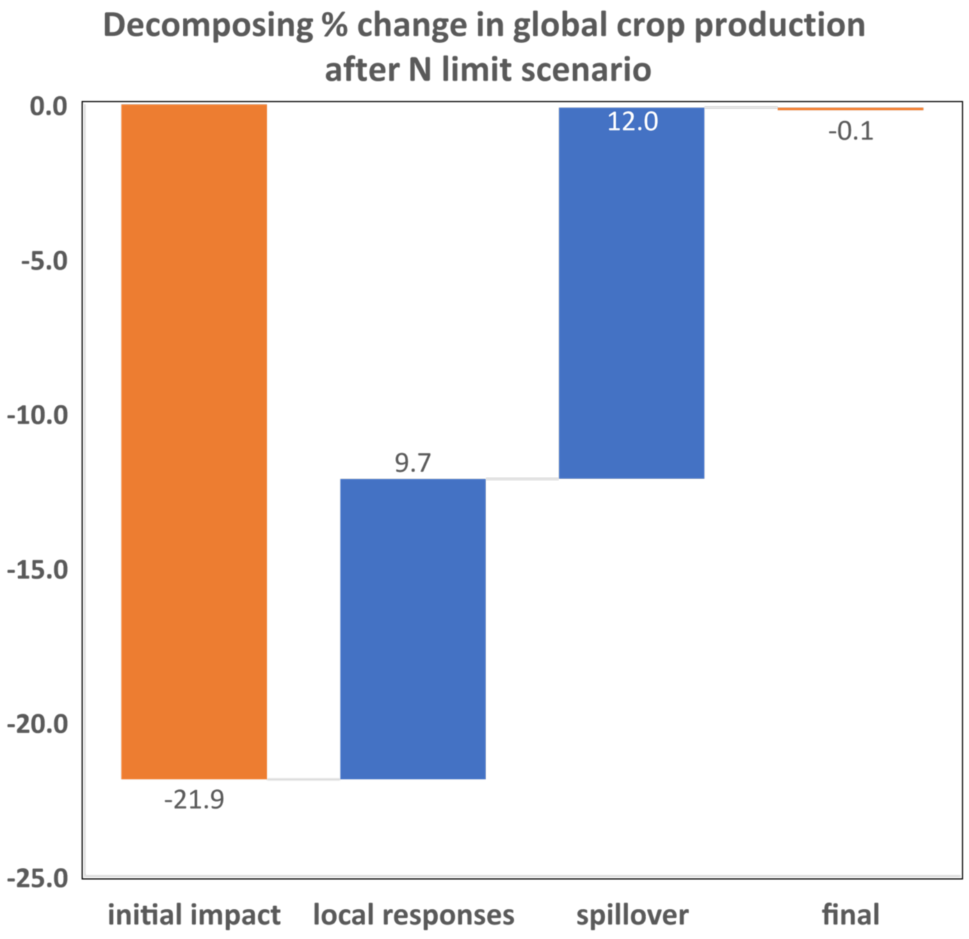


on-farm adaptations can moderate loss in production



- Major local decisions:
  - Reducing N/ha
  - Increasing irrigation water: rainfed-irrigated conversion
  - Lowering rents to maintain the market competitiveness

Spillover effects play significant role in moderating the loss in production



- Spillover through crop market
  - domestic and global trade
- Spillover through fertilizer market
  - domestic and global trade
- Spillover through labor mobility
  - Move to other locations

Wrap-up

Summary

- Nitrogen fertilizer is a key input to agricultural production, but it can also have negative environmental impacts.

- Reducing N to stay in the safe has two local impacts:
  - Local environmental benefits: This study has the potential to quantify the benefits, ecology
  - Local economic stresses: Impacts on local food price, food production, local community

- At the global level:
  - GHG emissions: Lower emission in production of Nitrogen;
  - New sustainability stresses

- We argue that the regional and global impacts on food system is moderated through local adjustments and remote spillovers

Wrap up: the impacts of nitrogen fertilizer limitation on planetary boundaries

- The workshop concluded that nitrogen fertilizer limitation is a necessary but not sufficient condition for maintaining all planetary boundaries.

- The workshop brought together a group of experts to discuss the impacts of nitrogen fertilizer limitation on planetary boundaries

- We explored how to use models like LPJmL and SIMPLE-G to better understand these impacts. This framework can be helpful for multiple GLASSNET communities like GGCMI, GTAP, and PB science community.

- Future directions
  - Feedback from SIMPLEG to LPJmL
  - More research is needed to understand the trade-offs between food production and PBs and market-mediated impacts.

Global-Local-Global Analysis of Systems Sustainability

GLASSNET

An International Network of Networks

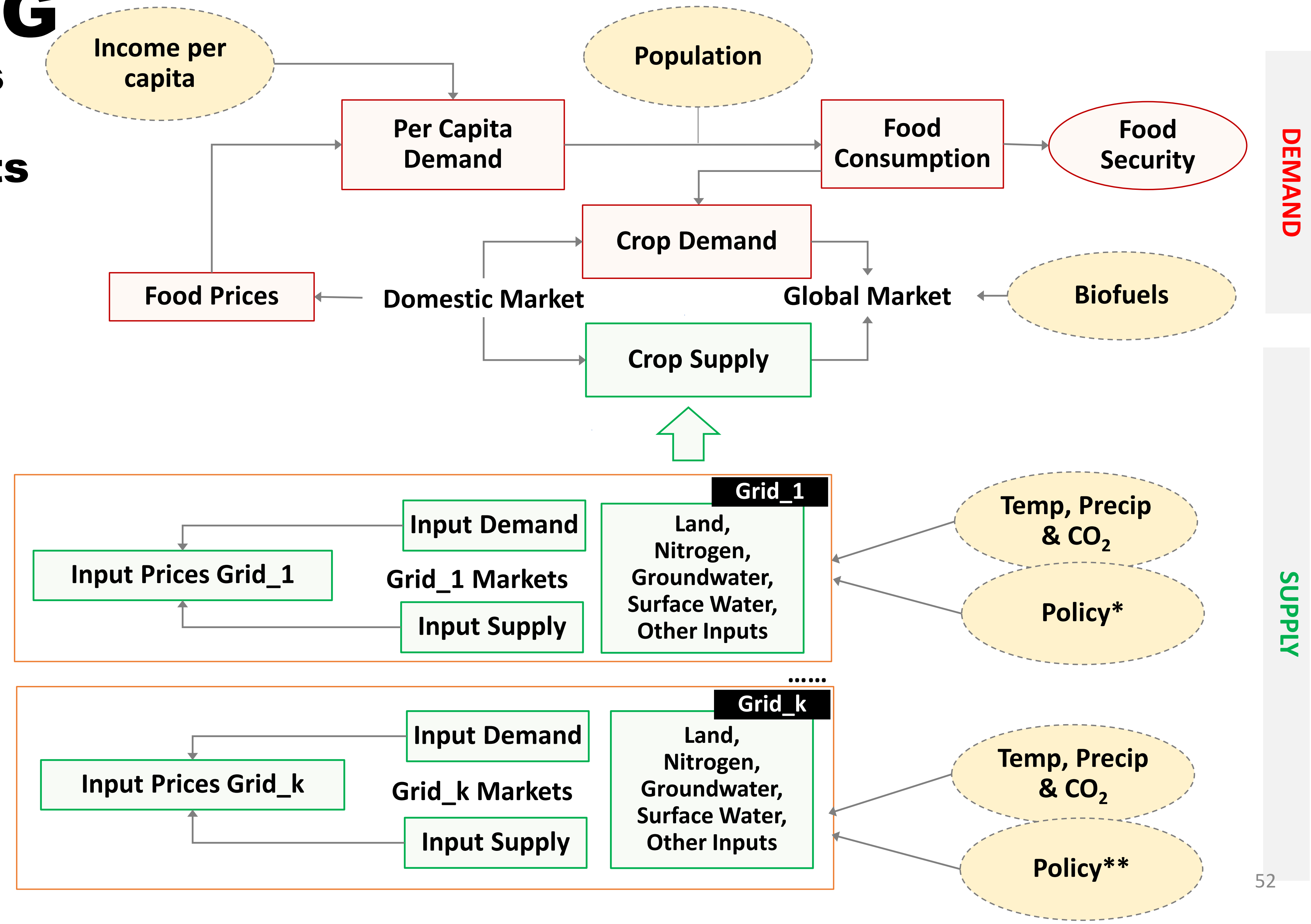
NSF

Thanks!

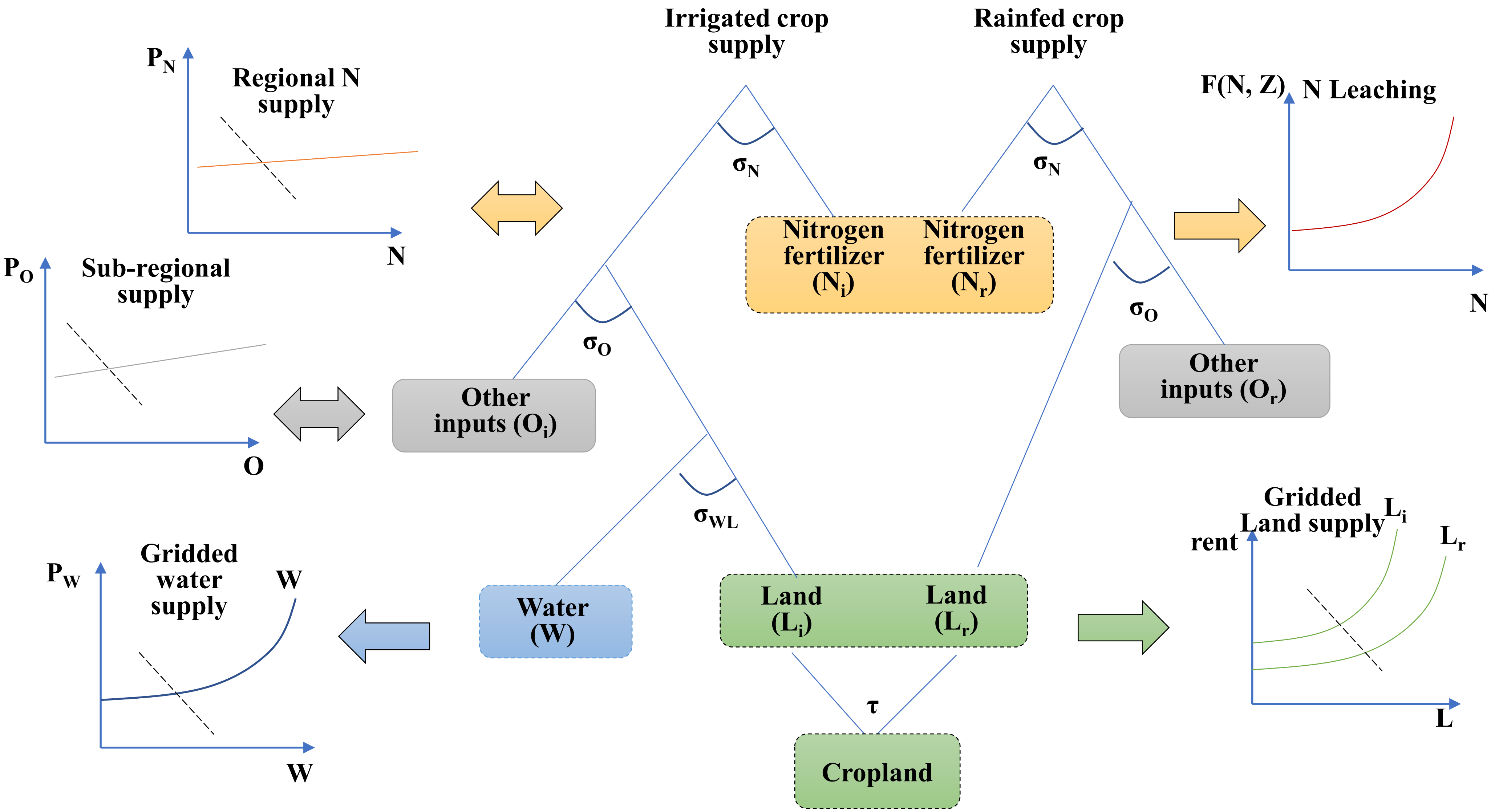
Extra slides

SIMPLE-G

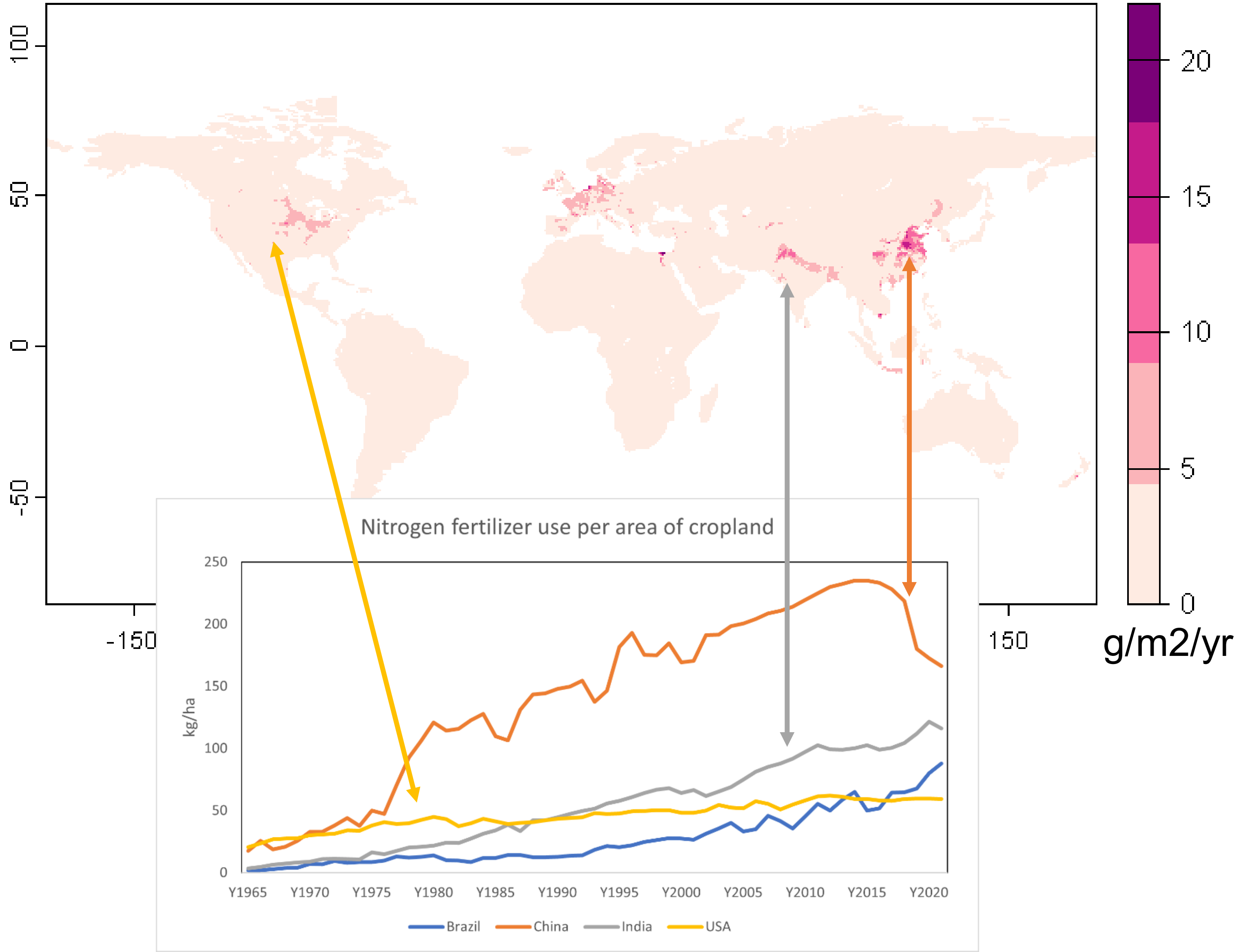
local changes will affect global markets



SIMPLE-G: supply of inputs and markets



LPJmL: current N fertilizer



- **Current application rates**
  - g/m2/yr (multiply by 10 to get kg/ha/year)
  - Around 2017
- **the N per acre varies by region, with rapid growth in China**
- **the N per ton of output has been steady due to growth in output**

=> N-based conservation policy has heterogeneous effect

Current parameter values

- **Nitrogen:**
  - **17 reg**
  - **Supply elasticity: 0.4 -1.4**
  - **CES Armington imports-local: 2.0**
  - **CET exports-local : -3.0**
  - **One global price**

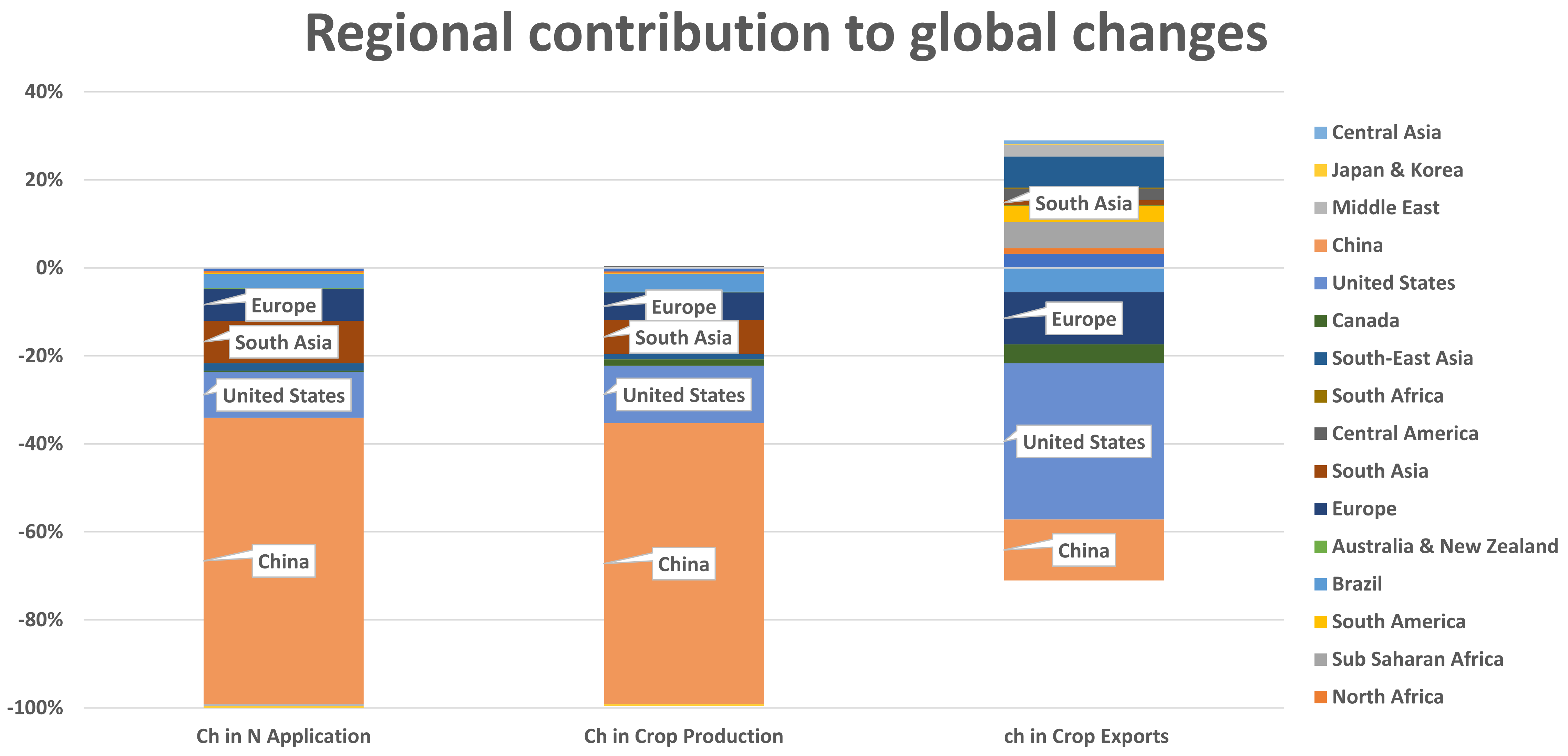
- **Non-land**
  - **135 reg**
  - **Supply elasticity: 1.34**
  - **Mobility:**
    - Perfect within sub-reg
    - Non between

- **Land**
  - **Supply elasticity: 0.0 -1.3**
  - **ETRN rfd-irr : -1.2**

- **Water**
  - **Supply elasticity: 0.2 - 1.1**
  - **ESUB land-water: 0.5 - 1.0**

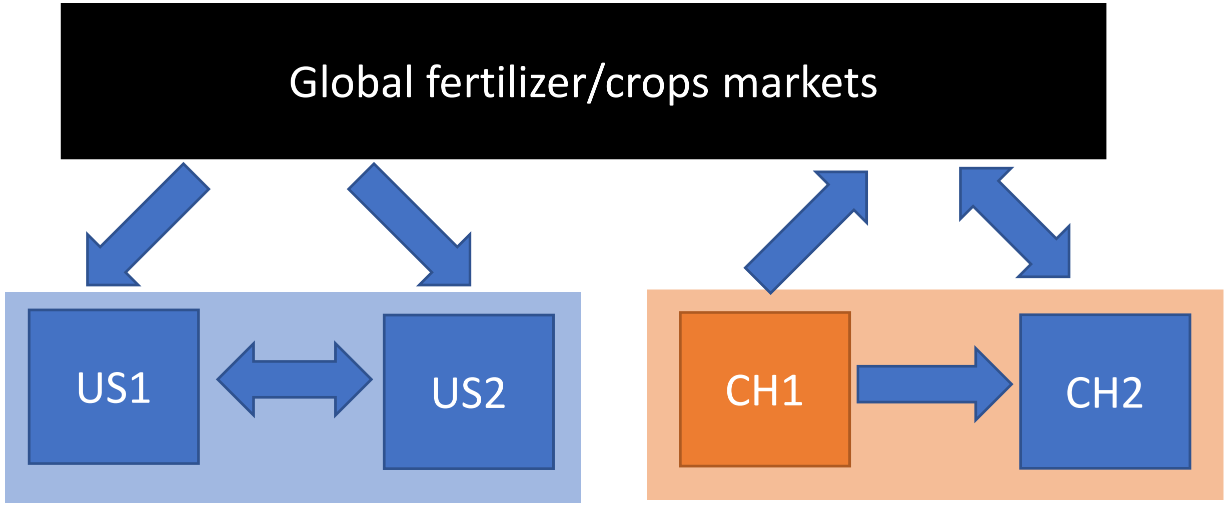
- **ECRP:**
  - **Estimated based on LPJmL quadratic: 0.0 -1.5**

SIMPLE-G results: Preliminary

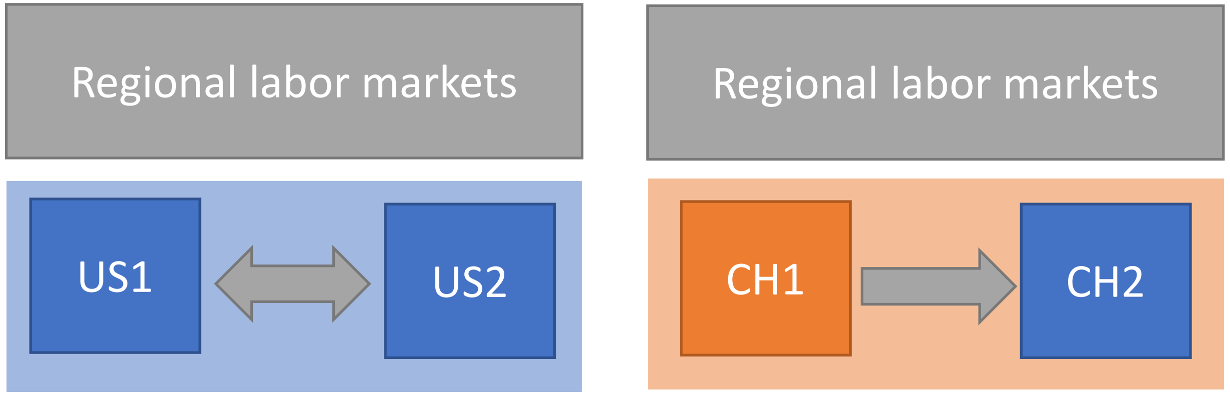


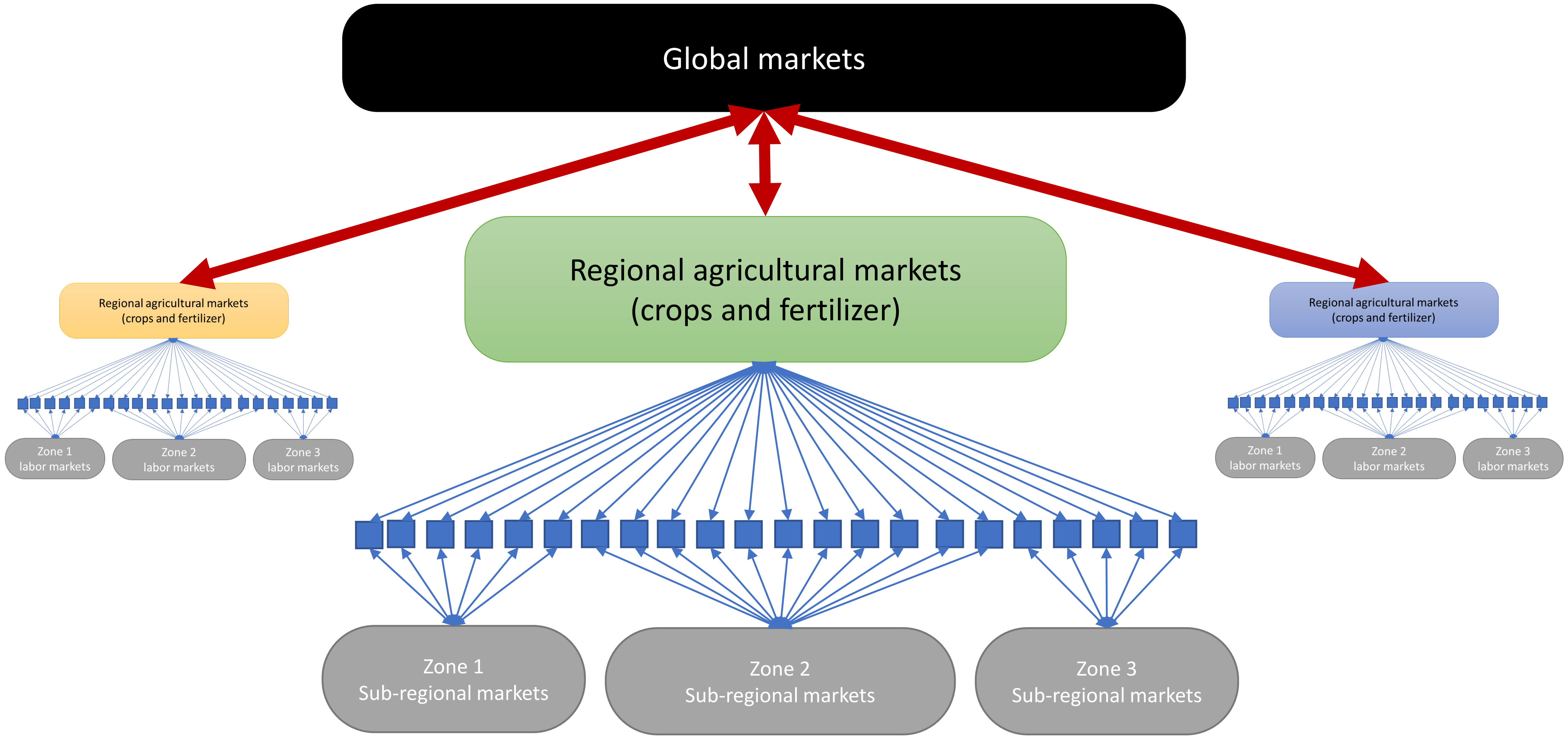
Market clearing assumptions

- Nitrogen fertilizer
  - 17 global region supplier
  - Three closures:
    - Segmented- Imperfect mobile: 17 demand segmented markets
    - Integrated- perfectly mobile: 17 demand integrated markets (Data from FAO)
    - Integrated- product differentiated by country for N with 135 demand (Data from FAO)



- Other inputs (Labor, capital, etc)
  - Non-traded
  - Two closure
    - Perfect mobile in each sub-region (135 sub-regional markets)
    - Imperfectly mobile CET
    - Gridded



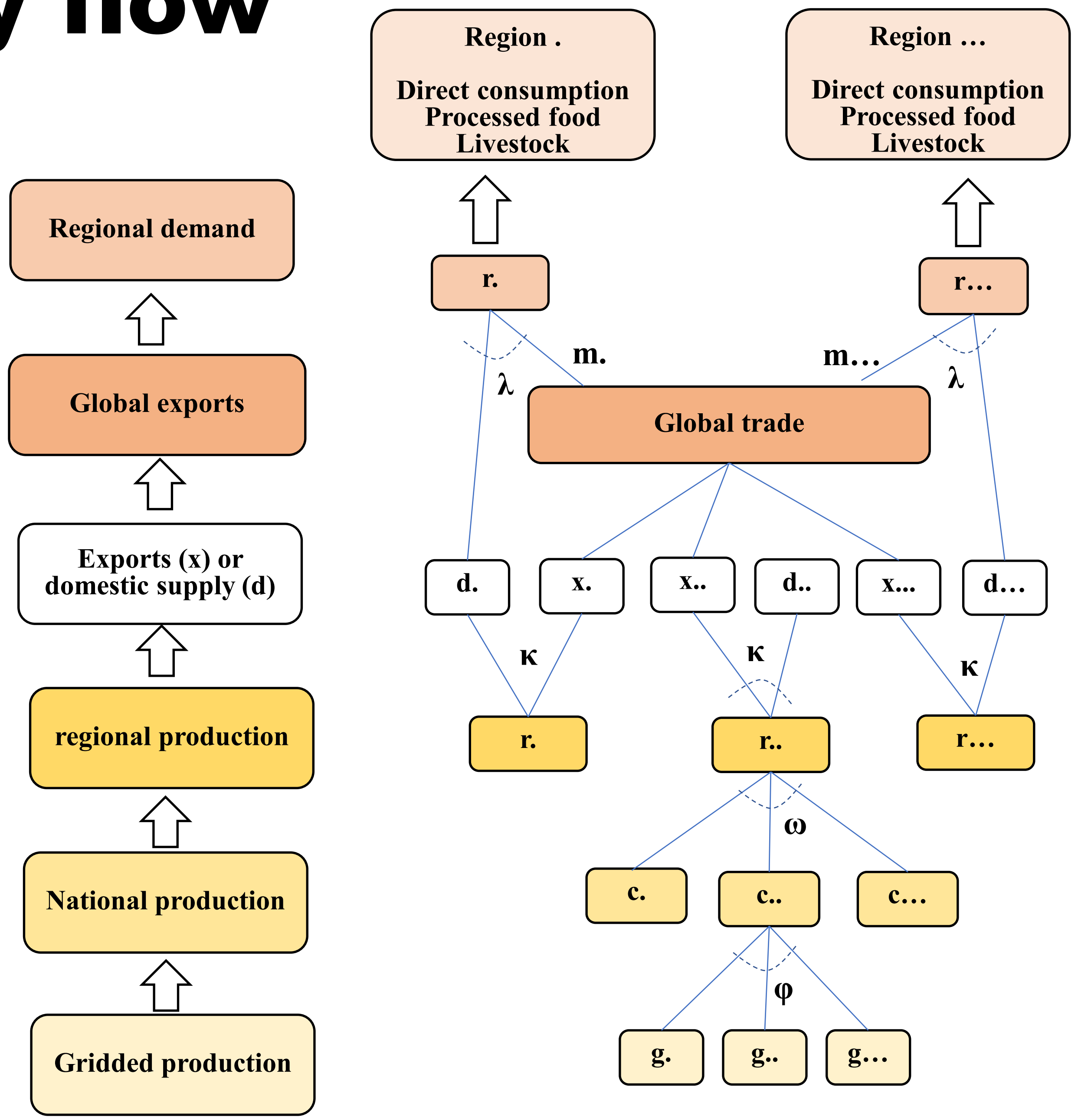


Global markets
Regional agricultural markets
(crops and fertilizer)
Regional agricultural markets
(crops and fertilizer)
Regional agricultural markets
(crops and fertilizer)
Zone 1
labor markets
Zone 2
labor markets
Zone 3
labor markets
Zone 1
Sub-regional markets
Zone 2
Sub-regional markets
Zone 3
Sub-regional markets
Zone 1
labor markets
Zone 2
labor markets
Zone 3
labor markets

Model: commodity flow

(Haqiqi et al, 2022)

- Index:
  - Grid cells: g
  - Country: c
  - Aggregate regions: r
  - Exports: x
  - Imports: m
  - Domestic supply: d
- Parameters:
  - Import-Domestic Armington: λ
  - Export CET: κ
  - Sub-regional Armington: ω
  - Gridded similarity: φ



SIMPLE-G: data processed

Variable	Value	Quantity	Implied price
Crops	Sale of crops (by CROP)	In corn-equivalent ton (price adjusted)	Price index ($ / ton)
Land	Payments to land (by LANDTYPE)	Cropland area in ha Irrigated and rainfed	Rent index ($ / ha)
Water	Payments to water (by waterSource)	Volume of Groundwater in m3 Volume of Surface water in m3 Index for other inputs	Unit cost ($ / m3)
Labor	Payment to labor	Number of farmworkers	Index ($ / person)
Other inputs	Total payment to other inputs	Index	Index

SIMPLE-G (gridded components) production inputs and crop outputs

	SIMPLE-G1*	SIMPLE-G*	SIMPLE-G- 2x3x8	SIMPLE-G1-land
Crops	Aggregated all crops	Aggregated all crops	**8 GTAP crops**	Aggregated all crops
Practices	Aggregated	**Irrigated & rainfed**	Irrigated & rainfed	Aggregated
Land	Cropland	Cropland	Cropland	**Cropland** **Managed forest** **Pasture land** **Other land**
Water	Aggregated water	**Groundwater** **Surface water** **Other irrigation inputs**	Aggregated water	Aggregated water
Labor	NA	One labor category	NA	NA
Other inputs	Aggregate other inputs	Aggregate other inputs	Aggregate other inputs	Aggregate other inputs

*** published**

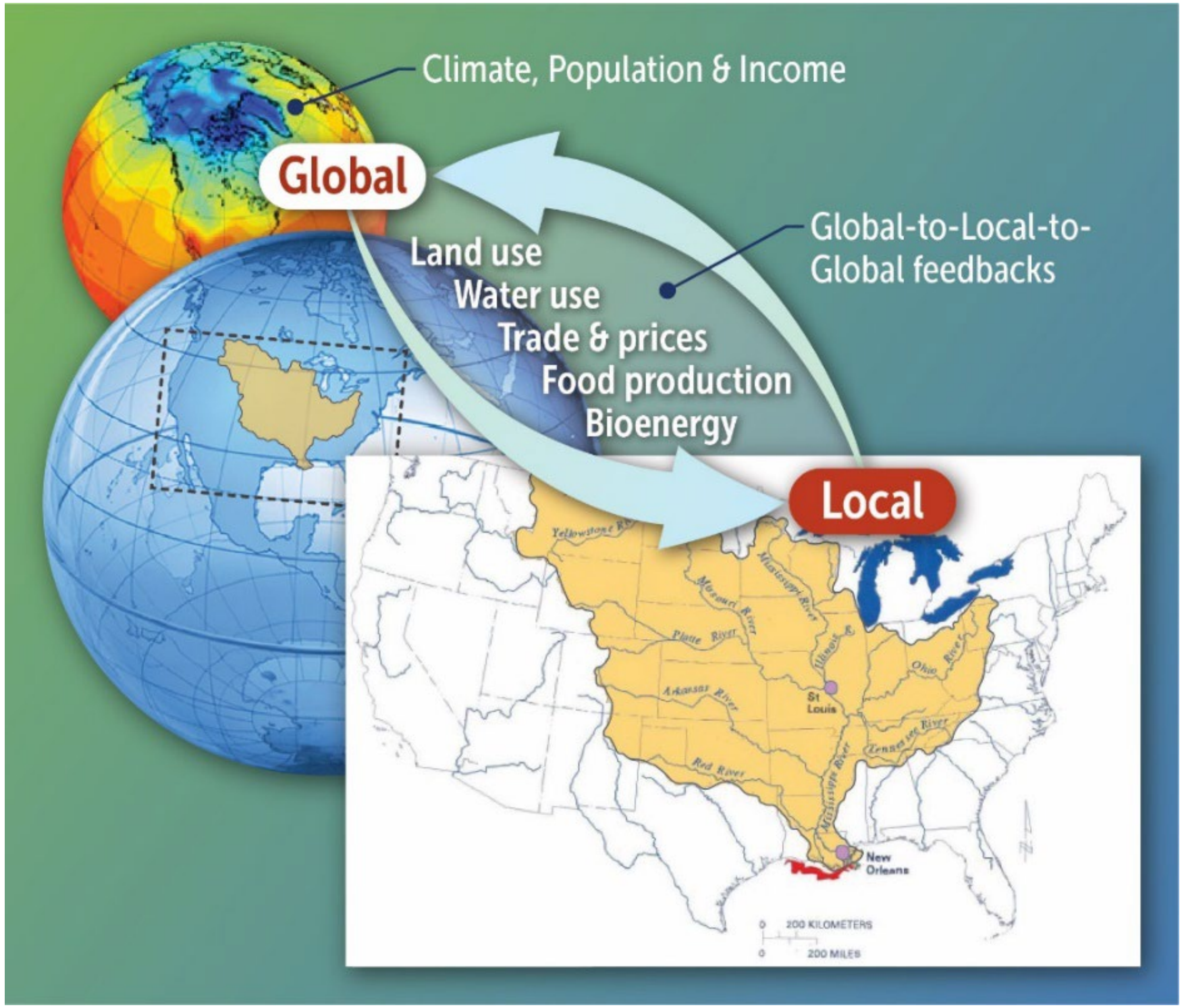
SIMPLE-G: Assumptions and modules

module	SIMPLE-G1	SIMPLE-G*	SIMPLE-G- 2x3x8	SIMPLE-G1-land
Trade	Armington	Armington	Armington	Armington
Crop similarity	gridded heterogeneity	gridded heterogeneity	gridded heterogeneity	gridded heterogeneity
Production	Nested CES	Nested CES	Nested CES	Nested CES
Land allocation	Gridded supply	QCET	QCET	**Nested QCET**
Water	Gridded supply	**Nested CES**	Gridded supply	Gridded supply
Labor	NA	Gridded supply	NA	NA
Fertilizer	NA	Regional supplu	NA	NA
Other inputs	Regional supply	Gridded supply	Gridded supply	Gridded supply

Overview of SIMPLE-G Global

- a Simplified International Model of agricultural Prices, Land use, and the Environment- Gridded
  - Partial equilibrium: exogenous income
  - Regional consumption of food: 17 regions
  - Armington trade Gridded nested CES production of crops: 1.4 million grid cells
  - Land, water, fertilizer, (labor), other inputs
- Application: regional problems
  - Nutrition and food security challenges*
  - Overall GHG in food system*
- Application: gridded
  - Climate change impacts*
  - Conservation and sustainability of water and land*
  - Biodiversity
  - Labor market and equity issues

GLASSNET seeks to support Global-to-Local-to-Global Analysis of Sustainable Land and Water Use



- **Sustainability research is inherently local**
- **However, *global forces are driving local sustainability* stresses**
- **The character of these stresses & *solutions vary by locality***
- **Furthermore, *local responses can have global consequences***
- ***Trans-disciplinary collaboration* is critical**

Selected References

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Baldos, U.L.C, I. Haqiqi, T.W. Hertel, J.M. Horridge and J. Liu (2020) "SIMPLE-G: A Multiscale Framework for Integration of Economic and Biophysical Determinants of Sustainability", *Environmental Modelling and Software* vol. 133(November):1-14. https://doi.org/10.1016/j.envsoft.2020.104805

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