From Field to Fork: Advancing Nitrogen Footprint Approaches for Sustainable Food Systems

Azusa Oita

Institute for Agro-Environmental Sciences,
National Agriculture and Food Research Organization (NARO), Japan

Leibniz Centre for Agricultural Landscape Research (ZALF), Germany

Research Seminar@Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM),
Universidad Politécnica de Madrid (UPM)
13 February 2026

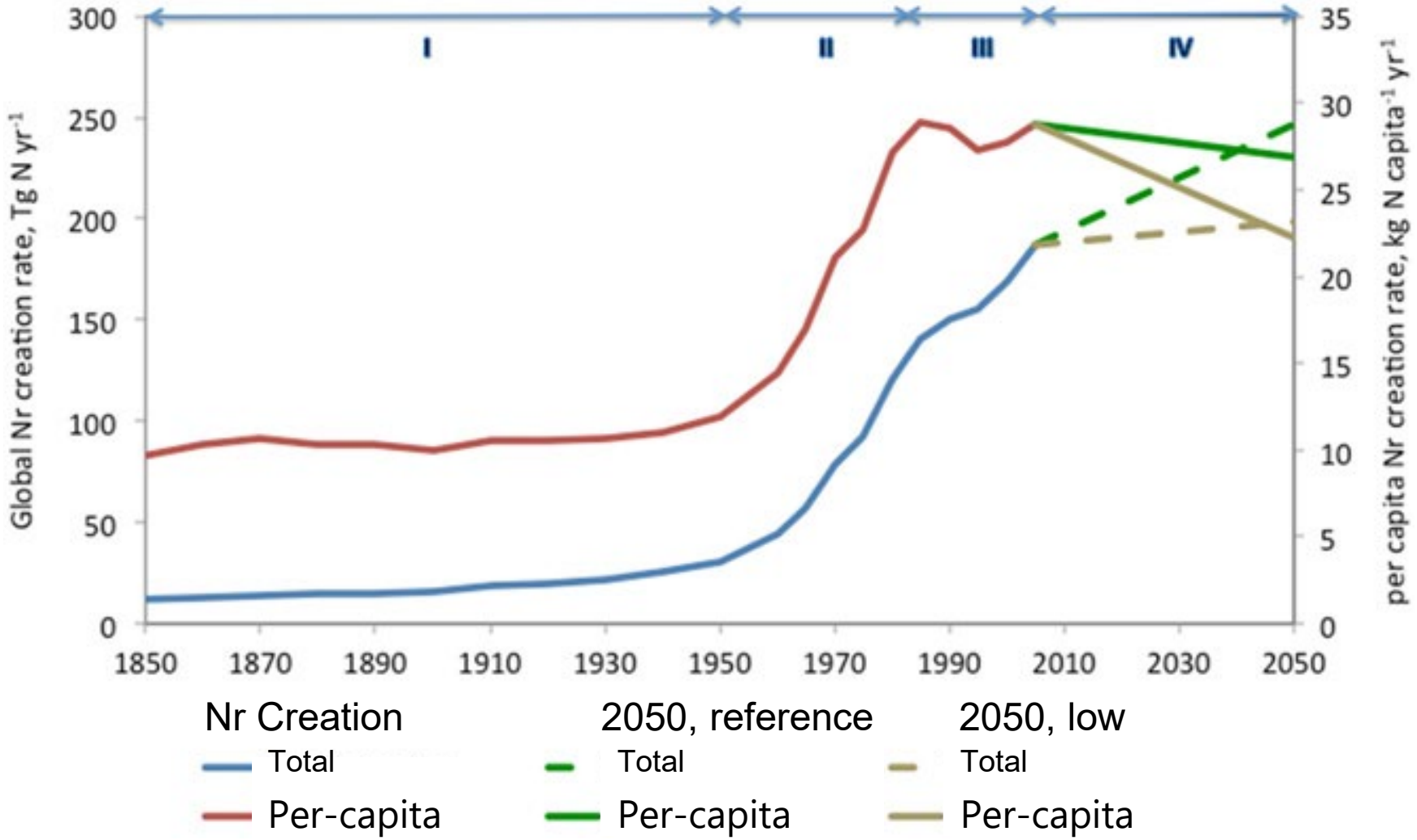
Background (1): what is the nitrogen (N) problem?

- 80% of reactive N (Nr; all N forms except N_2) input is lost as pollution (e.g., NO_x, NO_3^-) or as N_2.
- The global cost of N damage is around US$200–2000 billion per year.
- Multiple environmental impacts are caused by excess Nr in the environment.

Nr is a necessary resource and a source of pollution.

(Sutton et al., 2019)

Background (2): global reactive N creation per capita



(Galloway et al., 2014)

Outline of today's talk

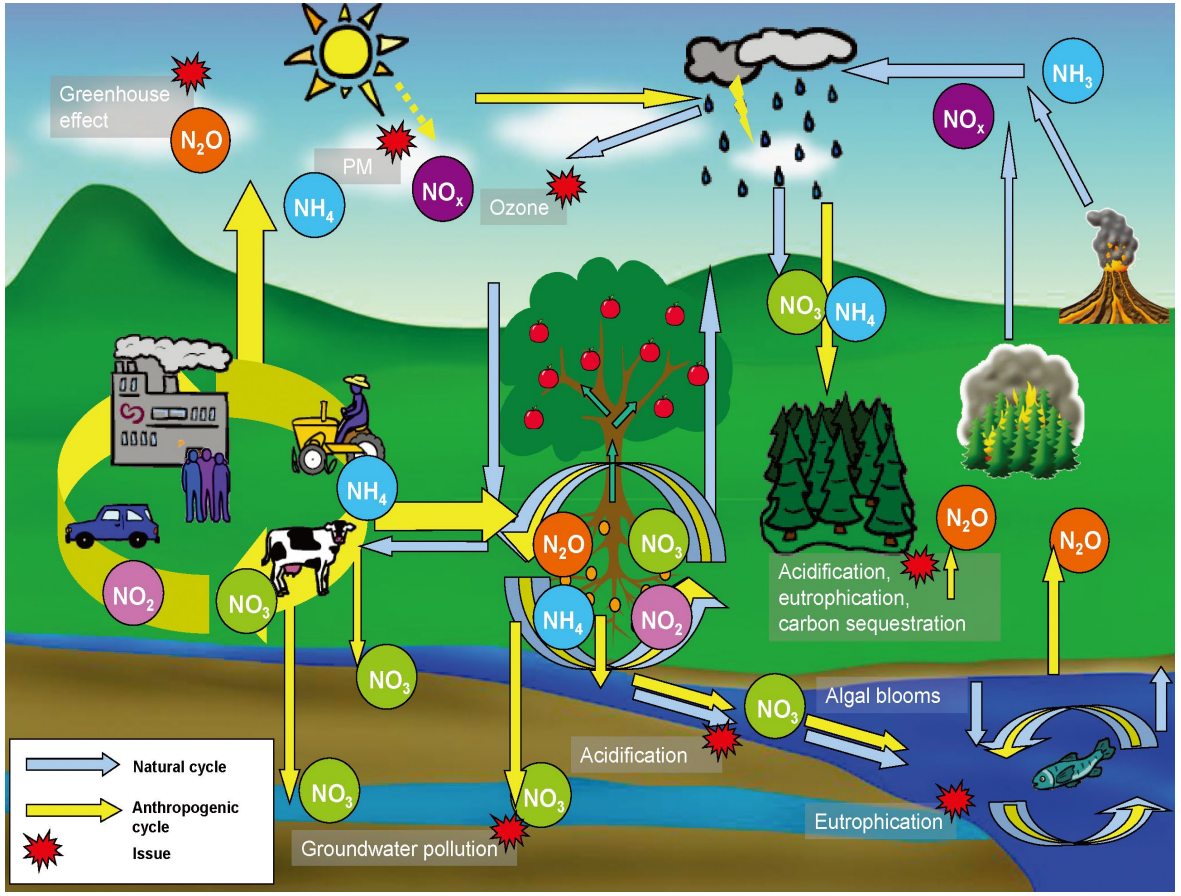
1. Background: The nitrogen problem
2. Nitrogen footprint approaches: models and progress
   (A) Bottom-up: consumer- and diet-based footprints
   (B) Top-down: global picture and international trade
   (C) Supply-chain attribution (NutrIO): linking demand to sectoral losses
3. Current interests and discussion

Motivation: linking production & consumption

Food on the table

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

The reactive N flows

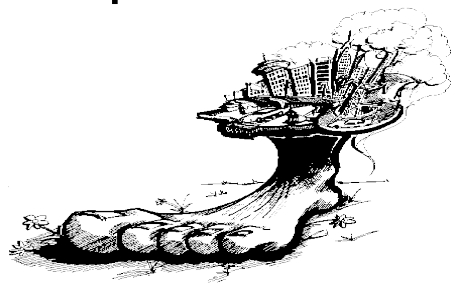


(Erisman et al., Ch2 in ENA, 2011)

What is the nitrogen footprint?

A nitrogen (N) footprint is the amount of Nr released to the environment due to resource consumption.

Driver: consumption



Pressure: N loss to the environment

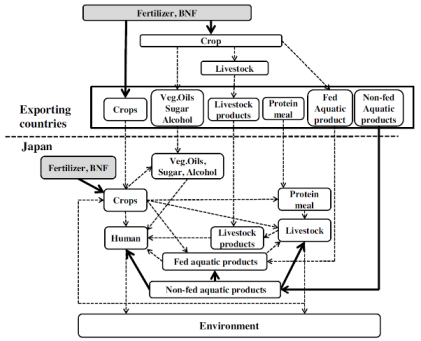
It connects use of resources, especially food, to environmental nitrogen losses.

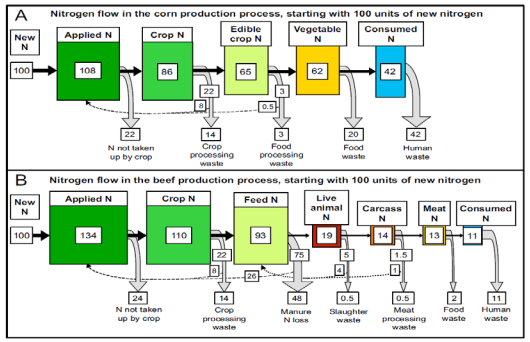
Food

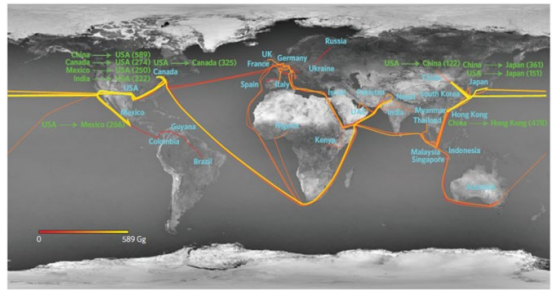
Energy

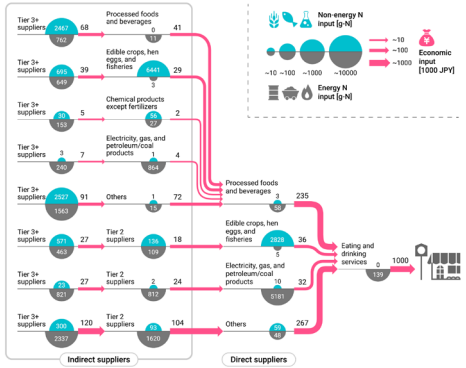
Non-food goods

Different methods for the N footprint analyses









Simplified trade

N-Input

(Shindo & Yanagawa, 2017)

Consumers

(A) N-Calculator

(Leach et al., 2012)

Global trade

(B) N-Multi-region

(Oita et al., Nat. Geoci., 2016)

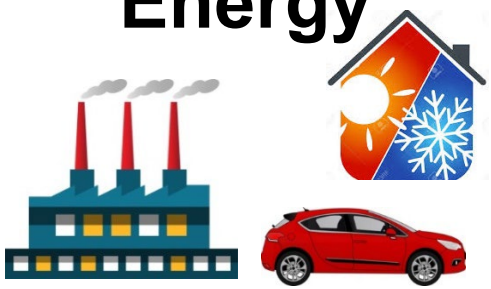
Supply-chains

(C) NutrIO

(Oita et al., ERL., 2021)

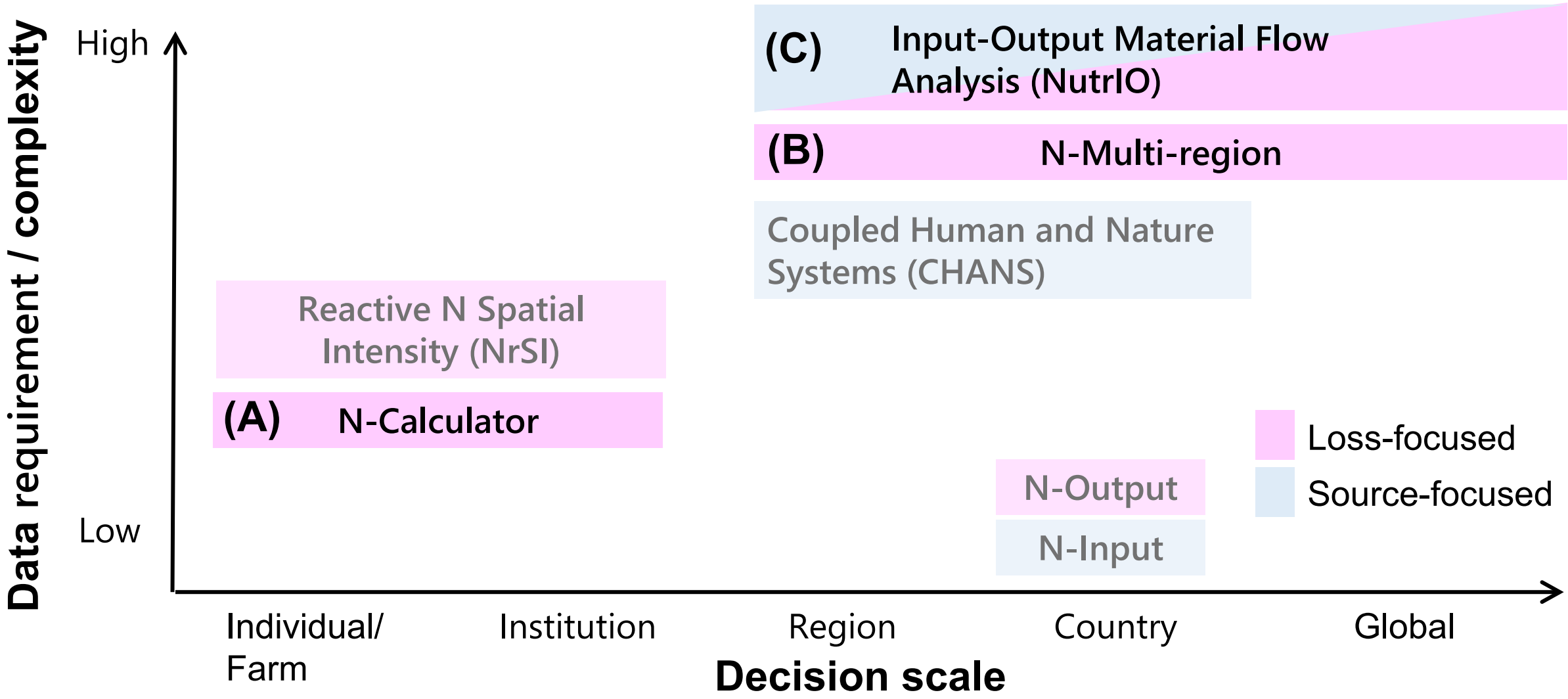
Food

Energy



Non-food goods

Why do we need different N footprint models?



(Based on Shibata et al., INMS Guidance Document, 2025)

(A) Bottom-up: the N-Calculator method framework

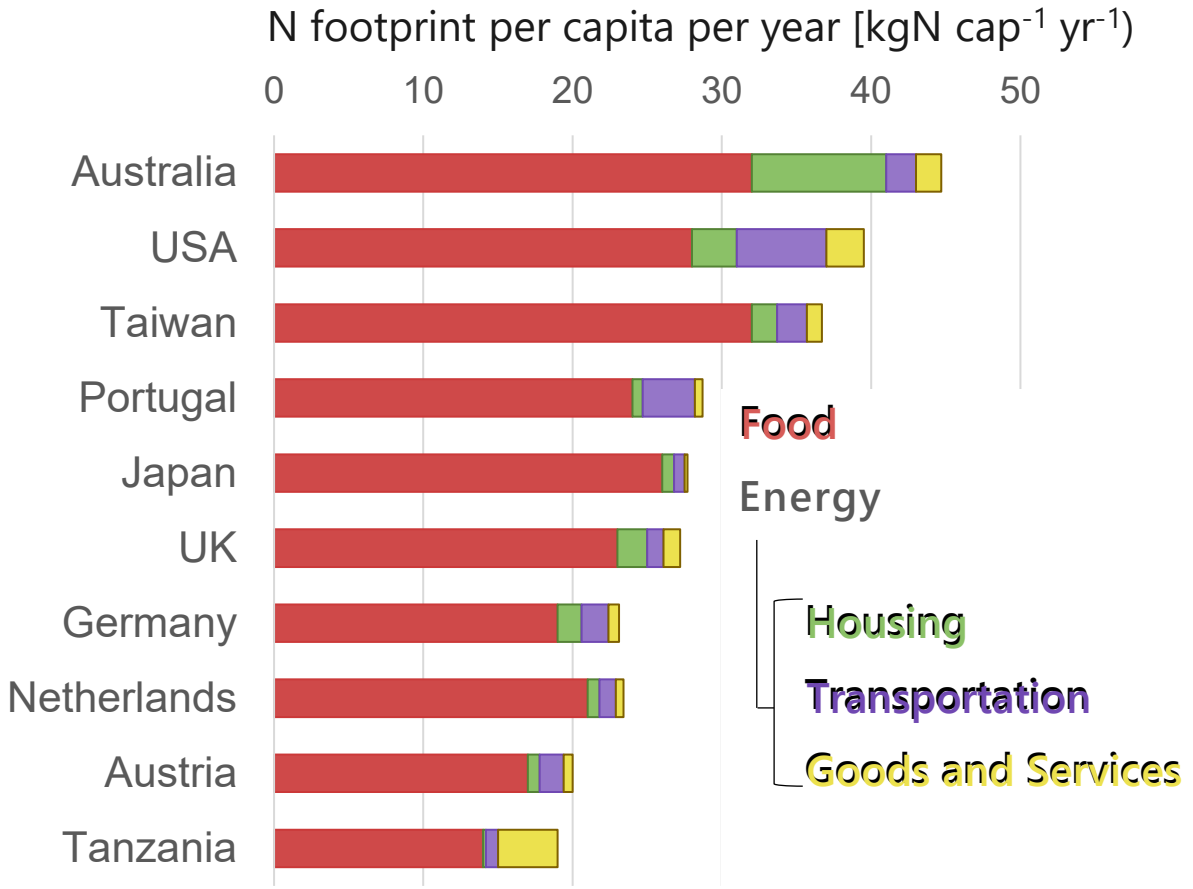
N footprint (NF) = **Food NF** + Energy NF

Food NF = Production NF + Consumption NF

Production NF **(Virtual N)** = Consumed N × **Virtual N Factor (VNF)**

Consumption NF **(Real N)** = Consumed N × N removal rate at wastewater treatment

Personal N footprint by country

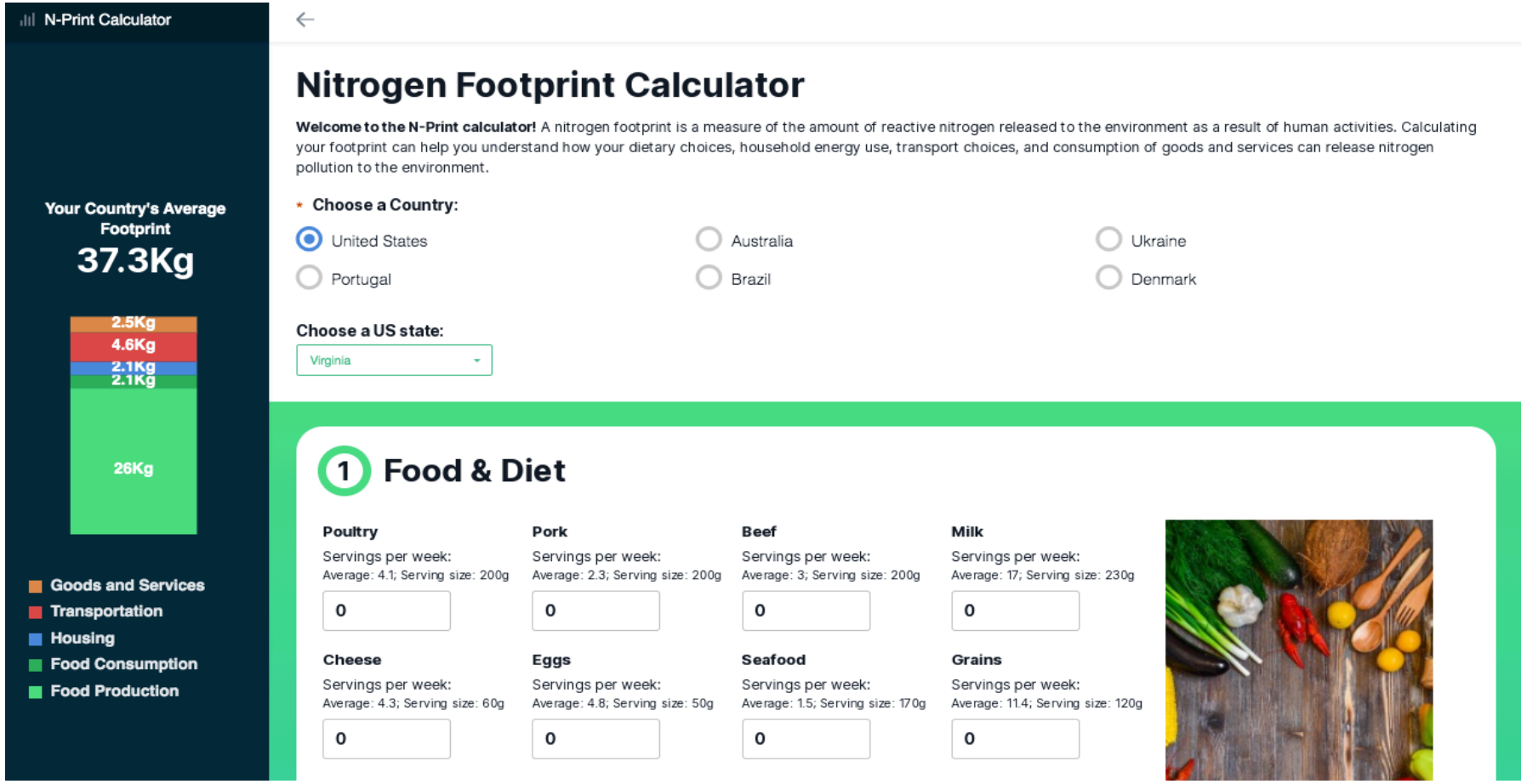


(Shibata et al., Ambio, 2017)

Food makes up more than 75% of the N footprint.

The web-based N footprint calculator

https://calc.nprint.org/::YYYC



The N-footprint register and food items to choose

Nitrogen Footprint of Food

~Your Diet can save the Earth !?~

NARO-MARCO 2018, Tsukuba, Japan

No.	menu	Virtual Nitrogen Footprint
10002	Rice (medium)	0.9
10023	Miso soup	0.7
10007	Omelette	7.9
10015	Caesar salad	2.1
10009	Pacific saury baked	0.5
10023	total VNF	12.1

10001

10015

10009

10021

Nitrogen Footprint of your menu is 12.1 !

n Footprints is the Nitrogen discharged to the environment

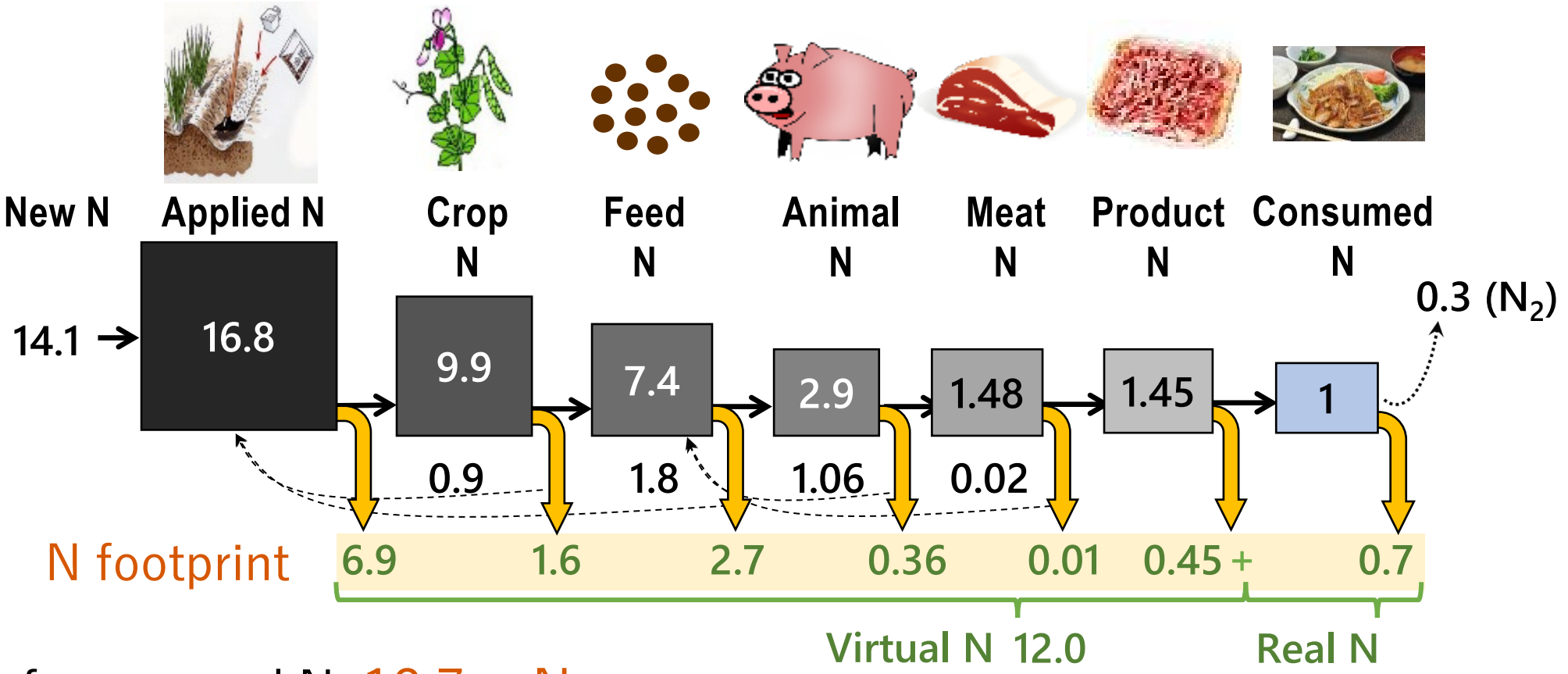
e start of making raw materials to our consumption.

not become too much !

The N footprint of the chosen menu

Simplified N flows for the N footprint calculation

Case of Japanese Pork



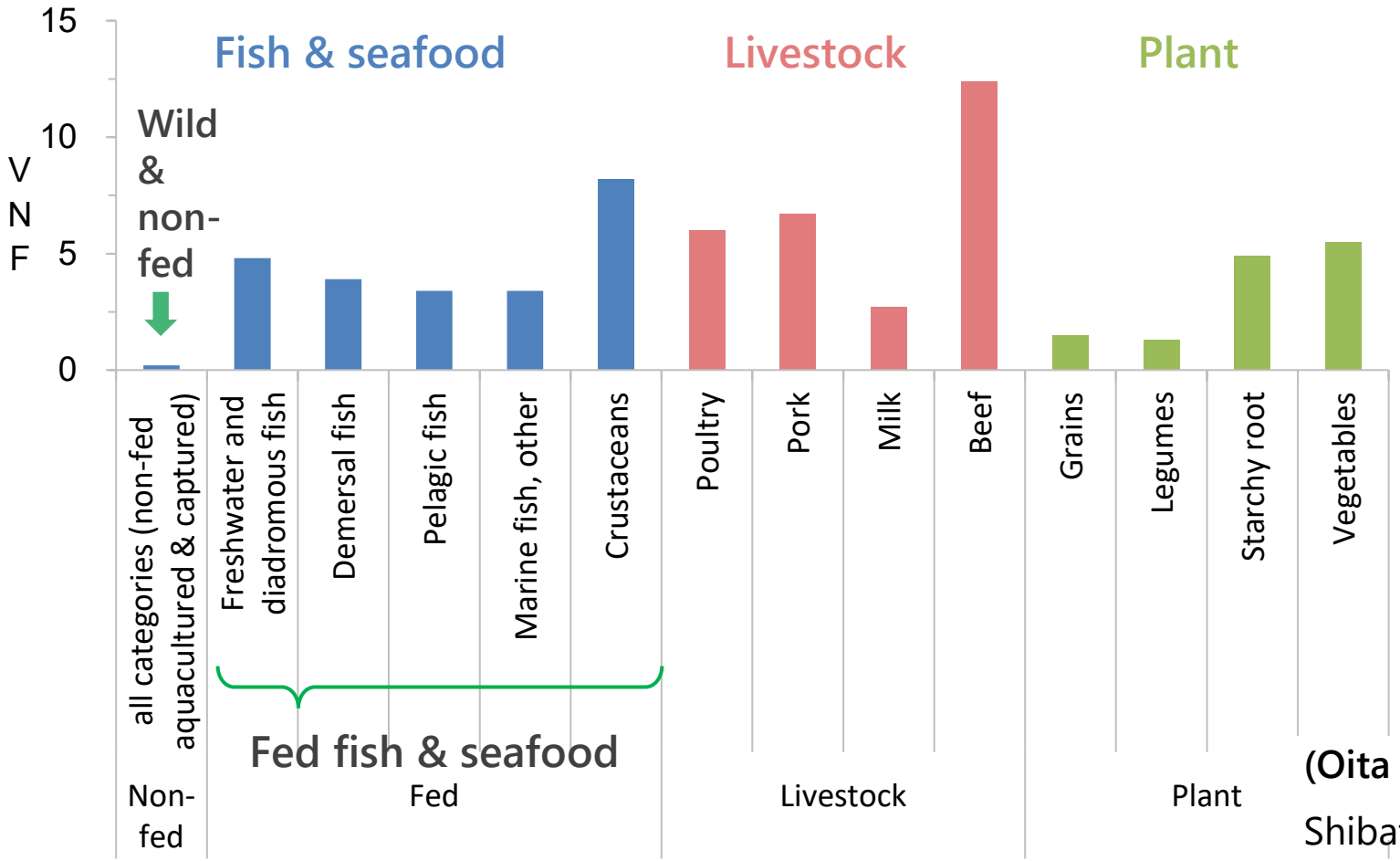
1 g of consumed N: 12.7 g-N

(included in pork protein)

12.0+0.7

(Shibata et al. 2014: Oita et al,. 2018a)

Virtual N Factors (VNF) of food items (detailed)



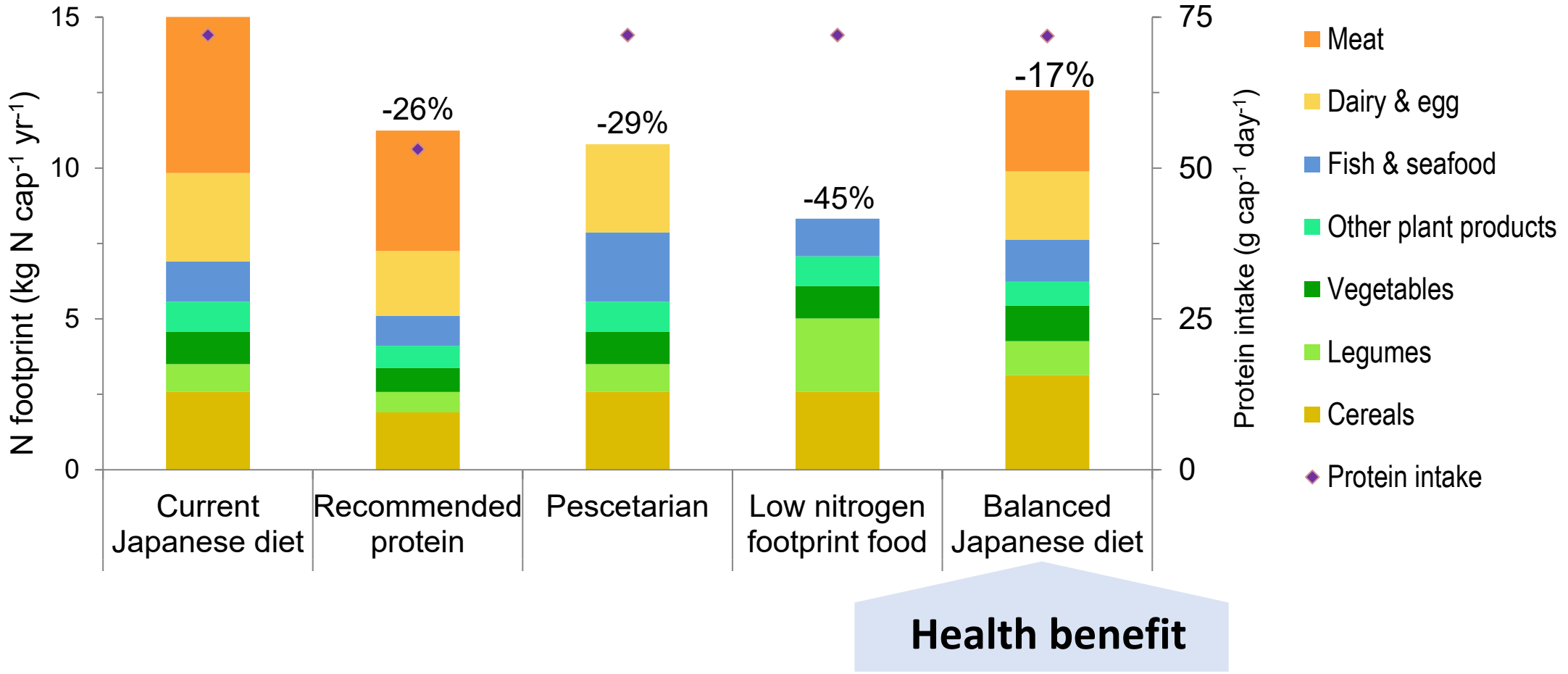
$$\text{Virtual N factor (VNF)} = \frac{\text{Production N loss}}{\text{N in food intake}}$$

(Oita et al., Ecological Indicators, 2016)

Shibata et al., Environmental research letters, 2014)

N loss intensity factor, VNF, varies among seafood.

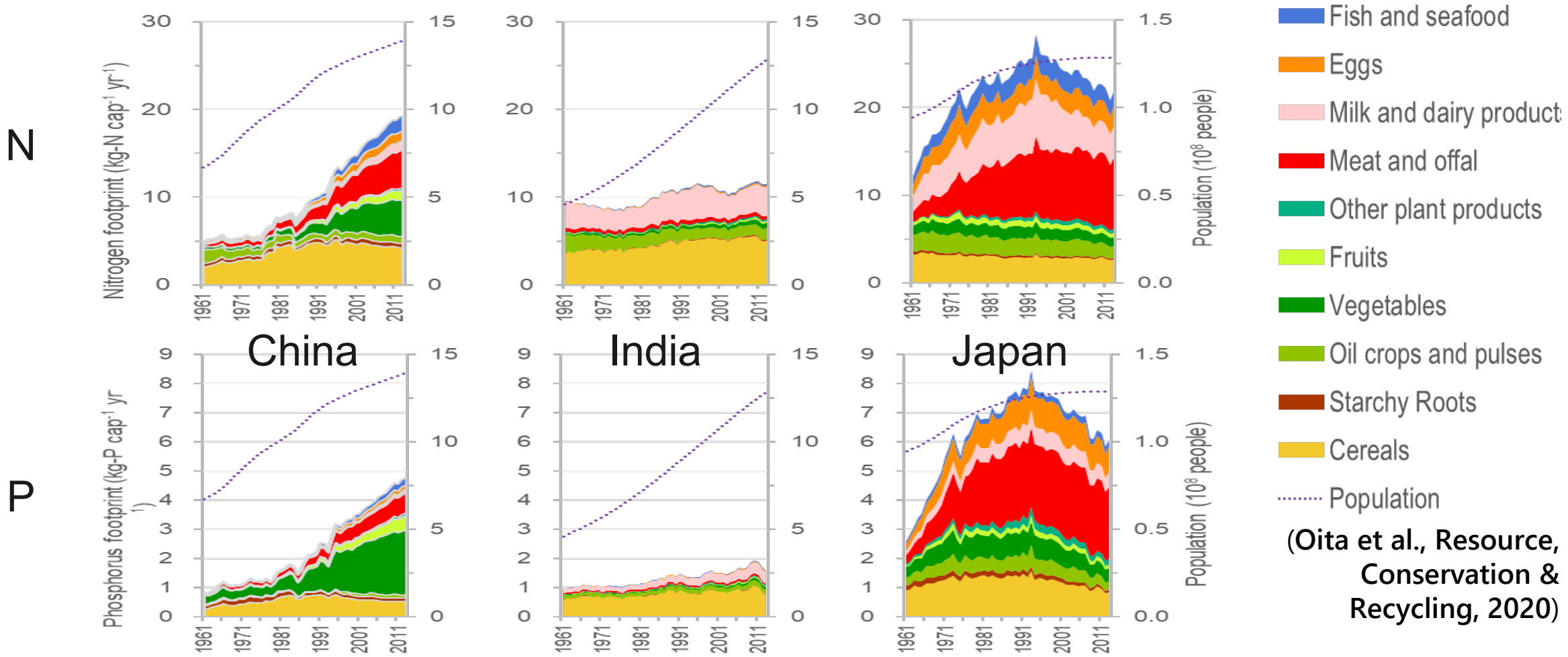
Diet scenarios: what changes the N footprint?



(Oita et al., Ambio, 2018)

Healthier diets can lower the N footprint.

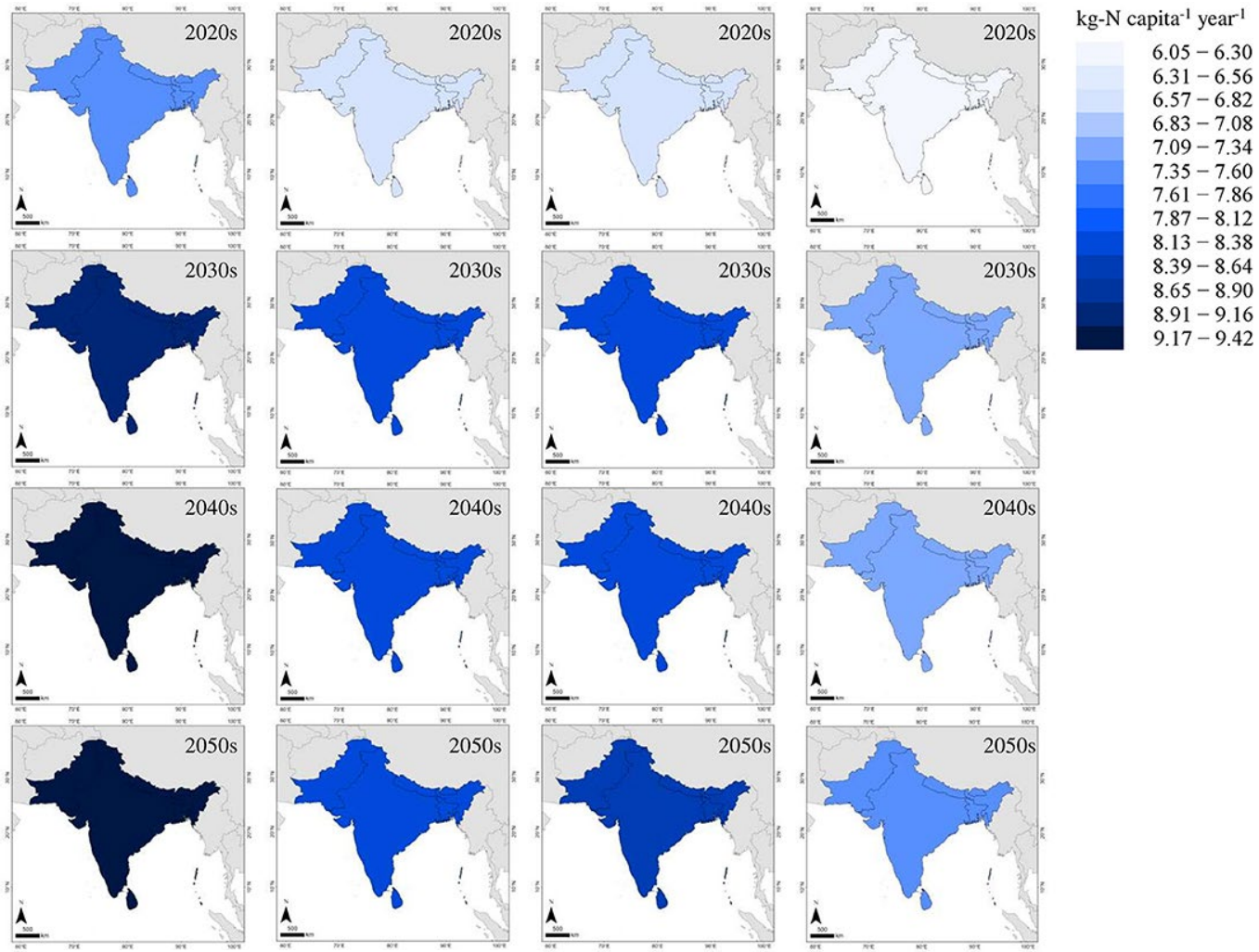
Time series: N footprints with P footprints



(**Oita et al., Resource, Conservation & Recycling, 2020**)

Meat, milk, vegetables & cereals affect N footprints.

Future technologies/diets scenarios

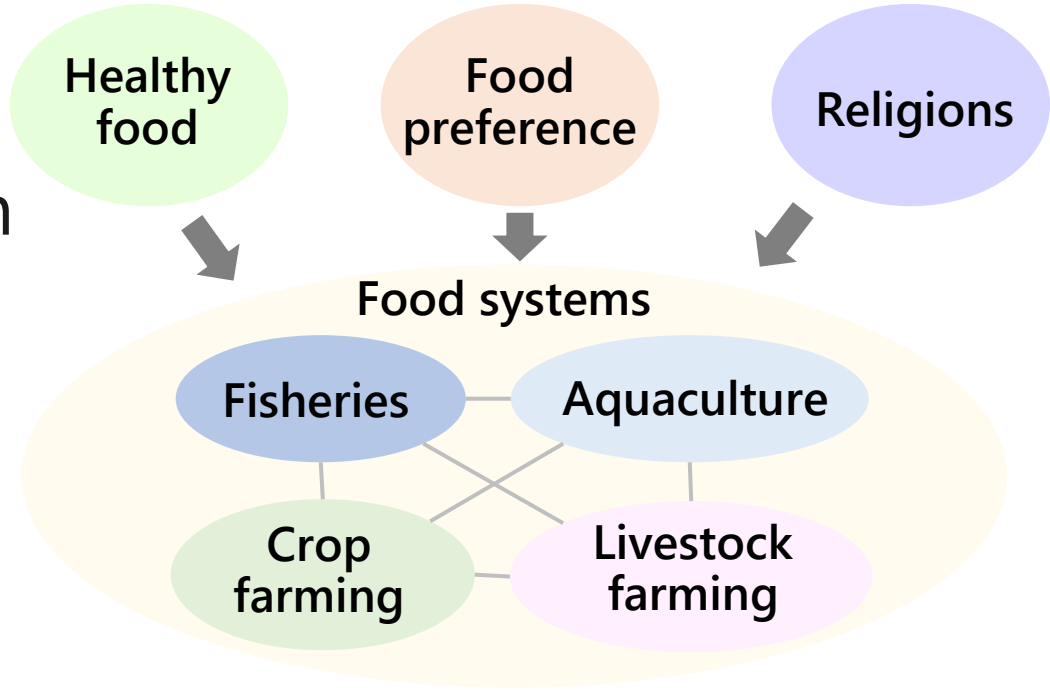


Current (early 2010s) estimation: 8.43 kg-N

(Dhar et al., 2022)

What the bottom-up approach can tell us

- Provides consumer-facing N loss intensities (VNFs) for foods and supports scenario analysis
- Highlights cross-country differences and key contributors in diets
- Can incorporate key cross-system interactions in an integrated accounting framework



(Based on Oita et al., Ecological Indicators, 2016)

(B) Top-down: from country to global analysis

N-Calculator method approach:

focus on each country

Development of the global model

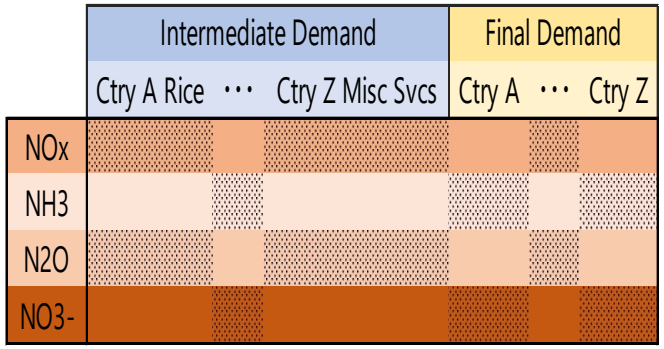
- What is the global situation?
- What are other influential products?
- How does international trade affect N losses?

Linking N losses to consuming countries

Air & water N losses by sectors

Estimated from:

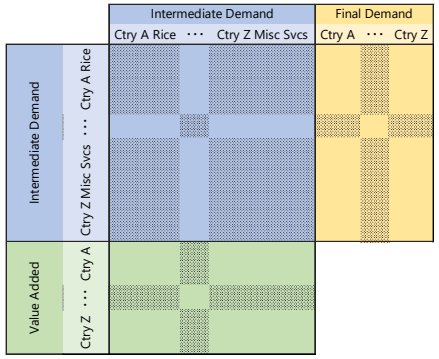
- Fertilizers
- Manure
- N factors
- Energy



Multi-Region Input-Output (MRIO) Table

World MRIO (Eora):

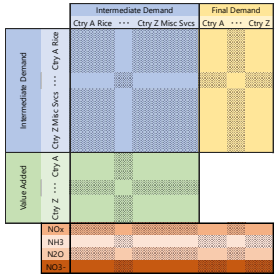
- Monetary trade data
- 188 countries
- 15000 sectors

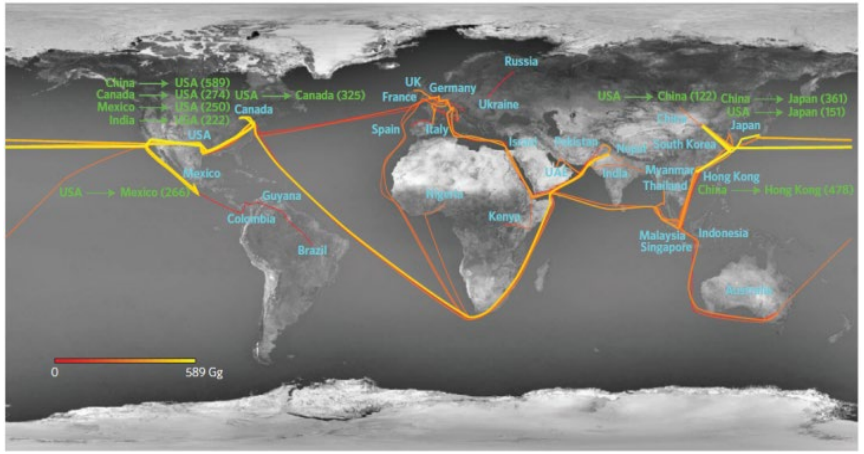


Global N footprint model

Enabled us to analyze

- Global supply chains
- NO_x, NH_3, ... separately

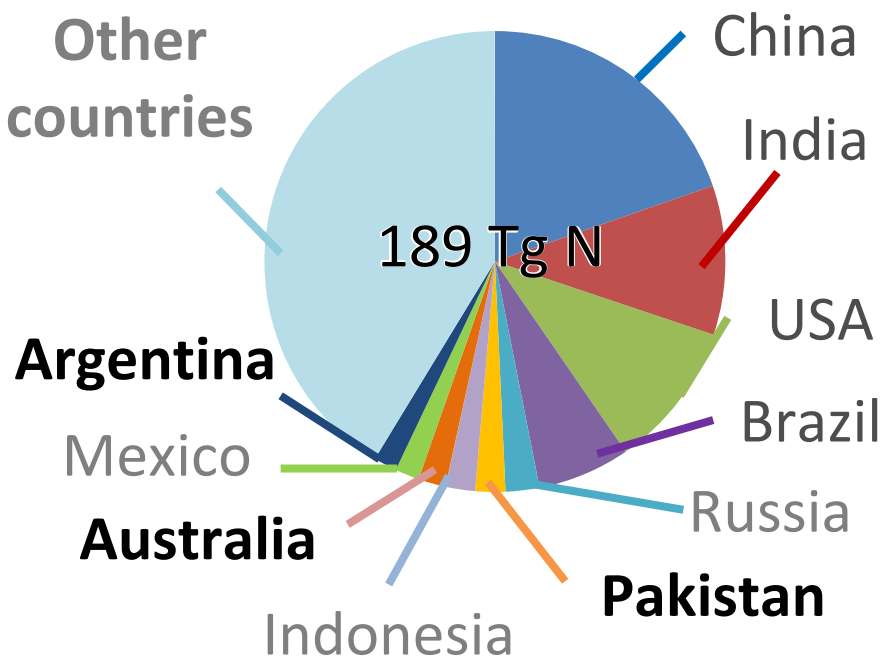




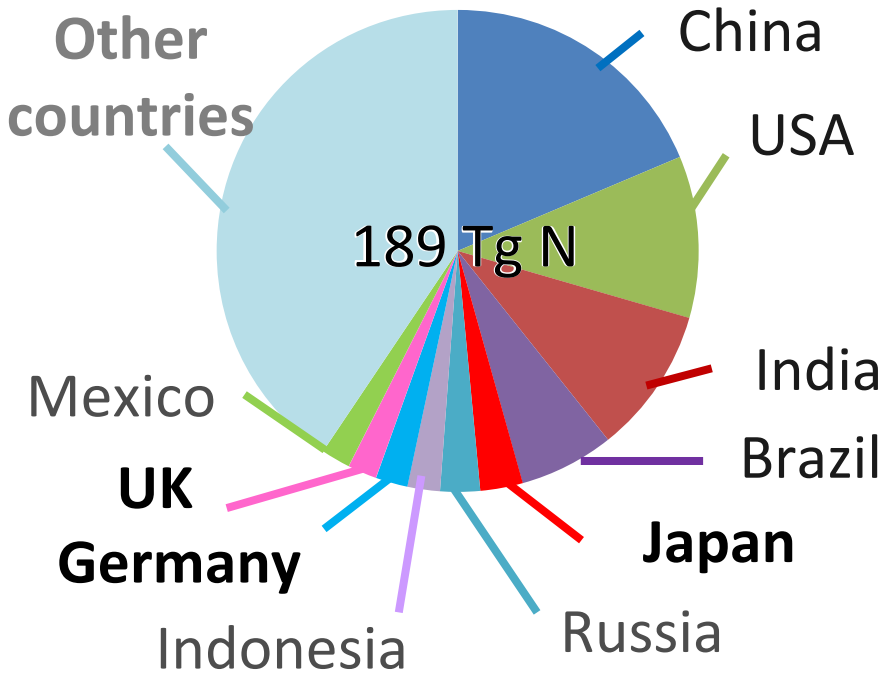
(Oita et al., Nature Geoscience, 2016)

Main countries of N losses and N footprints

N losses within the country



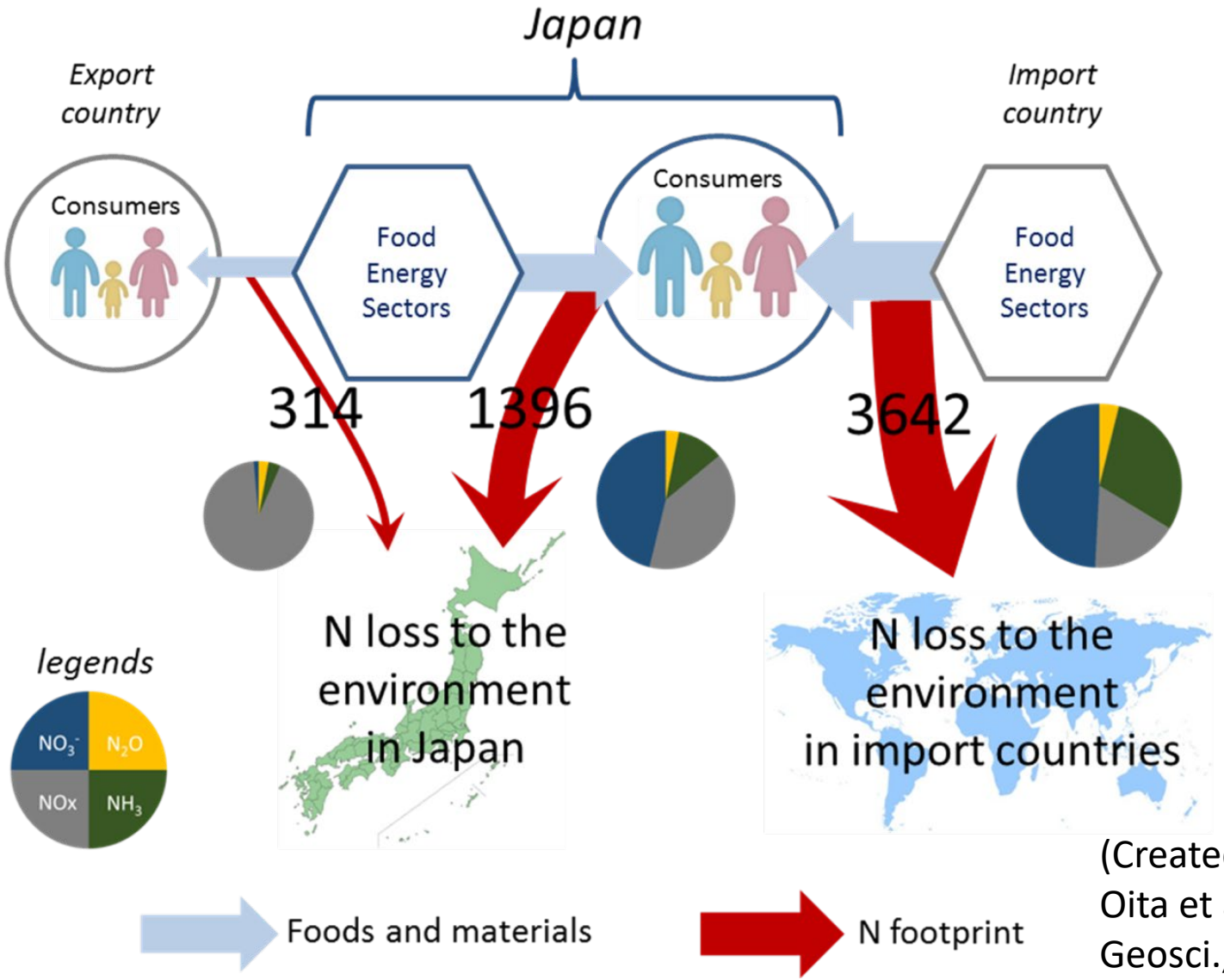
NFs (N losses for their consumption)



(Source: **Oita et al., Nature Geoscience, 2016**)

Quarter of the N footprint is embodied in int'l trade

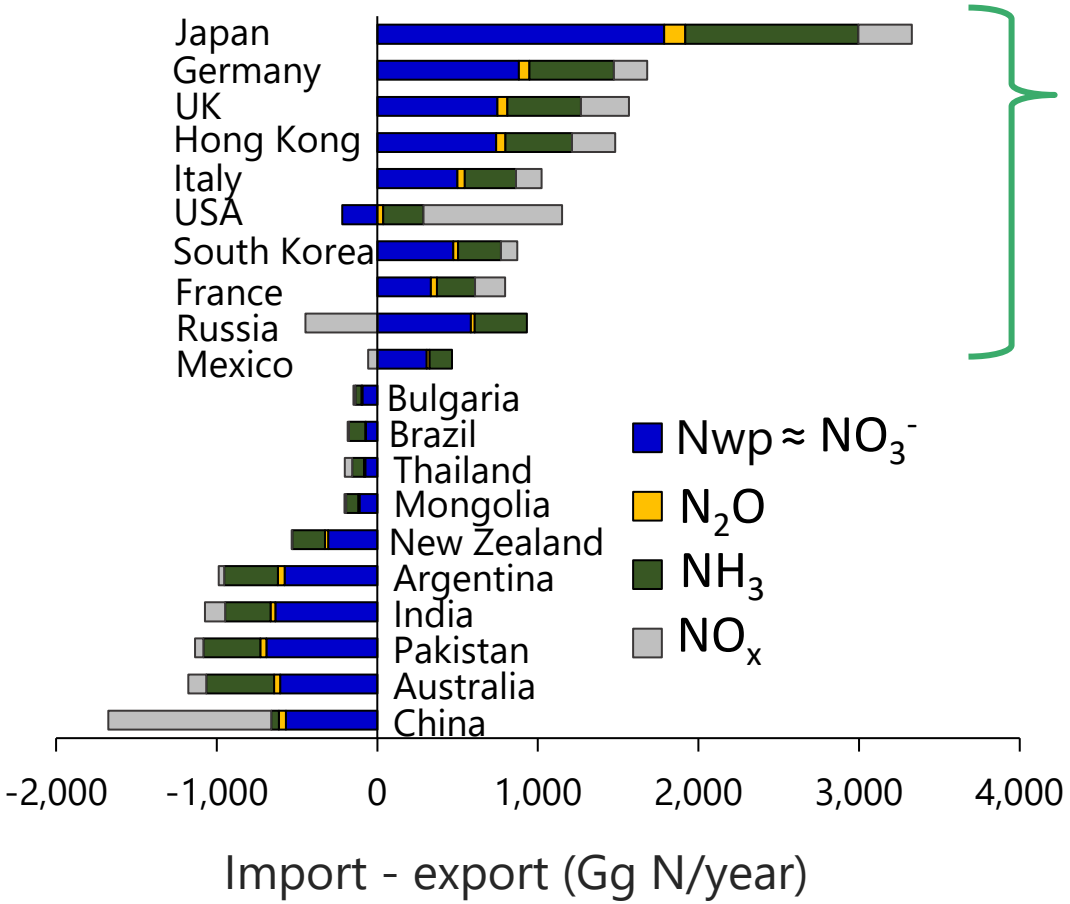
Japanese case of import/export



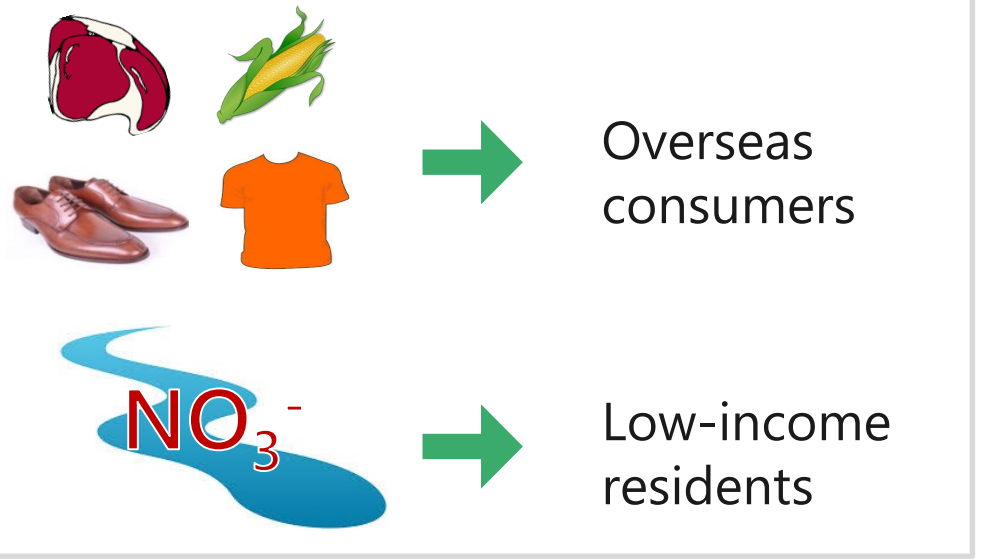
(Created from Oita et al., Nat. Geosci., 2016)

Trade-driven transfers

Trade-embodied N losses



Overseas N pollution for imported goods > Domestic N pollution for exported goods



(**Oita et al., Nature Geoscience, 2016**)

International agro-food trade drives local N pollution

What top-down can and cannot tell us

Can tell

- Economy-wide and trade-linked impacts (multi-country supply chains)
- Key countries/economic sectors
- Contributions by major nitrogen loss types (e.g., NO_x, NH_3, N_2O, NO_3^-)

Cannot tell

- Consumer heterogeneity (age, cultural/ belief-based dietary preferences)
- Item-level differences within sectors (e.g., wheat vs barley vs rye)
- Production-system choices within an item (seasonal vs greenhouse, organic vs conv.)

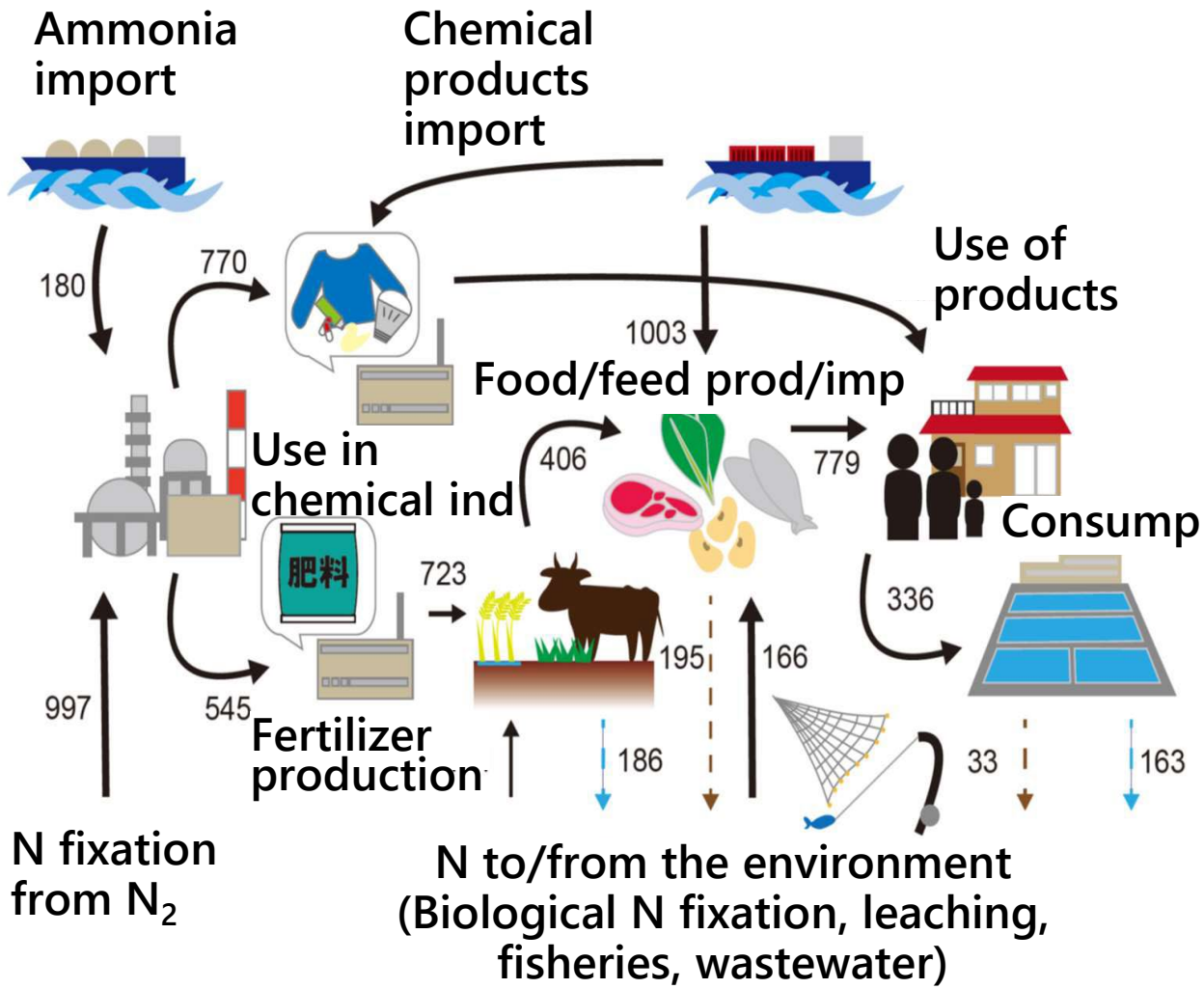
(C) Zooming in on supply chains with NutrIO

Global N footprint model:

focus on international trade

Development of the material-flow sensitive model

- How are Nr sources used?
- How is Nr used along supply chains?
- What are influential sectors?



(Katagiri et al., 2018)

Linking material-flow to input-output analysis

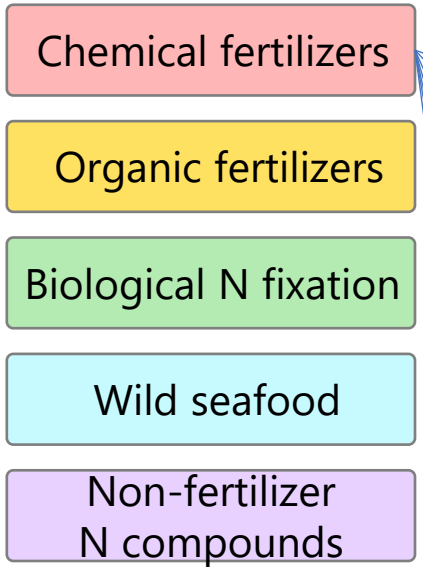
(1) Material-flow analysis

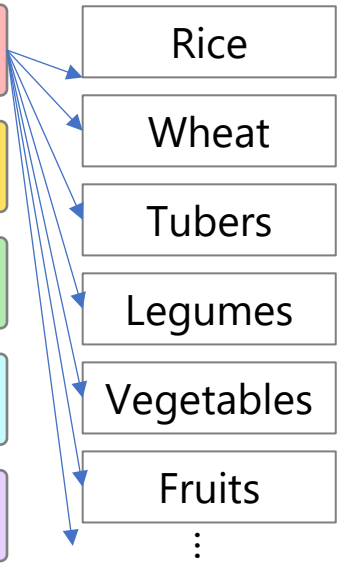
How much of each Nr source goes to which primary sectors?

(2) Input-output analysis

What are the intermediate producers of the Nr, and how is Nr eventually consumed?

Converting N flows to monetary flows, trace the Nr journey



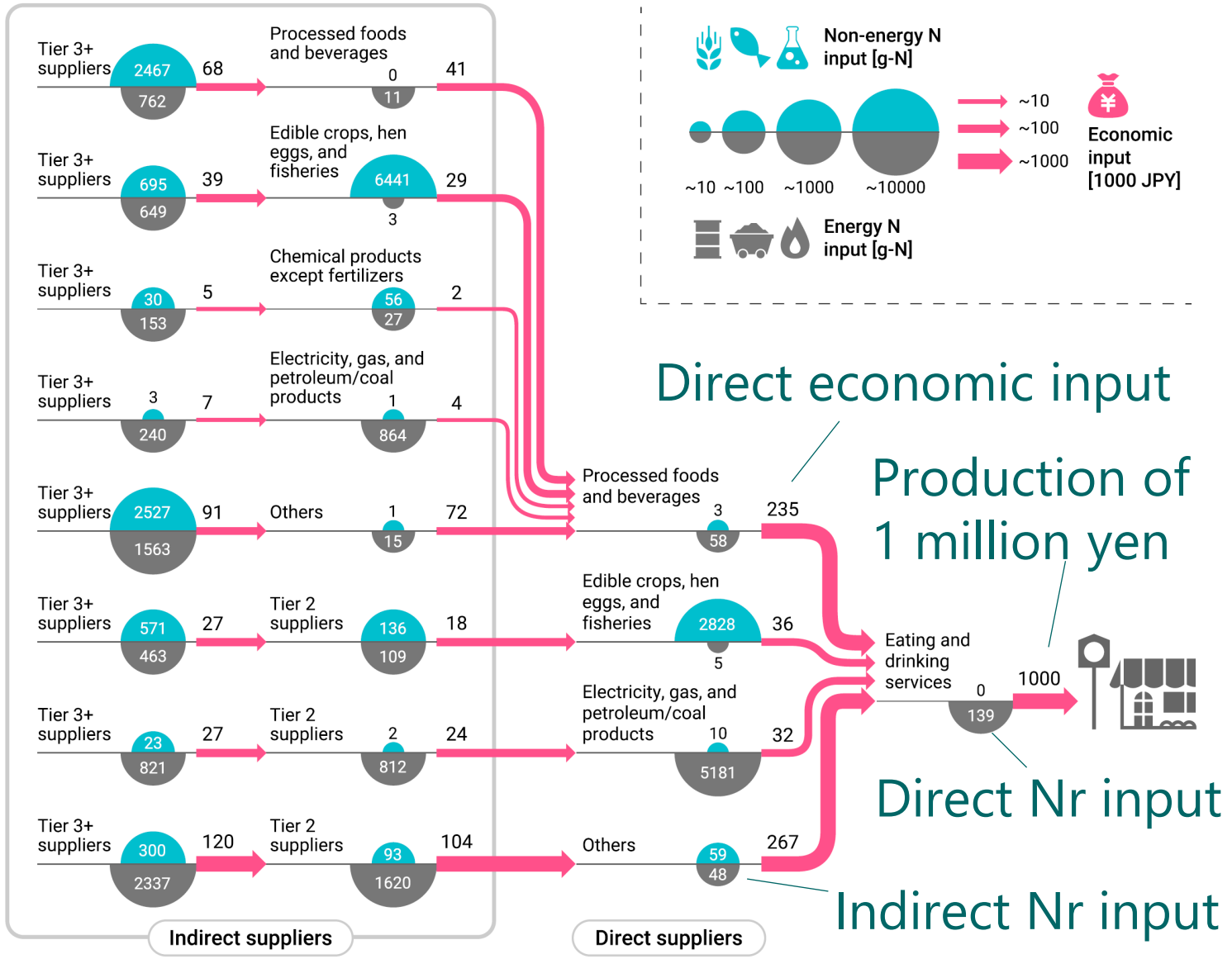


$$\frac{\text{Demand of Nr (Gg-N)}}{\text{Sectoral production (¥1M)}} \times \text{Spillover effect (Leontief Inverse Matrix)} \times \text{Consumption (¥1M)} = \text{NF}$$

Direct impact (N demand factors)

Direct and indirect impacts (N intensity)

Nr flow associated with production (Food service industry)

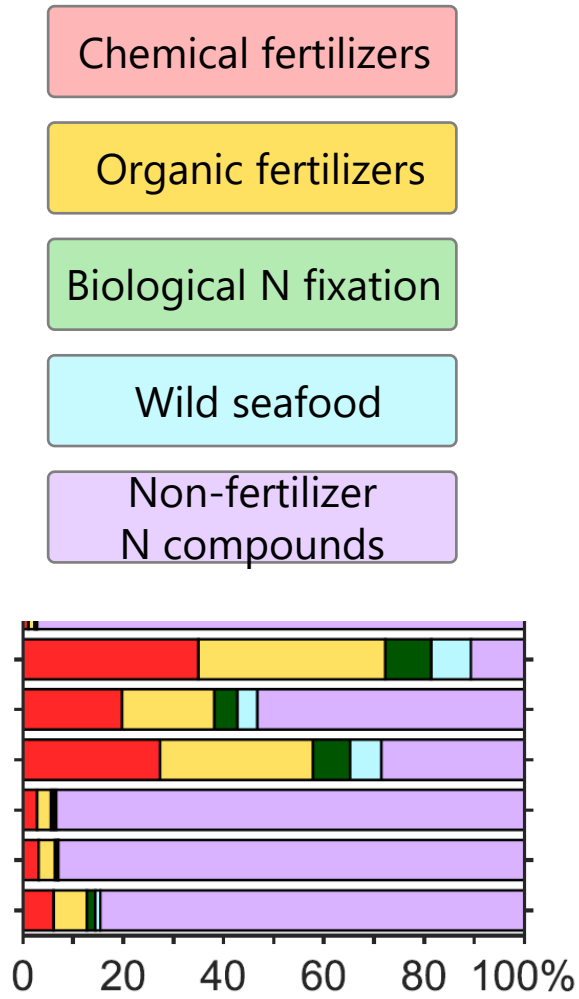


Food service industries have much non-energy Nr input through supply chains

(Oita et al., ERL, 2021)

What supply-chain attribution can tell us

- Shows which sectors and supply-chain links drive Nr-source demand
- Integrates multiple Nr sources (fertilizer, chemical products, energy) in one framework
- Helps identify priority leverage points for interventions



Current interests: Making N footprint results usable

- **Linking drivers to impacts**:

  connecting production/consumption drivers with environmental outcomes
- **From statistics to integrated data**:

  combining economic IO/trade analysis, nutrient flow data, and scenario modelling
- **Communication & engagement:**

  making nitrogen impacts visible to consumers and stakeholders
- **Policy relevance**:

  translating footprint evidence into practical policy and management actions

Questions and Discussion

Discussion prompts:

-Who has the biggest leverage to reduce nitrogen losses:
consumers, retailers, farmers, policy makers?

-What tools or facilitation mechanisms would be most effective in practice:
one integrated tool, separate tools, or linked tools?

-How should we handle data gaps in practice:
interpolation/extrapolation, substitution with proxies, or scenario ranges?

Contact

Azusa Oita NARO (Japan)/ZALF (Germany) oita.azusa855@naro.go.jp