UCLouvain

KU LEUVEN

Metrics for sustainable food economies

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In a nutshell

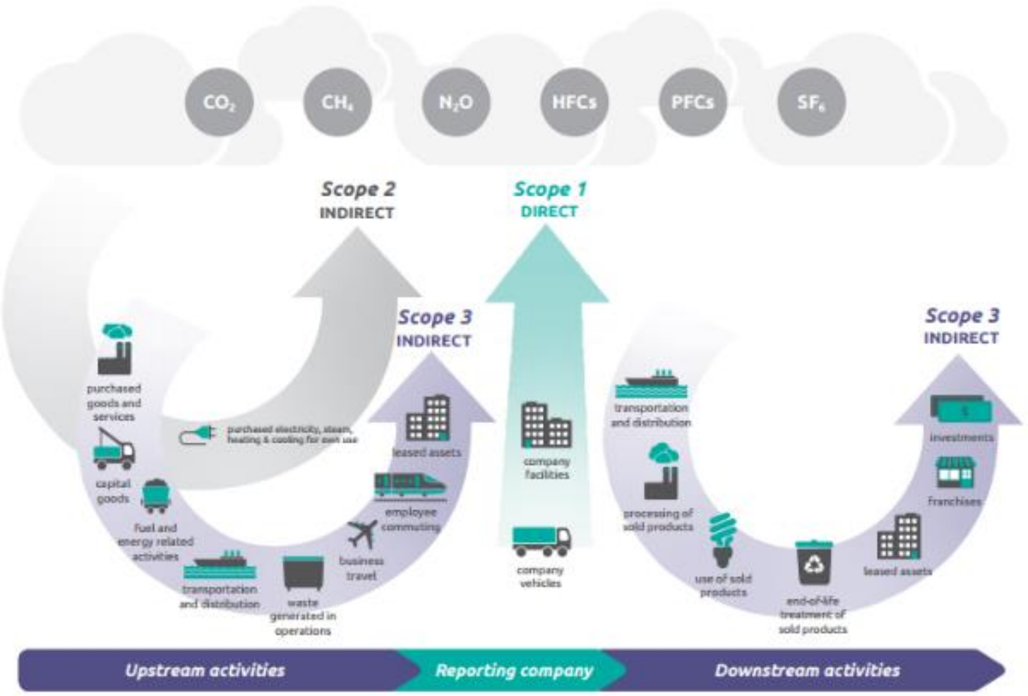
- Planetary boundaries (climate change, biodiversity, N&P) at the macro/aggregate level to which micro-level activities contribute
- ***Challenge 1***: To be able do decide how to change these activities, we need to know how they contribute to these boundaries accurately (measuring the right thing in the correct way)
- ***Challenge 2***: But we also need to know how these activities interact with each other and how they relate to socio-economic dimensions (cost, culture) to make societal choices
- ***Challenge 3***: We need to translate knowledge into actions in complex food systems

Challenges

1. Trade-off in terms of timing (now, later)
2. Trade-off between sectors (food, buildings, transport, industry,…)
3. Trade-off between activities within sectors (plant, animal)
4. Trade-off between impact categories (land, biodiversity)
5. Dynamic, non-linear, variable, uncertain and context-specific nature of boundaries, activities and their interrelationships

Specific challenge

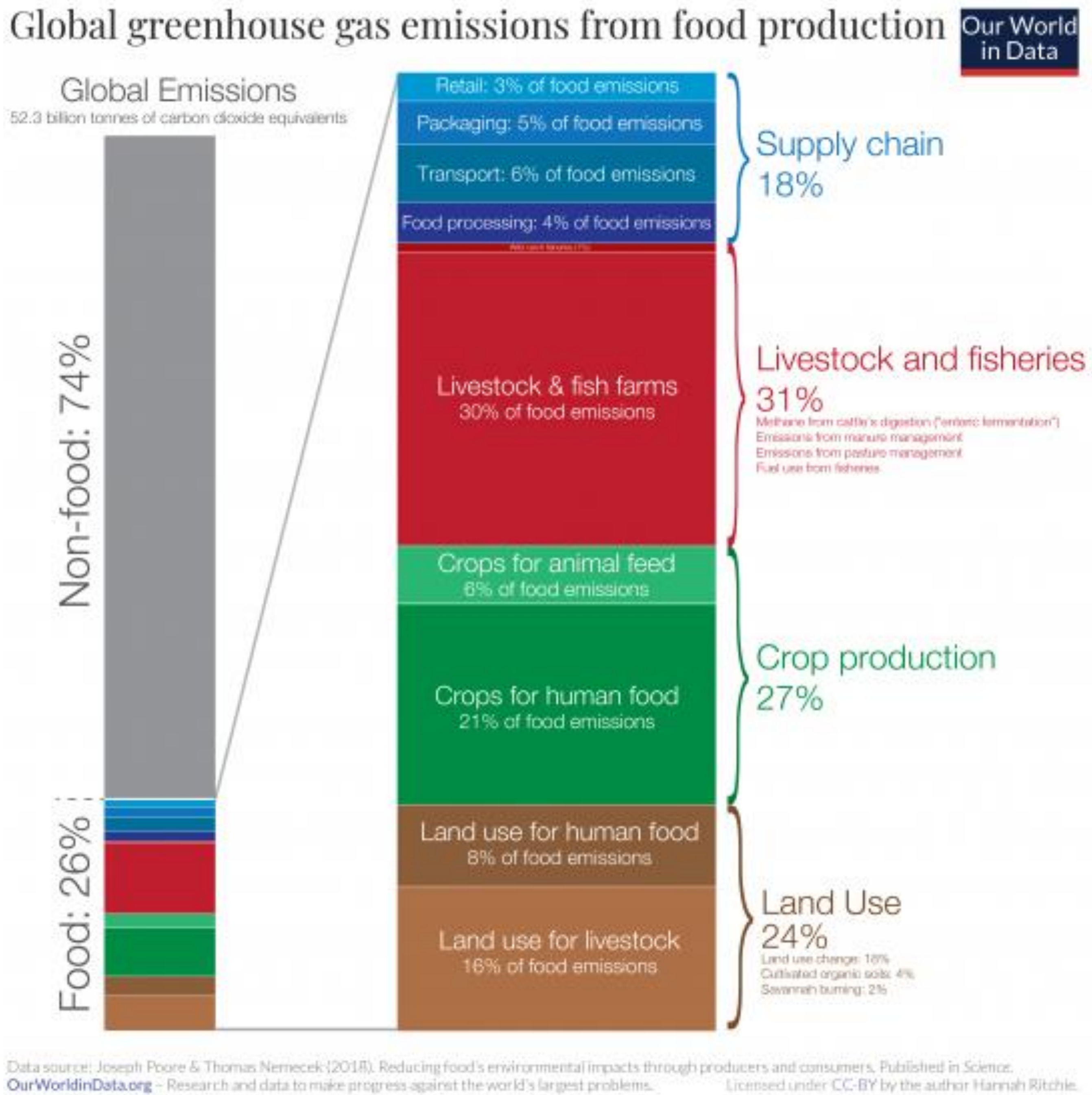
International collaboration leads to accounting rules that are different from scientific life-cycle accounting, thus creating an additional trade-off between nations (linked to cap-and-trade/negotiate dynamics)



https://ghgprotocol.org/blog/you-too-can-master-value-chain-emissions

Maakt vlucht meer of minder binnen Europa nu een verschil of niet voor het klimaat?

Of je binnen Europa met de trein of met het vliegtuig reist, het maakt geen verschil uit voor het klimaat. Dat zegt tenminste transporteconoom Stef Proost van de



Paradox?

BELGIUM:
Agriculture: 9-10%
Of which livestock: 6-7%

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

WCED, 1987. Our Common Future (Brundtland report)

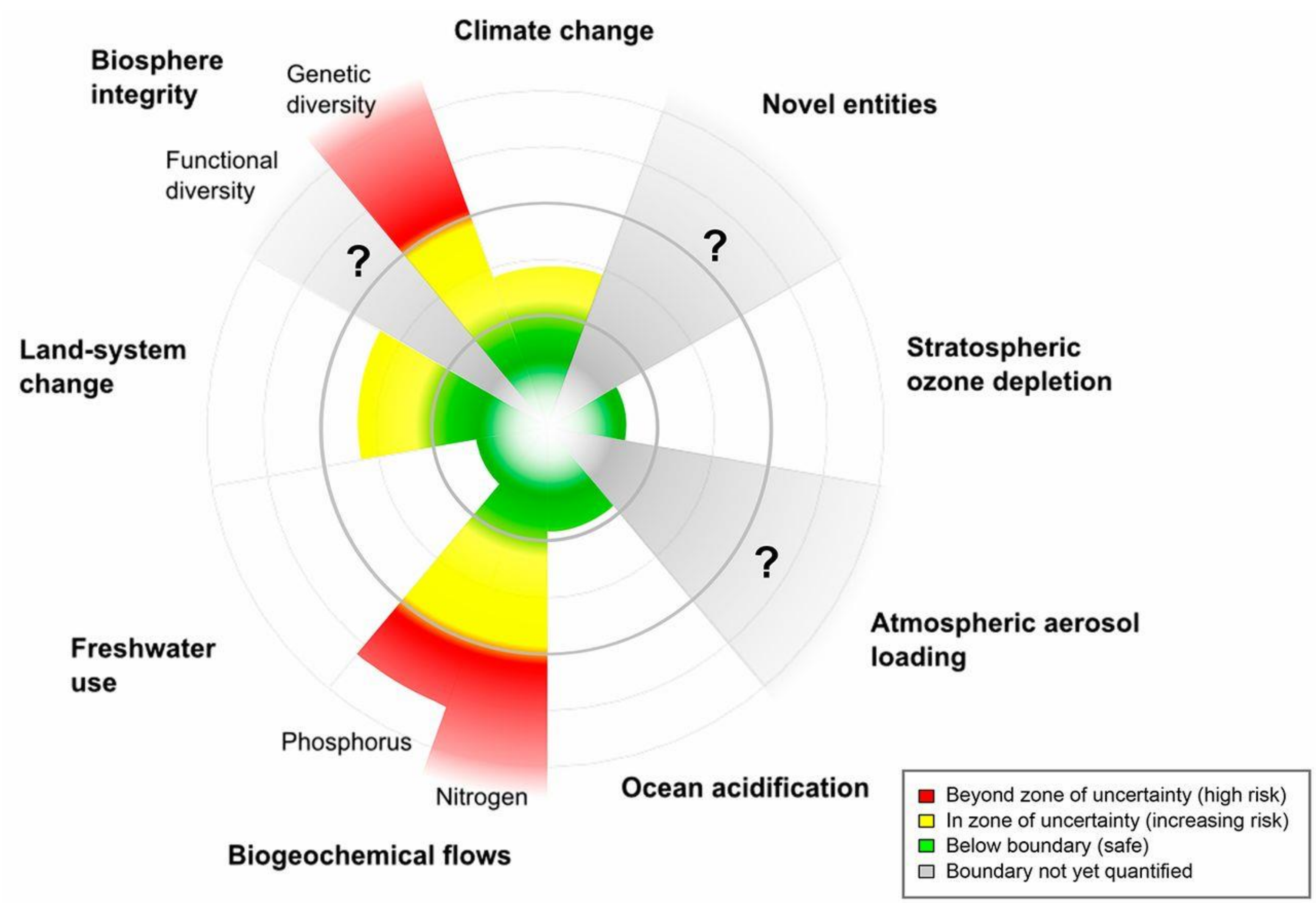
“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

It contains within it two key concepts:

- The concept of **needs**, in particular the essential needs of the world’s poor, to which overriding priority should be given;
- The idea of **limitations** by the state of technology and social organization on the environment’s ability to meet present and future needs”

WCED, 1987. Our Common Future (Brundtland report)

Fig. 3 The current status of the control variables for seven of the nine planetary boundaries.



Will Steffen et al. Science 2015;347:1259855

Limitations

	Control variable	Boundary (uncertainty range)
Climate change	Greenhouse-gas (CH_4 and N_2O) emissions	5 Gt of carbon dioxide equivalent per year (4·7–5·4)
Nitrogen cycling	Nitrogen application	90 Tg of nitrogen per year (65–90;* 90–130†)
Phosphorus cycling	Phosphorus application	8 Tg of phosphorus per year (6–12;* 8–16†)
Freshwater use	Consumptive water use	2500 km^3 per year (1000–4000)
Biodiversity loss	Extinction rate	Ten extinctions per million species-years (1–80)
Land-system change	Cropland use	13 million km^2 (11–15)

*Lower boundary range if improved production practices and redistribution are not adopted. †Upper boundary range if improved production practices and redistribution are adopted and 50% of applied phosphorus is recycled.

Table 2: **Scientific targets for six key Earth system processes and the control variables used to quantify the boundaries**

Willet et al., 2019, The Lancet

Needs

Willet et al., 2019, The Lancet

	Macronutrient intake (possible range), g/day	Caloric intake, kcal/day
Whole grains*		
Rice, wheat, corn, and other†	232 (total gains 0–60% of energy)	811
Tubers or starchy vegetables		
Potatoes and cassava	50 (0–100)	39
Vegetables		
All vegetables	300 (200–600)	..
Dark green vegetables	100	23
Red and orange vegetables	100	30
Other vegetables	100	25
Fruits		
All fruit	200 (100–300)	126
Dairy foods		
Whole milk or derivative equivalents (eg, cheese)	250 (0–500)	153
Protein sources‡		
Beef and lamb	7 (0–14)	15
Pork	7 (0–14)	15
Chicken and other poultry	29 (0–58)	62
Eggs	13 (0–25)	19
Fish§	28 (0–100)	40
Legumes		
Dry beans, lentils, and peas*	50 (0–100)	172
Soy foods	25 (0–50)	112
Peanuts	25 (0–75)	142
Tree nuts	25	149
Added fats		
Palm oil	6·8 (0–6·8)	60
Unsaturated oils¶	40 (20–80)	354
Dairy fats (included in milk)	0	0
Lard or tallow‖	5 (0–5)	36
Added sugars		
All sweeteners	31 (0–31)	120

For an individual, an optimal energy intake to maintain a healthy weight will depend on body size and level of physical activity. Processing of foods such as partial hydrogenation of oils, refining of grains, and addition of salt and preservatives can substantially affect health but is not addressed in this table. *Wheat, rice, dry beans, and lentils are dry, raw. †Mix and amount of grains can vary to maintain isocaloric intake. ‡Beef and lamb are exchangeable with pork and vice versa. Chicken and other poultry is exchangeable with eggs, fish, or plant protein sources. Legumes, peanuts, tree nuts, seeds, and soy are interchangeable. §Seafood consist of fish and shellfish (eg, mussels and shrimps) and originate from both capture and from farming. Although seafood is a highly diverse group that contains both animals and plants, the focus of this report is solely on animals. ¶Unsaturated oils are 20% each of olive, soybean, rapeseed, sunflower, and peanut oil. ‖Some lard or tallow are optional in instances when pigs or cattle are consumed.

Table 1: **Healthy reference diet, with possible ranges, for an intake of 2500 kcal/day**

CHAD
$1

Source: TIME, 2016, Hungry Planet: What the World Eats, time.com

AUSTRALIA
$377

Source: TIME, 2016, Hungry Planet: What the World Eats, time.com

Needs

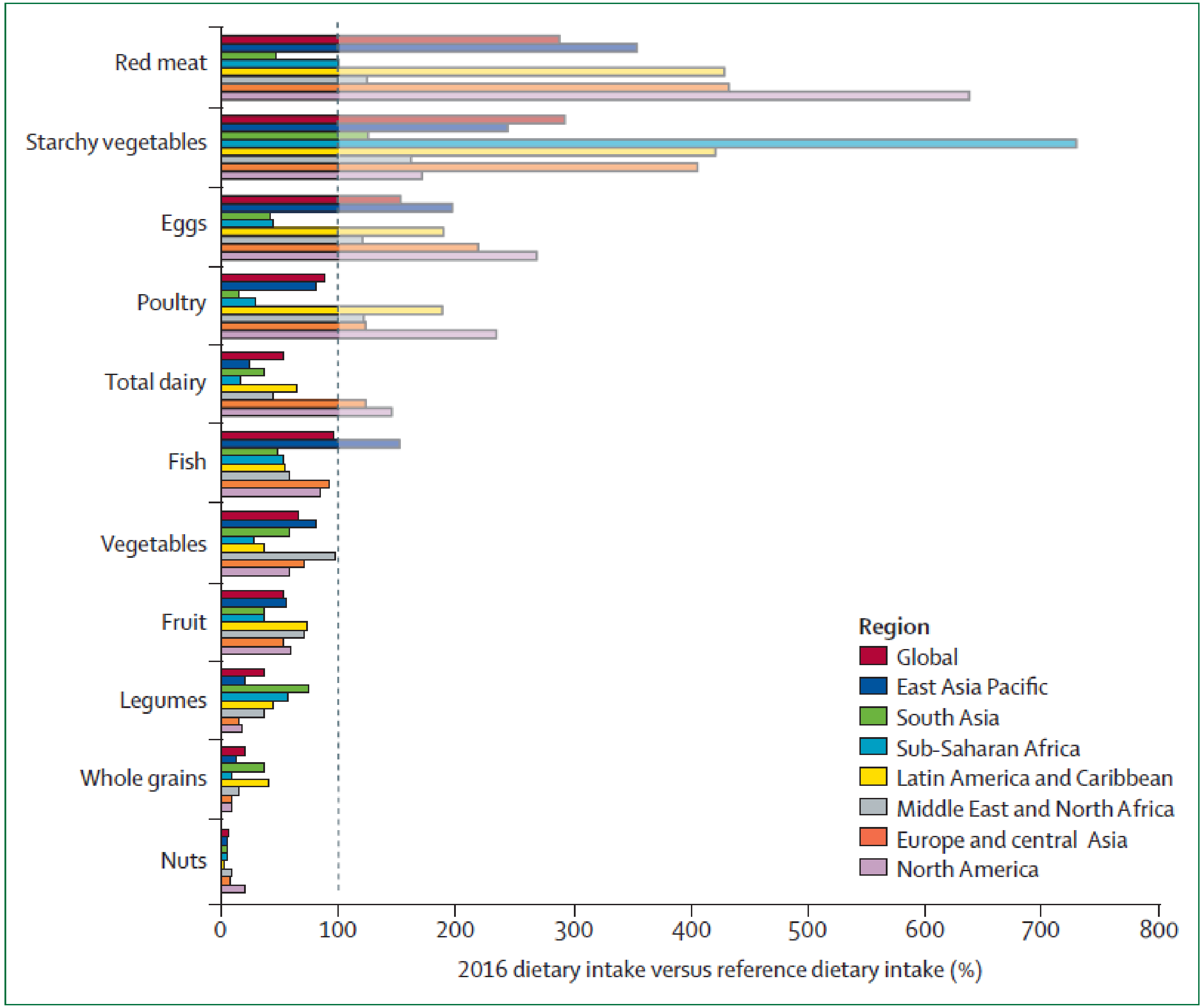


Figure 1: **Diet gap between dietary patterns in 2016 and reference diet intakes of food**
Data on 2016 intakes are from the Global Burden of Disease database.[130] The dotted line represents intakes in reference diet (table 1).

Willet et al., 2019, The Lancet

The doughnut of social and planetary boundaries (2017)

www.kateraworth.com

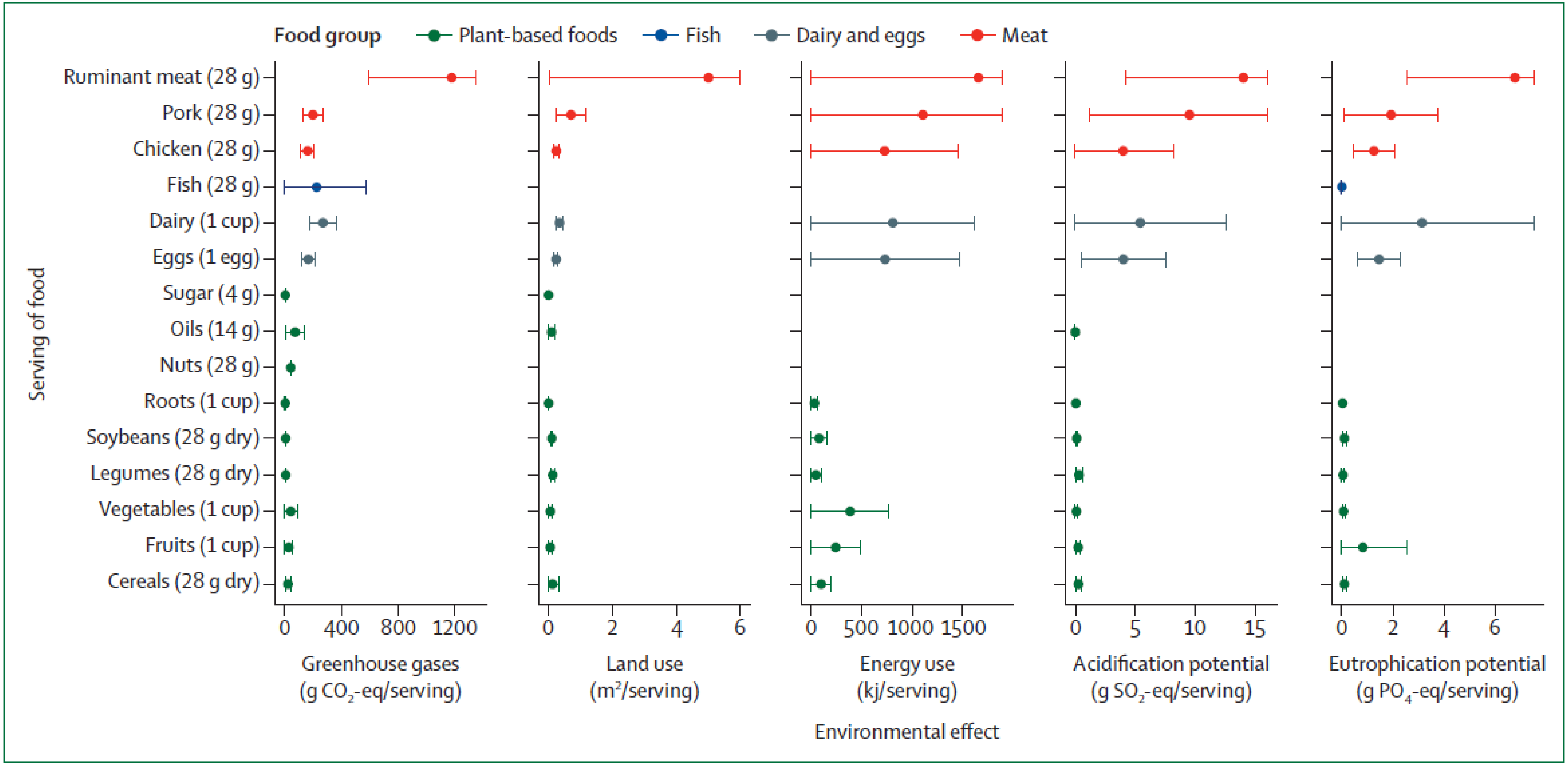


Figure 4: **Environmental effects per serving of food produced**

Bars are mean (SD).[5,216] Some results are missing for fish due to lack of data for some impact categories (eg, land use stemming from plant-based feeds in aquaculture). This was, however, accounted for in the global food systems modeling framework used in Section 3. CO_2=carbon dioxide. Eq=equivalent. PO_4=phosphate. SO_2=sulphur dioxide.

Willet et al., 2019, The Lancet

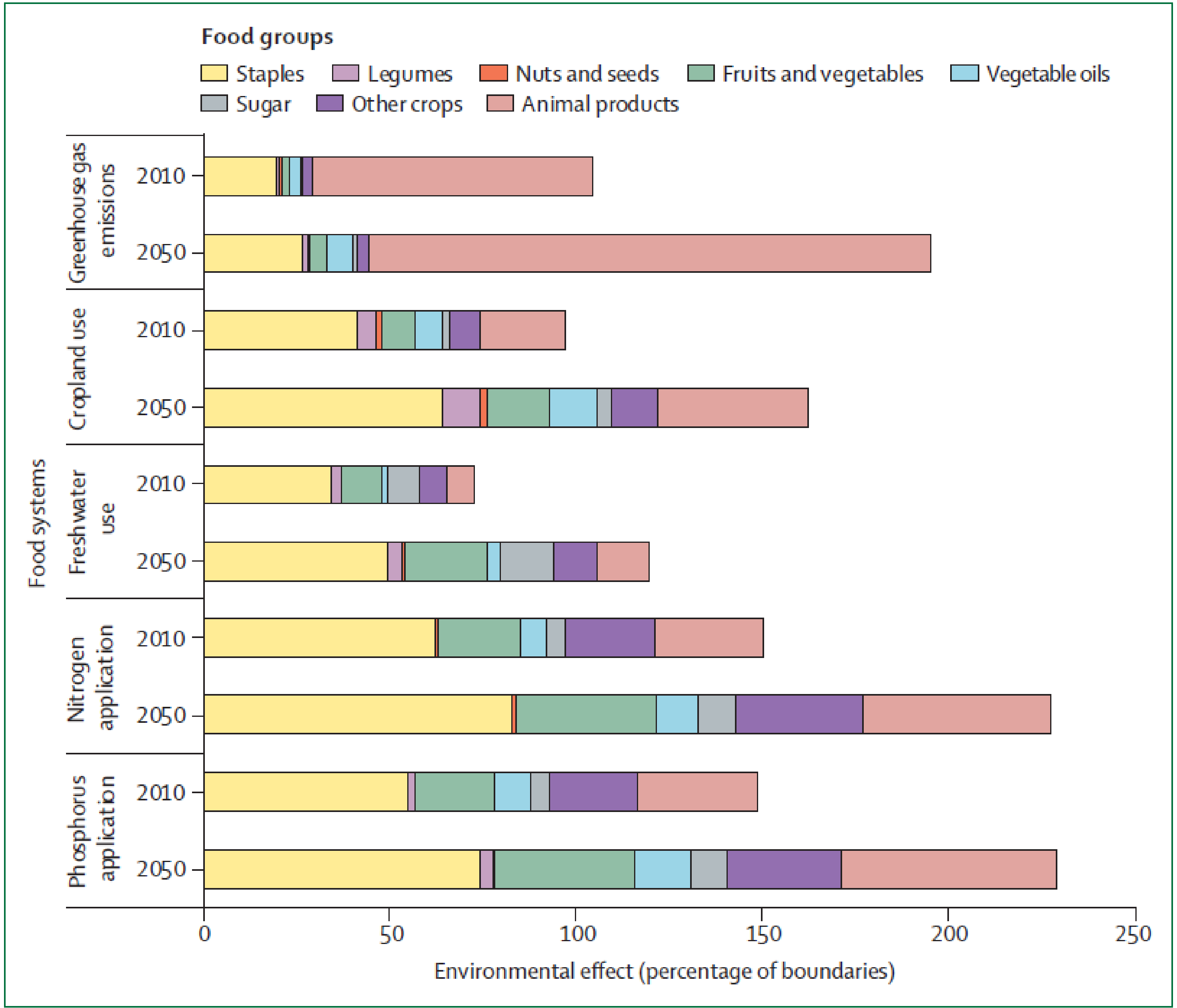


Figure 5: Environmental effects in 2010 and 2050 by food groups on various Earth systems based on business-as-usual projections for consumption and production

Willet et al., 2019, The Lancet

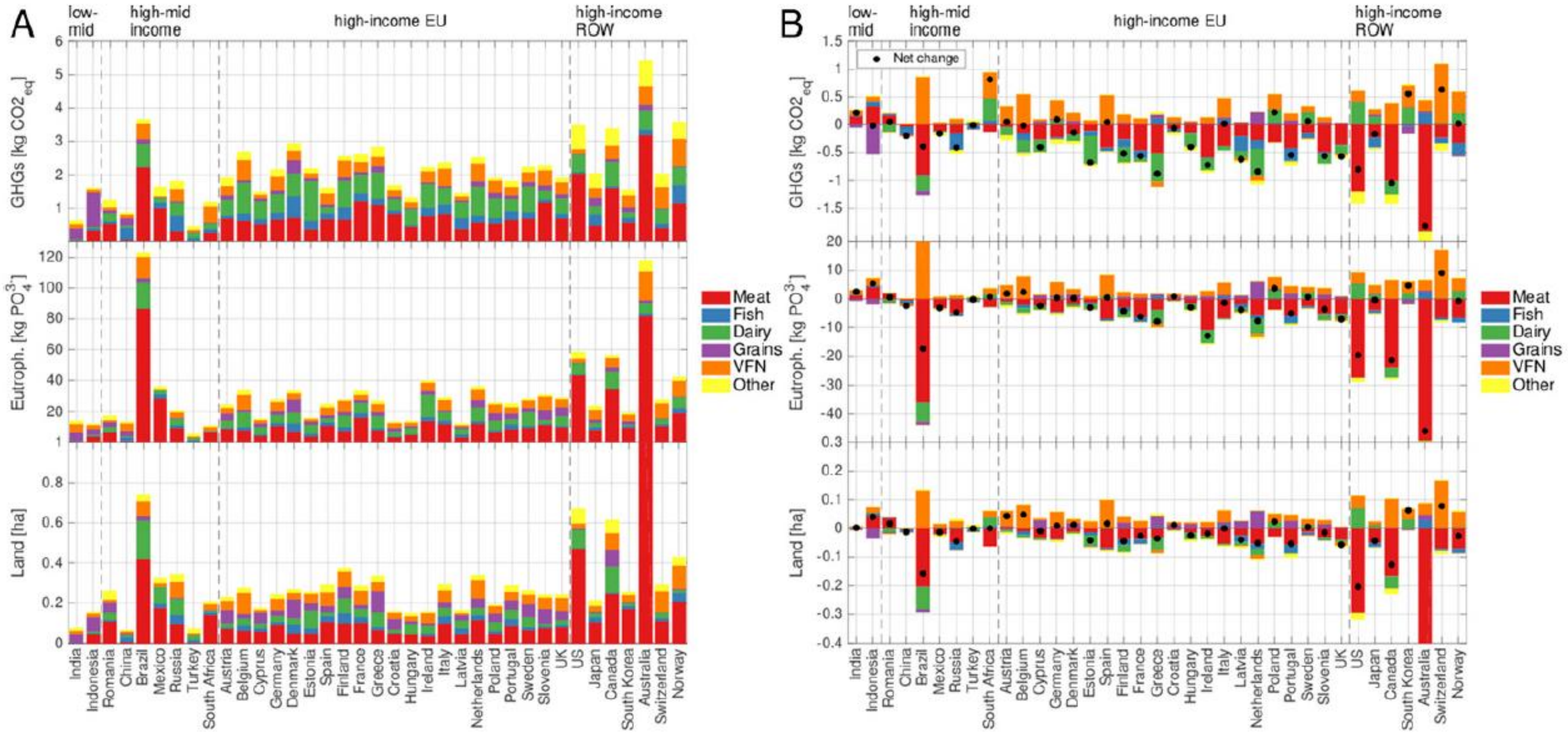


Fig. 2. (*A*) Absolute environmental impacts of average diets for different national income groups per person. (*B*) Differences in environmental impacts between average and recommended diets per person. Net change and change by food group are shown. Both panels give GHG and eutrophication emissions in terms of per day and land use in ongoing, yearly requirement. Land use in Australia has been truncated in both panels for ease of visualization (in *A*, total Australian land use is 3.3 ha; in *B* the change is a reduction of 1.0 ha).

Behrens et al., 2017, PNAS

Key challenge 1

- How to measure contributions to these boundaries accurately? How to measure the right thing in a correct and consistent way?
- Taking into account:
  - Trade-off between sectors (food, buildings, transport, industry,…)
  - Trade-off between activities within sectors (plant, animal) → **displacement effects**
  - Trade-off between impact categories (land, biodiversity) → **weighing impacts**
  - Dynamic, non-linear, variable, uncertain and context-specific nature of boundaries, activities and their interrelationships

Main LCA phases (ISO 14040)

- Step 1: Defining the goal and scope of the study
- Step 2: Making a model of the product life cycle with all the environmental inputs and outputs = life cycle inventory (LCI)
- Step 3: Understanding the environmental relevance of all the inputs and outputs = life cycle impact assessment (LCIA)
- Step 4: The interpretation of the study

Source: Goedkoop et al. (2016), Introduction to LCA with SimaPro

Goal and scope definition

- **Reason** for executing LCA (questions which need to be answered)
- Precise **definition** of product, its life cycle and function it fulfills
- Definition of **functional unit** (especially when products are to be compared): kg, ha, kcal, kg protein,…
- Description of **system boundaries** and how to deal with **co-production**
- **Data** and data quality requirements, assumptions and limitations
- **Requirements** regarding LCIA procedure + interpretation
- Intended **audiences** and how results will be communicated
- If applicable, how **peer review** will be made
- Type and format of the **report** required for the study

System boundaries

1. **First order**: only the production of materials and transport are included (this is rarely used in LCA)
2. **Second order**: All processes during the life cycle are included but the capital goods are left out.
3. **Third order**: All processes including capital goods are included. Usually capital goods are only modeled in first order mode (only production of materials needed to produce the capital goods are included)

Inputs or outputs are not considered if they are below certain threshold (mass flow, economic value, contribution to environmental load)

Dealing with multifunctional processes

- System expansion (consequential modeling)

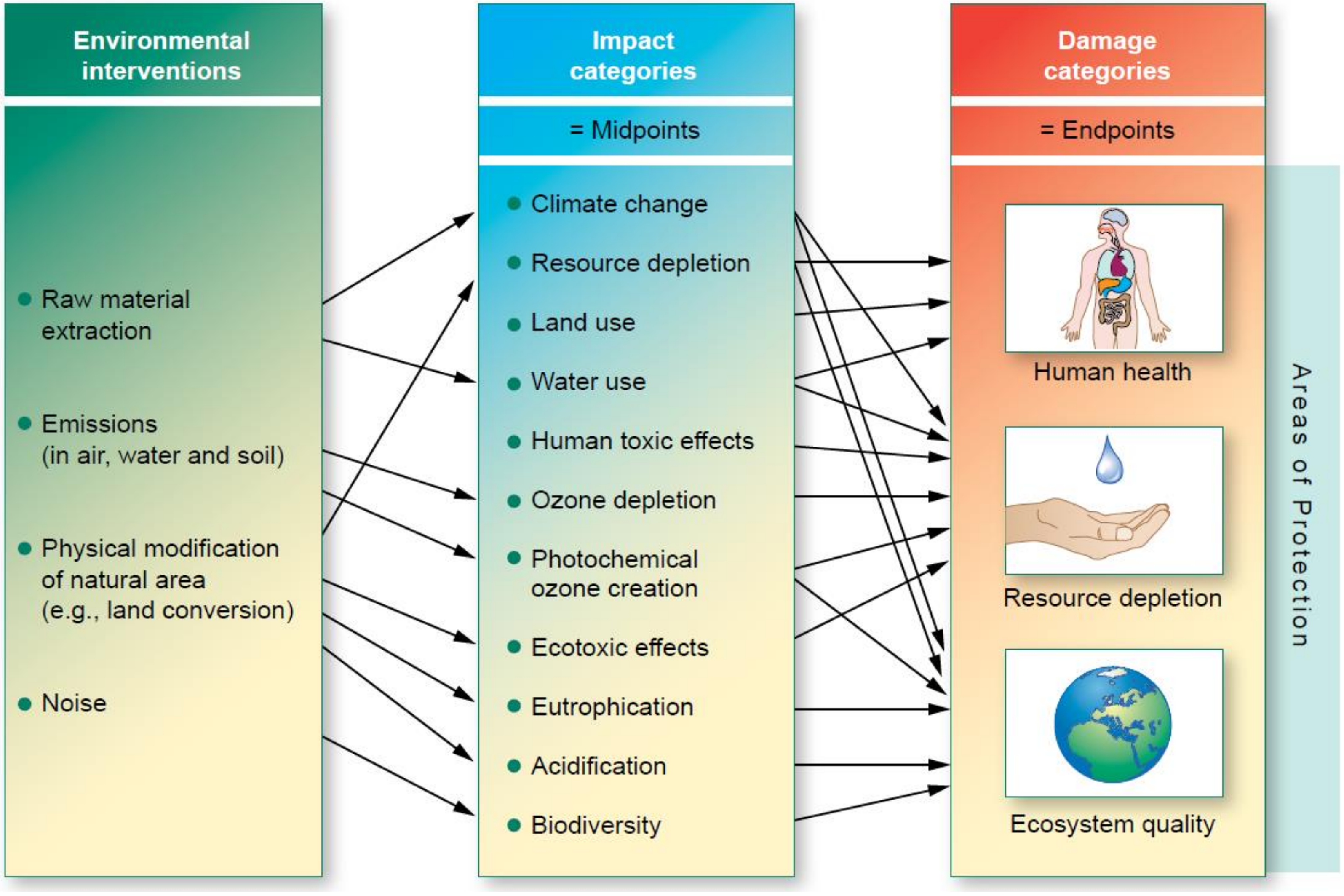
- Allocation (attributional modeling):
    1. Subdivide the multifunctional process
    2. Determine a physical causality for allocation
    3. Use economic revenue as the key for allocation when physical relationship cannot be established

Inventory

1. **Foreground** data: specific data needed for modeling system. Typically, it is data that describe a particular product system or a specialized production system.

2. **Background** data: data for production of generic materials, energy, transport and waste management (in SimaPro databases—ecoinvent—and from literature)

Impact assessment



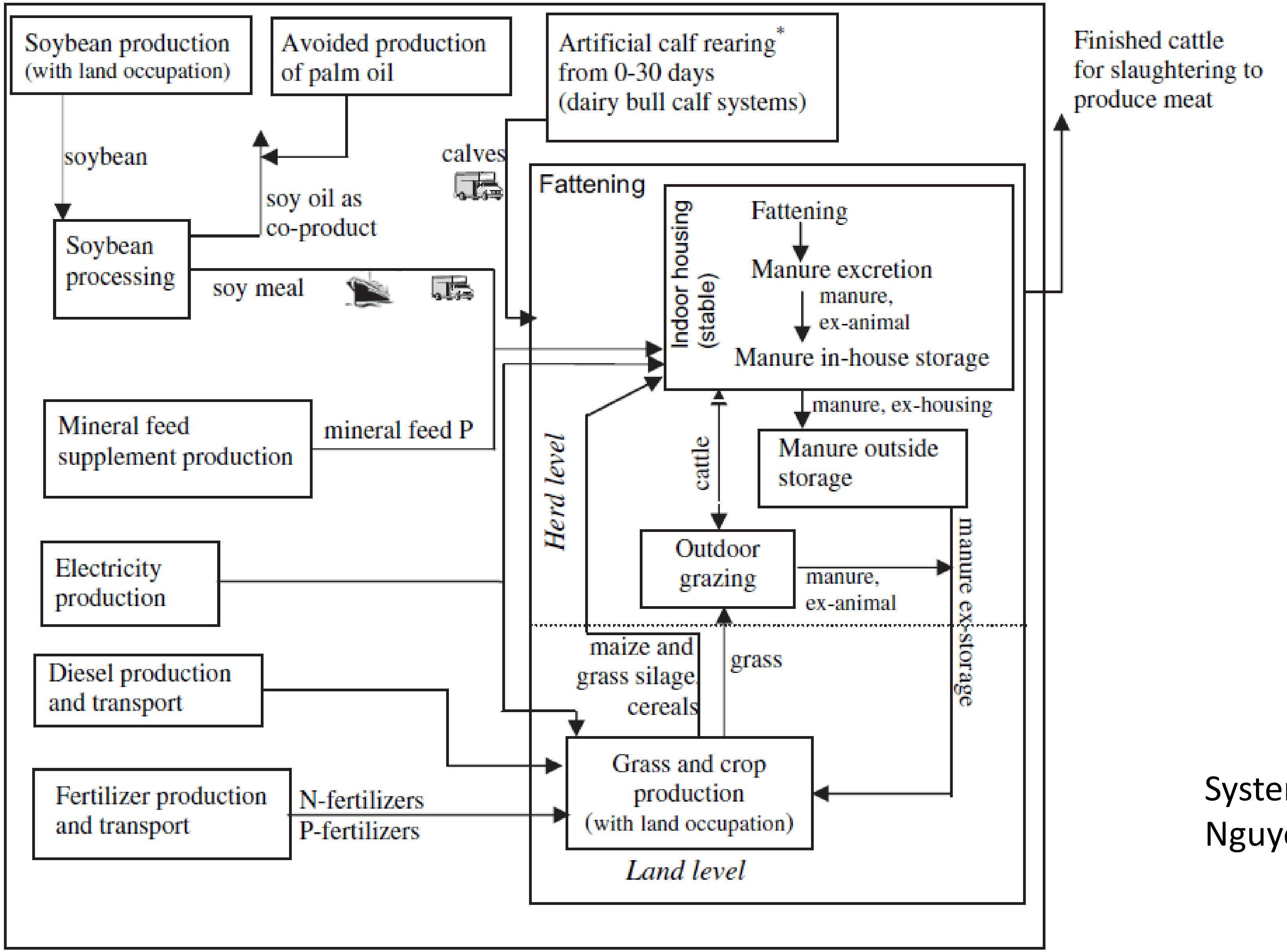
Source: UNEP/SETAC, 2011, Towards a Life Cycle Sustainability Assessment

Interpretation

- Uncertainty analysis
  - Variation in the data
  - Correctness (representativeness) of the model
  - Incompleteness of the model
- Sensitivity analysis
- Contribution analysis

An example

- Nguyen et al. (2010). Environmental consequences of different beef production systems in the EU. Journal of Cleaner Production 18, 756-766.
- Functional unit: one kg meat slaughter weight delivered from farms
- SimaPro/ecoinvent, five impact categories
- Also effect of indirect **land use change** included: carbon emissions from land conversion depreciated over 20 years



System boundaries
Nguyen et al. (2010)

Fig. 1. System boundary of beef fattening. Legend: transport by truck; transport by ship. * For the suckler cow–calf system, calf rearing was modelled to be integrated in beef fattening, whereas for the dairy bull calf systems, it was considered as a separate process.

Table 7
Comparative LCA of the four systems per kg meat (slaughter weight) delivered from farms.

Impact category	Unit	Suckler cow–calf SCC	Dairy bull calf/age at slaughter		
			A/12 months	B/16 months	C (Steers)/ 24 months
Global warming (without land use consideration)	kg CO_2e	27.3	16.0	17.9	19.9
Acidification	g SO_2e	210	101	131	173
Eutrophication	g NO_3e	1651	622	737	1140
Non-renewable energy	MJ primary	59.2	41.3	41.7	48.2
Land occupation	m^2year	42.9	16.5	16.7	22.7
Grassland		36.9	0	2.0	18.2
Highly productive		6.81	0	1.97	8.34
Moderately productive		0	0	0	9.82
Low productive		30.07	0	0	0
Cropland		6.0	16.5	14.7	4.5
Cereals		5.94	12.39	11.48	4.50
Soy meal		0.05	4.11	3.25	0.04

Nguyen et al. (2010)

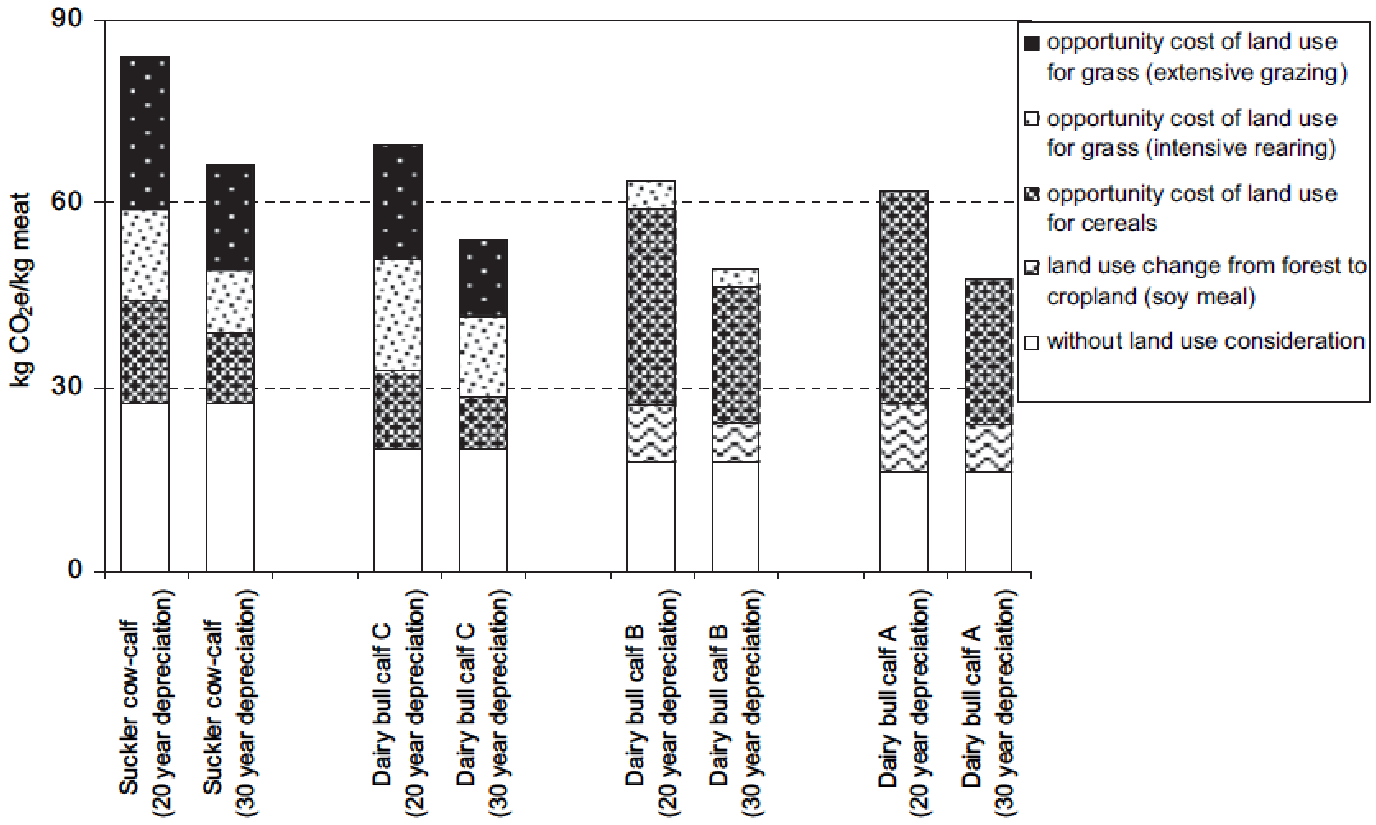


Fig. 3. Potential effect of land use on GHG emissions from EU beef fattening systems.

Table 6
Estimated carbon emissions from land conversion.

Region	Forest to cropland		Forest to grassland	
	Total carbon lost weighted average t C/ha[a]	kg CO_2/ m^2 year[c]	Total carbon lost weighted average t C/ha[b]	kg CO_2/ m^2 year[c]
Developed Pacific	129.8	2.4	106.4	1.9
North Africa and Middle East	110.5	2.0	88.3	1.6
Canada	148.8	2.7	100.0	1.8
The United States	193.6	3.5	159.0	2.9
Latin America	163.7	3.0	139.9	2.6
South and Southeast Asia	225.7	4.1	202.1	3.7
Africa	95.9	1.8	66.0	1.2
Europe	170.9	3.1	138.6	2.5
Former Soviet Union	149.6	2.7	107.6	2.0
Weighted average	153.1	2.8	120.4	2.2

[a] Total C lost = biomass C + ongoing C uptake + soil C × 25% (Searchinger et al., 2008).
[b] Total C lost = biomass C + ongoing C uptake + soil C × 0% (Murty et al., 2002).
[c] kg CO_2/m^2year = weighted average t C/ha × 3.67 t CO2/t C × 1000 kg/t ÷ 10,000 m^2/ha ÷ 20 years.

Nguyen et al. (2010)

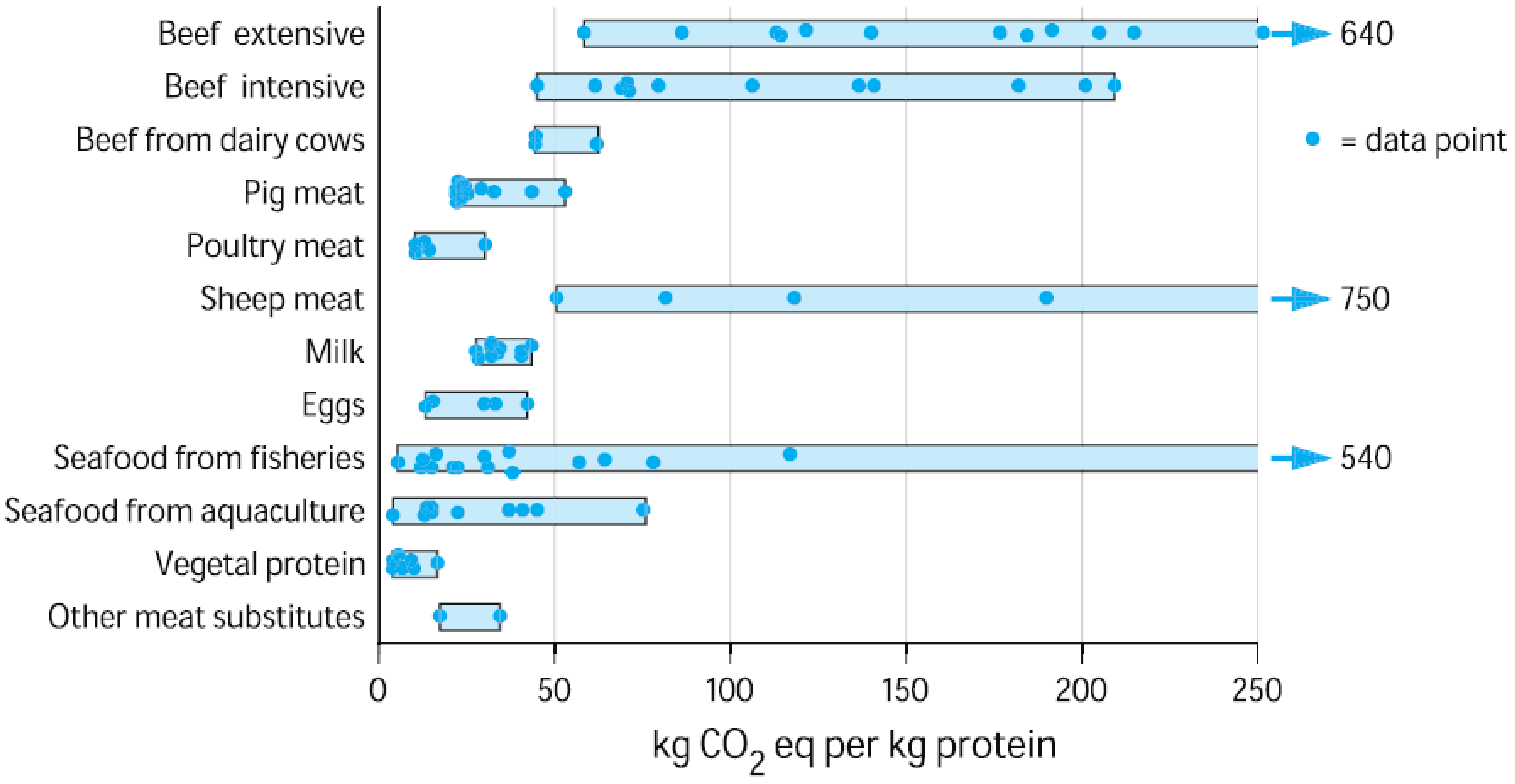


Fig. 1. Carbon footprints per kilogram of protein.

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The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of wholemeal bread production in Italy

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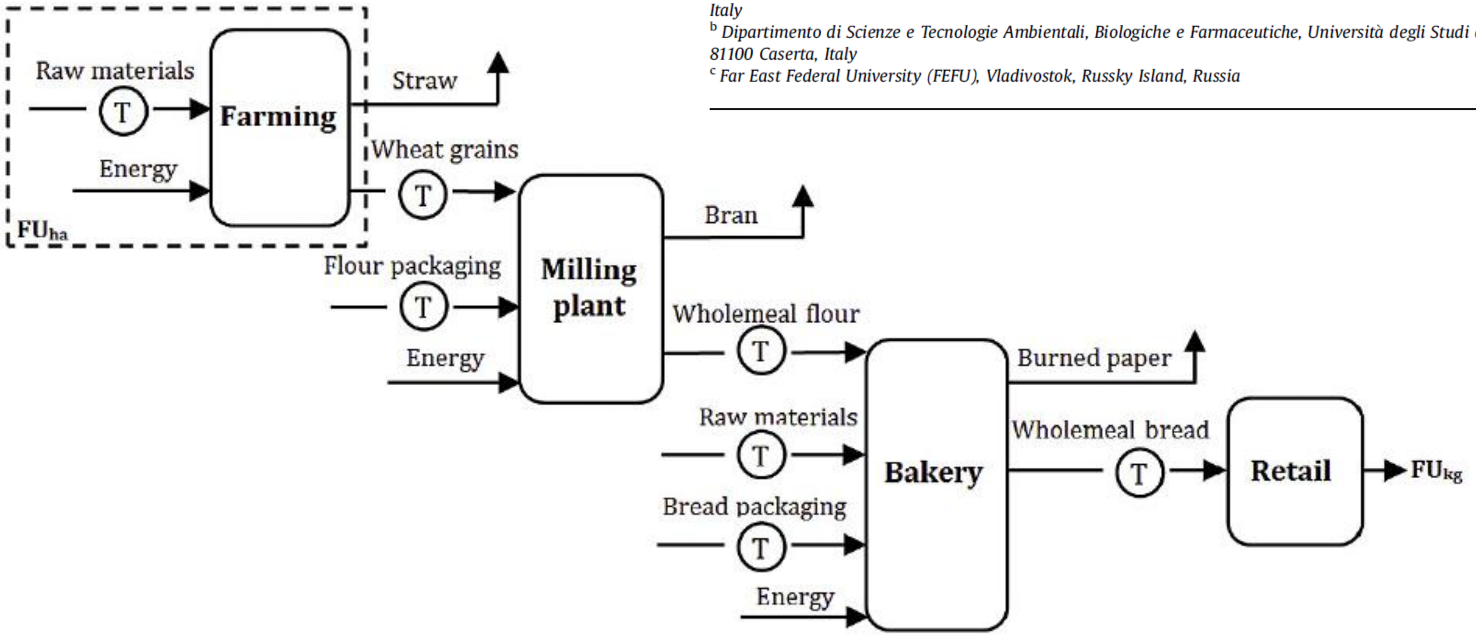


Fig. 1. Boundaries system of the Life Cycle Assessment of organic and conventional wholemeal bread produced in central Italy by a small-medium bakery and sold in retail shops as packaged loafs of 1 kg (T is transport).

Table 7
GHG emissions of each phase of the life cycle of organic and conventional wholemeal bread production and distribution, per functional unit (FU_{kg}) of wholemeal bread and per unit of area (hectare). The wheat cultivation for the production of 1 kg of wholemeal bread (1 FU_{kg}) is 8,52 m^2 in organic farming and 2,13 m^2 in conventional farming.

Life cycle phases	kg CO_2eq FU_{kg}^{-1}	Mg CO_2eq ha^{-1}
Organic wheat seeds	0,1	0,12
Packaging of wheat seeds	0,001	0001
Direct and indirect soil emissions	0,42	0,5
Fuel production and consumption	0,46	0,5
Transport	0,005	0006
Total organic farming	**0,98**	**1,15**
Conventional wheat seeds	0,02	0,10
Packaging of wheat seeds	0,00005	0,0002
Fertilizers production	0,34	1,6
Fungicide, pesticides and herbicide	0,002	0008
Direct and indirect soil emissions	0,13	0,6
Fuel production and consumption	0,11	0,5
Transport	0,004	0,02
Total conventional farming	**0,61**	**2,87**
Hydro Electric Power	0,0004	
Packaging of flour (paper)	0,004	
Transport	0,01	
Total milling	**0,015**	
Electricity (IT energetic mix)	0,174	
Salt	0,0002	
Packaging (paper, HDPE)	0,008	
Transport	0,16	
Total Bakery	**0,35**	
Transport of the FU	0,21	
Total Retail	**0,21**	

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-12622-7 OPEN

The greenhouse gas impacts of converting food production in England and Wales to organic methods

Laurence G. Smith [1,2], Guy J.D. Kirk [1*], Philip J. Jones [3] & Adrian G. Williams[1]

Agriculture is a major contributor to global greenhouse gas (GHG) emissions and must feature in efforts to reduce emissions. Organic farming might contribute to this through decreased use of farm inputs and increased soil carbon sequestration, but it might also exacerbate emissions through greater food production elsewhere to make up for lower organic yields. To date there has been no rigorous assessment of this potential at national scales. Here we assess the consequences for net GHG emissions of a 100% shift to organic food production in England and Wales using life-cycle assessment. We predict major shortfalls in production of most agricultural products against a conventional baseline. Direct GHG emissions are reduced with organic farming, but when increased overseas land use to compensate for shortfalls in domestic supply are factored in, net emissions are greater. Enhanced soil carbon sequestration could offset only a small part of the higher overseas emissions.

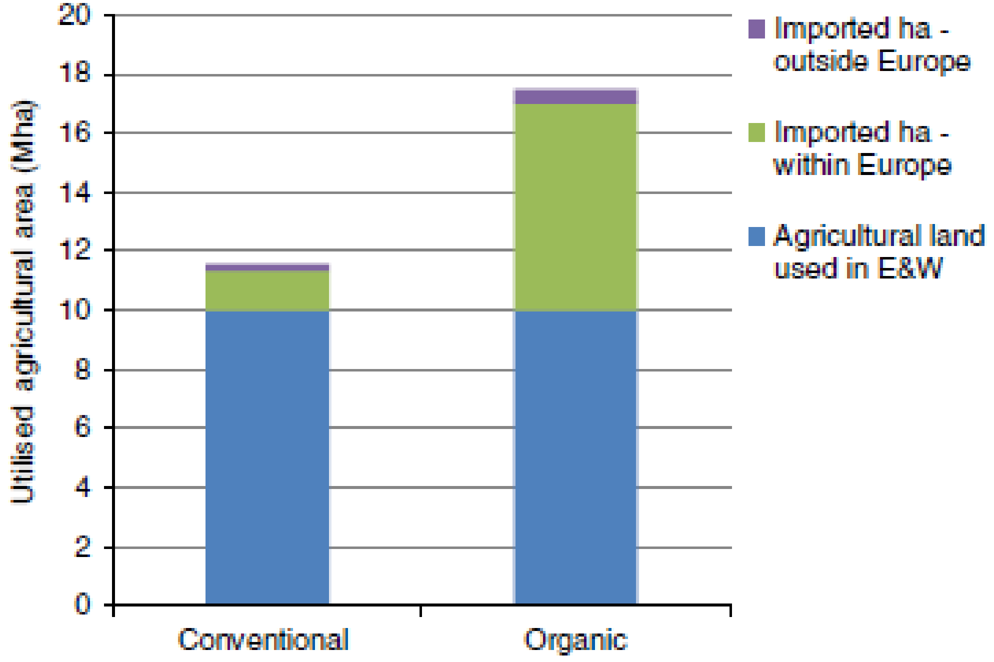
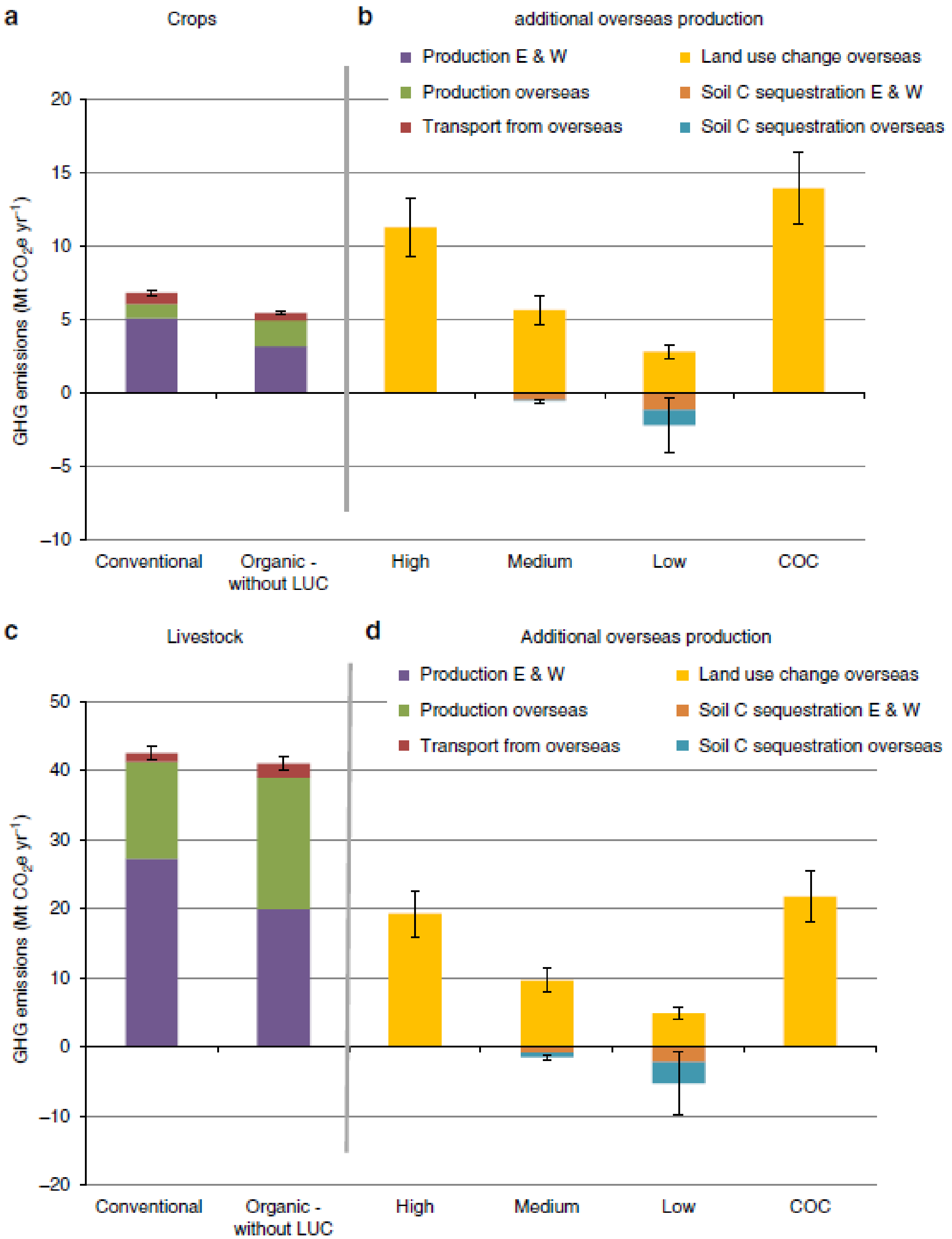


Fig. 4 Overseas land area needed for imported food. The area required to offset shortfalls in domestic production under organic methods is over five times that under conventional methods, largely due to imports of oilseeds, pork, poultry meat, eggs and milk. Note only the products listed in Fig. 1 are included; products that are not produced in the UK on a large scale (such as maize, rice, tea, coffee and sugar cane) are excluded (Methods). Source Data are provided as a Source Data file



High: all LUC from grassland, no CS

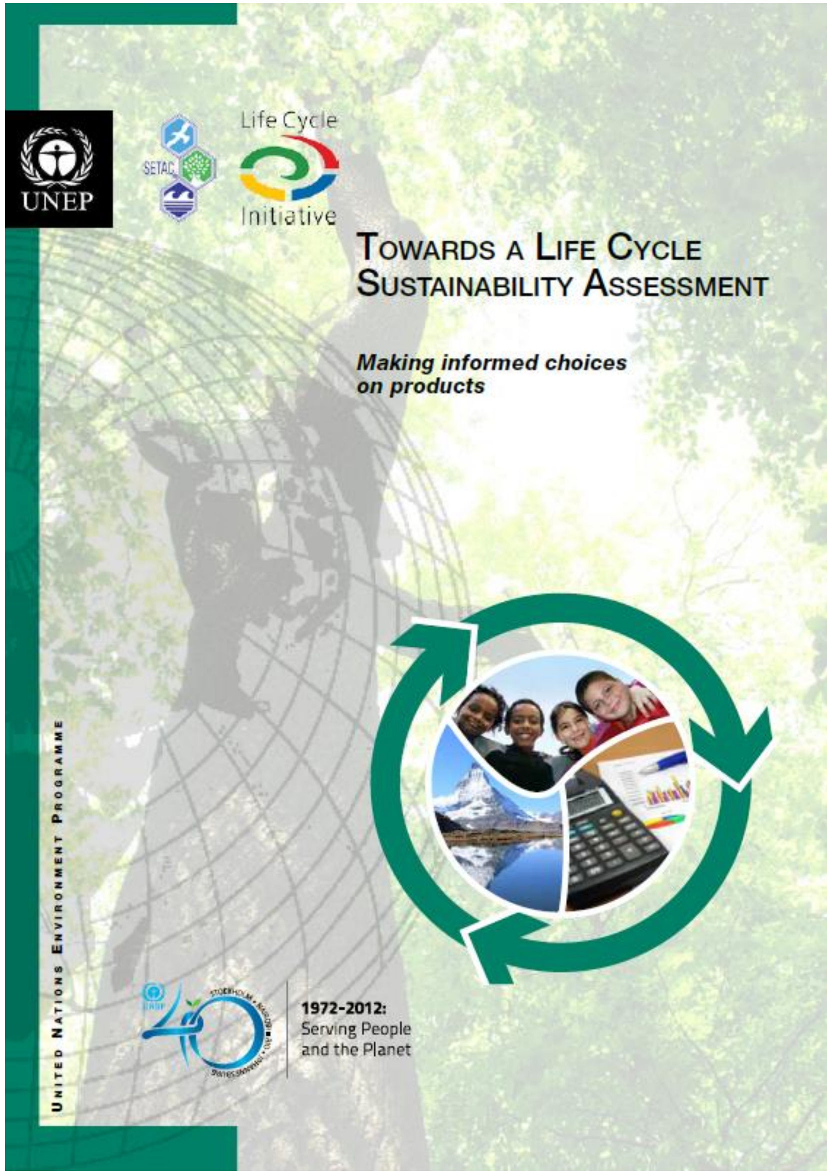
Medium: 50% LUC from grassland, moderate CS

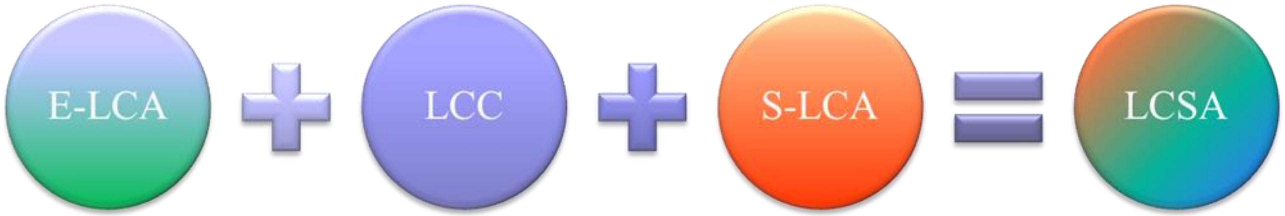
Low: 25% LIC from grassland, high CS

COC: Carbon opportunity costs following Searchinger et al.

Key challenge 2

- How do activities interact with each other and how they relate to socio-economic dimensions (cost, culture) to make societal choices
- What underlying values do we apply?
  - Whose values matter? Anthropocentric versus ecocentric
  - Can we discount the future?
  - Is substitution allowed? Weak versus strong sustainability

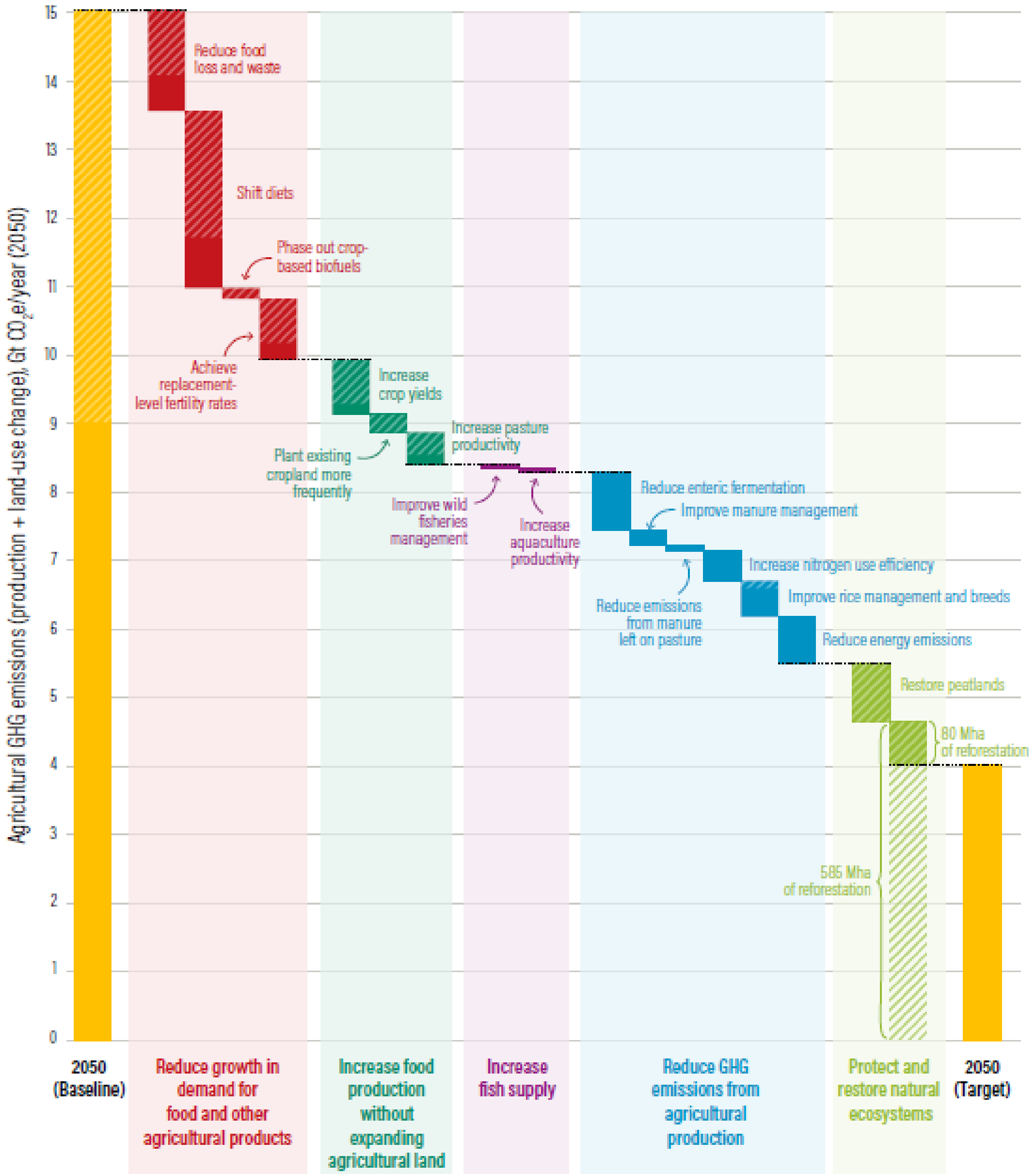


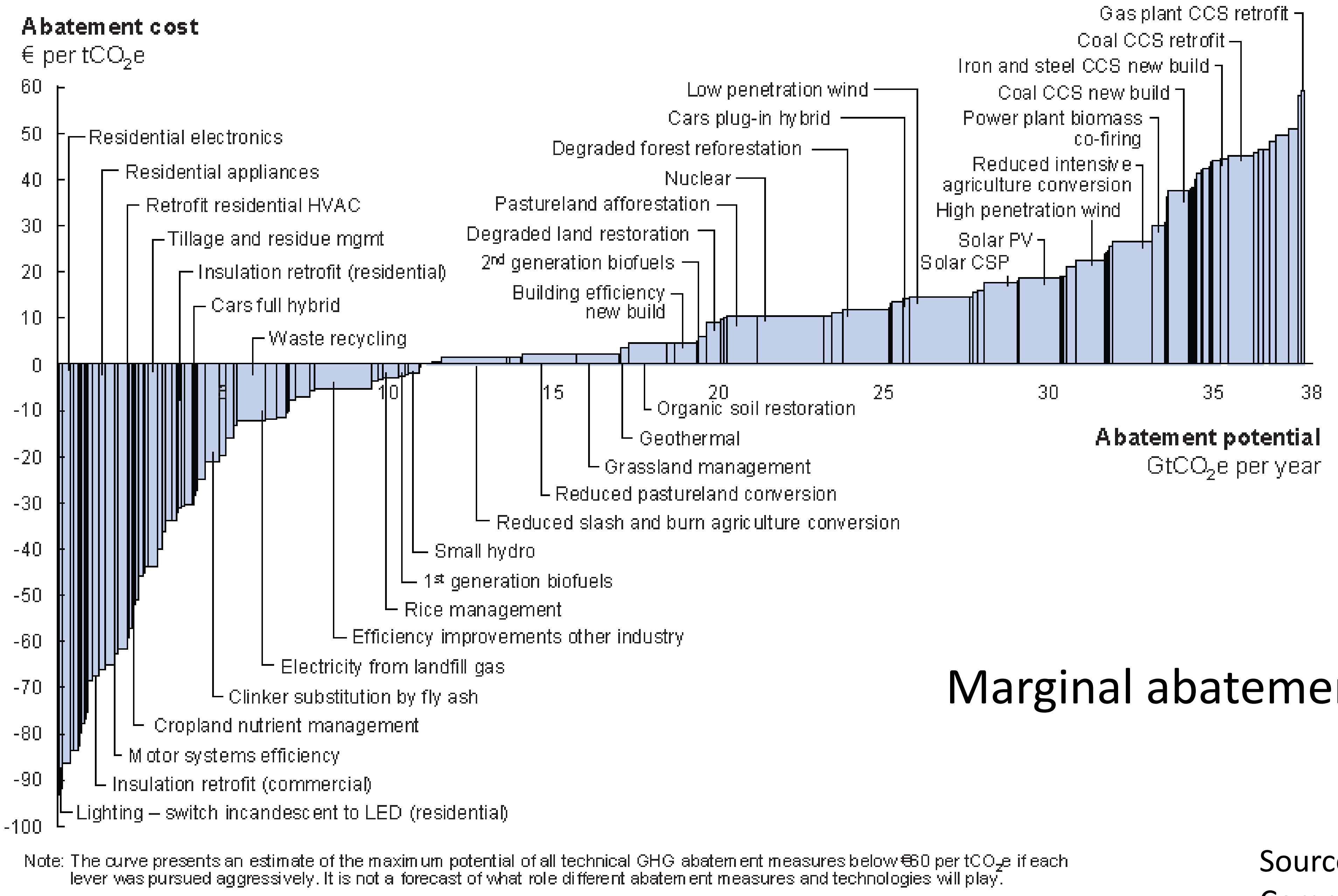


LCSA	life cycle sustainability assessment
E-LCA	environmental life cycle assessment
LCC	life cycle costing
S-LCA	social life cycle assessment

Scenarios…

Figure 23 | Under the Breakthrough Technologies scenario, agricultural greenhouse gas emissions would fall dramatically but reforestation and peatland restoration would be necessary to meet the target of 4 gigatons per year



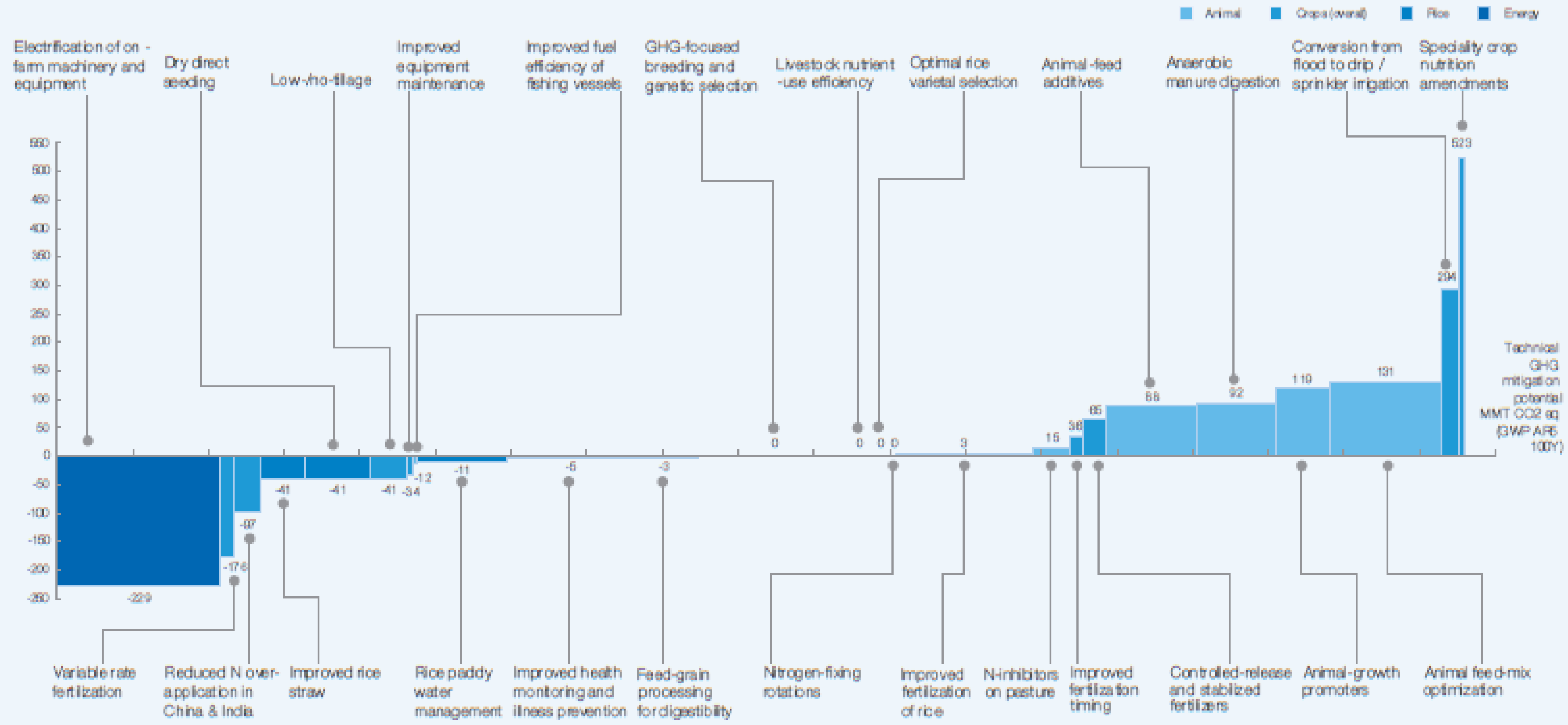


Marginal abatement cost curves

Source: McKinsey & Company

GHG-efficient food production practices

Estimated cost of GHG abatement, USD/t c02eq (20-year AR5 GWP values)



% of total rice, crops, animal protein, and energy emissions that will be decreased through the use of the above practices

Rice	Crops	Animal Protein	Energy
-40%	-25%	-20%	-100%

NOTE: The horizontal axis reflects greenhouse gas mitigation potential for each lever; the vertical axis displays the average abatement cost ($/tCO2 equivalent) for each lever

Source: McKinsey & Company analysis

WEF, 2020, Incentivizing Food Systems Transformation based on McKinsey & Company

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An assessment of the total external costs of UK agriculture

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Abstract

This trans-disciplinary study assesses total external environmental and health costs of modern agriculture in the UK. A wide range of datasets have been analysed to assess cost distribution across sectors. We calculate the annual total external costs of UK agriculture in 1996 to be £2343 m (range for 1990–1996: £1149–3907 m), equivalent to £208/ha of arable and permanent pasture. Significant costs arise from contamination of drinking water with pesticides (£120 m/year), nitrate (£16 m), *Cryptosporidium* (£23 m) and phosphate and soil (£55 m), from damage to wildlife, habitats, hedgerows and drystone walls (£125 m), from emissions of gases (£1113 m), from soil erosion and organic carbon losses (£106 m), from food poisoning (£169 m), and from bovine spongiform encephalopathy (BSE) (£607 m). This study has only estimated those externalities that give rise to financial costs, and so is likely to underestimate the total negative impacts of modern agriculture. These data help to identify policy priorities, particularly over the most efficient way to internalise these external costs into prices. This would imply a redirection of public subsidies towards encouraging those positive externalities under-provided in the market place, combined with a mix of advisory and institutional mechanisms, regulatory and legal measures, and economic instruments to correct negative

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PII: S0308-521X(00)00031-7

Table 1
The annual total external costs of UK agriculture, 1996 (range values for 1990–1996)[a]

Cost category	UK (£ million)	Range[b] (£ million)
1. Damage to natural capital — water		
1a. Pesticides in sources of drinking water	120	84–129
1b. Nitrate in sources of drinking water	16	8–33
1c. Phosphate and soil in sources of drinking water	55	22–90
1d. Zoonoses (esp. *Cryptosporidium*) in sources of drinking water	23	15–30
1e. Eutrophication and pollution incidents (fertilisers, animal wastes, sheep dips)	6	4–7
1f. Monitoring and advice on pesticides and nutrients	11	8–11
2. Damage to natural capital — air		
2a. Emissions of methane	280	248–376
2b. Emissions of ammonia	48	23–72
2c. Emissions of nitrous oxide	738	418–1700
2d. Emissions of carbon dioxide	47	35–85
3. Damage to natural capital — soil		
3a. Off-site damage caused by erosion[c]	14	8–30
3b. Organic matter and carbon dioxide losses from soils	82	59–140
4. Damage to natural capital — biodiversity and landscape		
4a. Biodiversity/wildlife losses (habitats and species)	25	10–35
4b. Hedgerows and drystone walls	99	73–122
4c. Bee colony losses	2	1–2
4d. Agricultural biodiversity	+[d]	+
5. Damage to human health — pesticides		
5a. Acute effects	1	0.4–1.6
5b. Chronic effects	+	+
6. Damage to human health — nitrate	0	0
7. Damage to human health: microorganisms and other disease agents		
7a. Bacterial and viral outbreaks in food	169	100–243
7b. Antibiotic resistance	+	+
7c. BSE[e] and nvCJD	607	33–800
Total	2343	1149–3907

[a] This table does not include private costs borne by farmers themselves.
[b] The ranges for costs do not represent formal standard deviations of the data as this is impossible given the huge variation in types of data and contexts. The ranges represent best estimates for higher and lower quartiles for costs incurred annually during the 1990s. The range values for the external costs in category 2 are calculated from the ranges stated in studies of external costs of each of these gases, rather than the variation of emissions during the 1990s.
[c] The offsite damage caused by erosion in category 3a does not include the costs of removing soils/sediments from drinking water (these are in cost category 1c).
[d] +, Not yet able to calculate costs.
[e] BSE costs are an average for 1996 and 1997.

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Calculating environmental cost indicators of apple farm practices indicates large differences between growers

Bernd Annaert, Yanne Goossens, Annemie Geeraerd, Erik Mathijs & Liesbet Vranken

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Table 5. External costs per hectare and per kilogram related to the expected global warming, acidification and eutrophication impacts of the three production groups.

	Conventional	Integrated	Organic
Costs per hectare			
Global warming (€/ha)	1045.2	1005.0	1206.0
Acidification (€/ha)	21.2*/**	24.2	30.9
Eutrophication (€/ha)	16.6	15.5	19.4
Total external cost (€/ha)	1083.0	1044.7	1256.3
Costs per kilogram			
Global warming (0.01€/kg)	2.6	2.2	6.1*/***
Acidification (0.01€/kg)	0.1	0.1	0.1*/***
Eutrophication (0.01€/kg)	0.03	0.03	0.1*/***
Total external cost (0.01€/kg)	2.7	2.3	6.3*/***

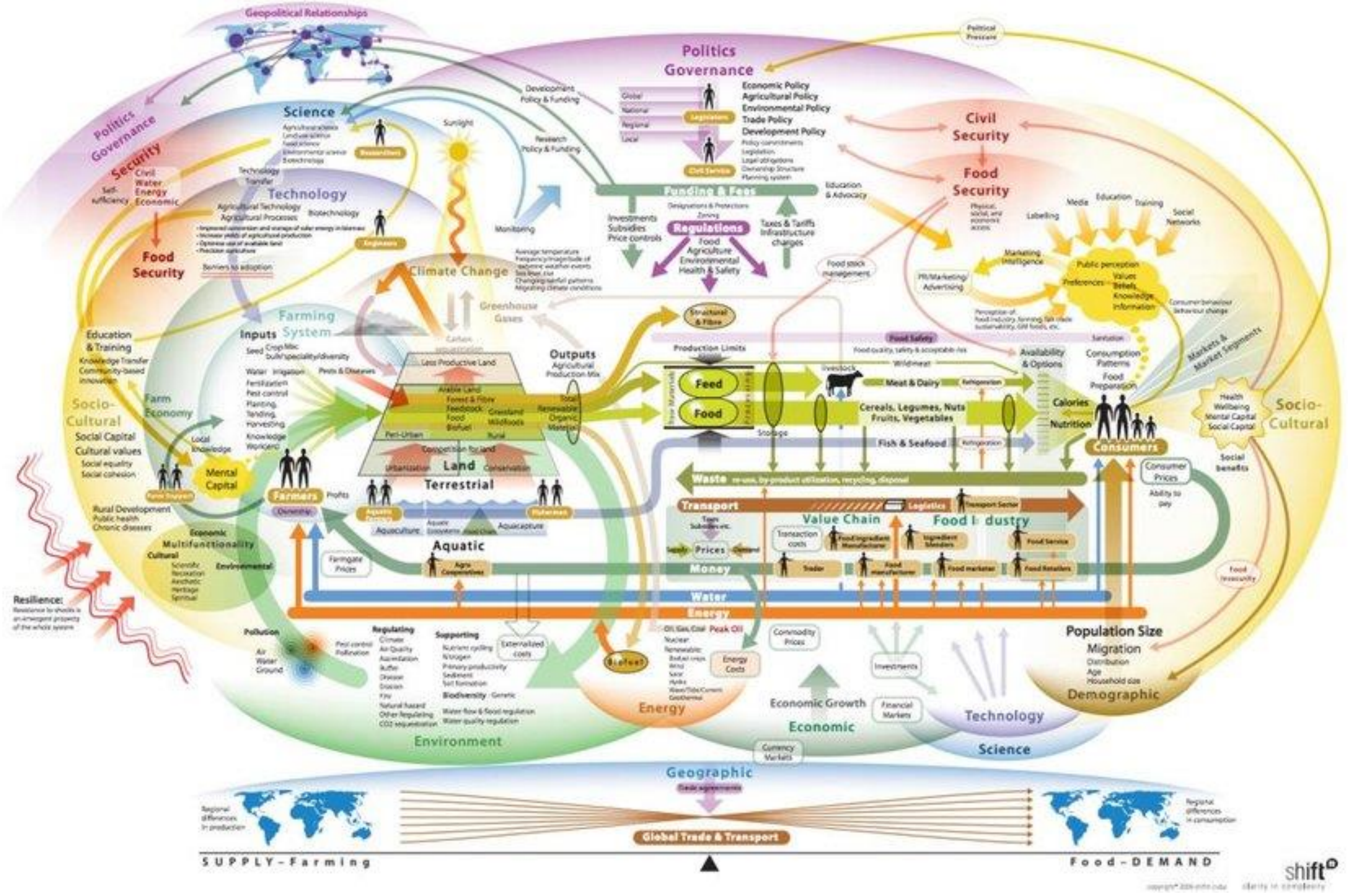
*Significantly different from the integrated group ($p < .01$) (based on Kolmogorov–Smirnov test).
**Significantly different from the organic group ($p < .01$) (based on Kolmogorov–Smirnov test).
***Significantly different from the conventional group ($p < .01$) (based on Kolmogorov–Smirnov test).

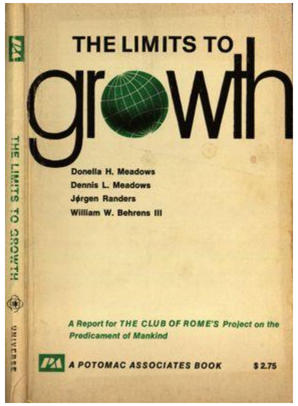
Key challenge 3

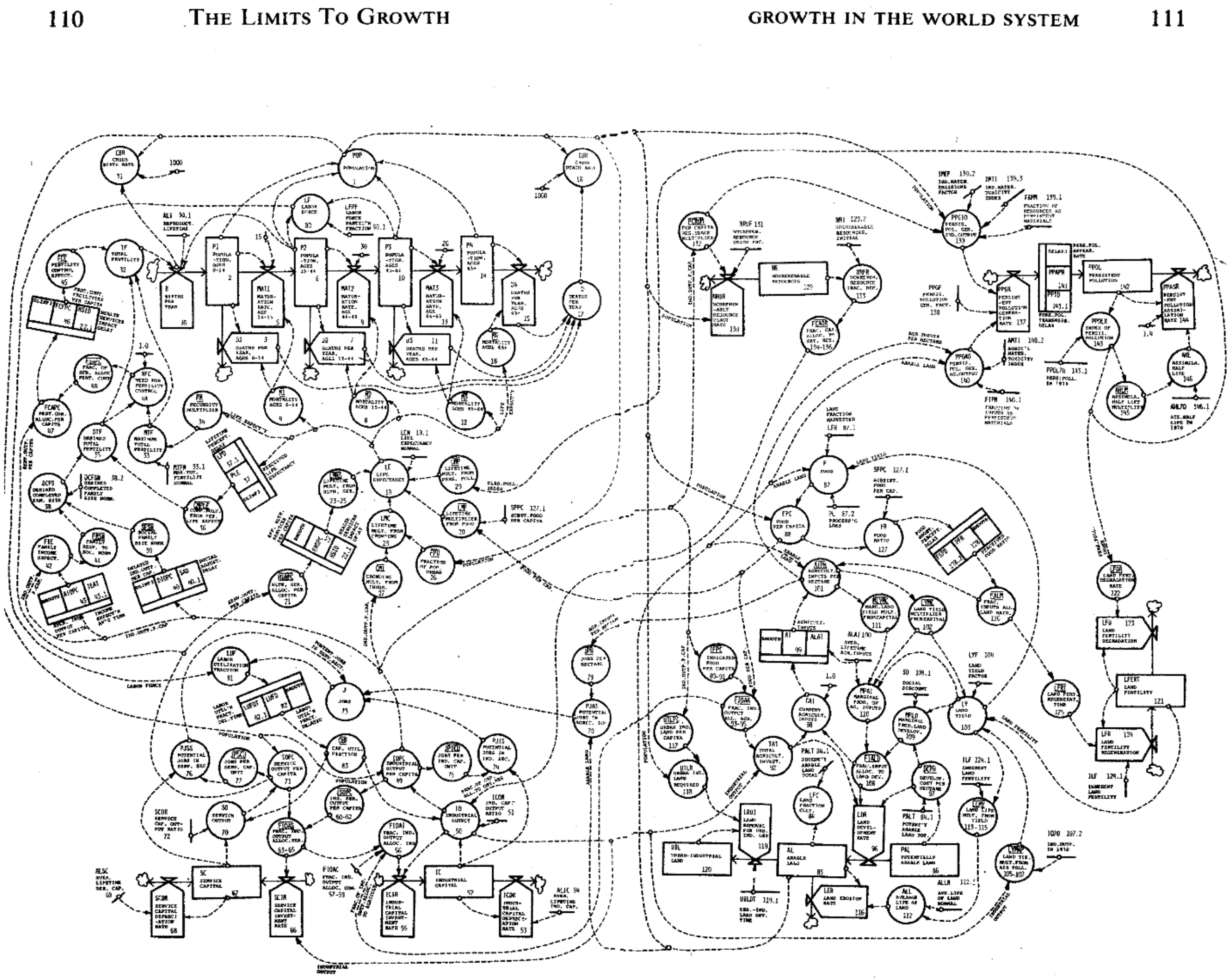
We need to translate knowledge into actions in complex food systems

- Difficult to determine **boundaries**
- May be **open**
- May have a **memory**
- May be **nested**
- May produce **emergent** phenomena (sum > parts)
- Relationships are **non-linear** and contain **feedback** loops:
  - entities seeking balance but can show oscillating, chaotic or exponential behavior
  - unintended consequences

Global Food System Map







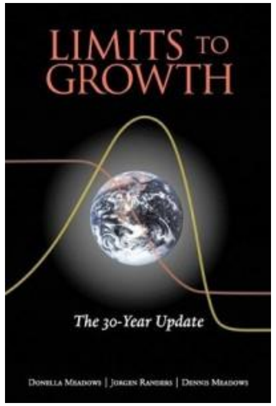
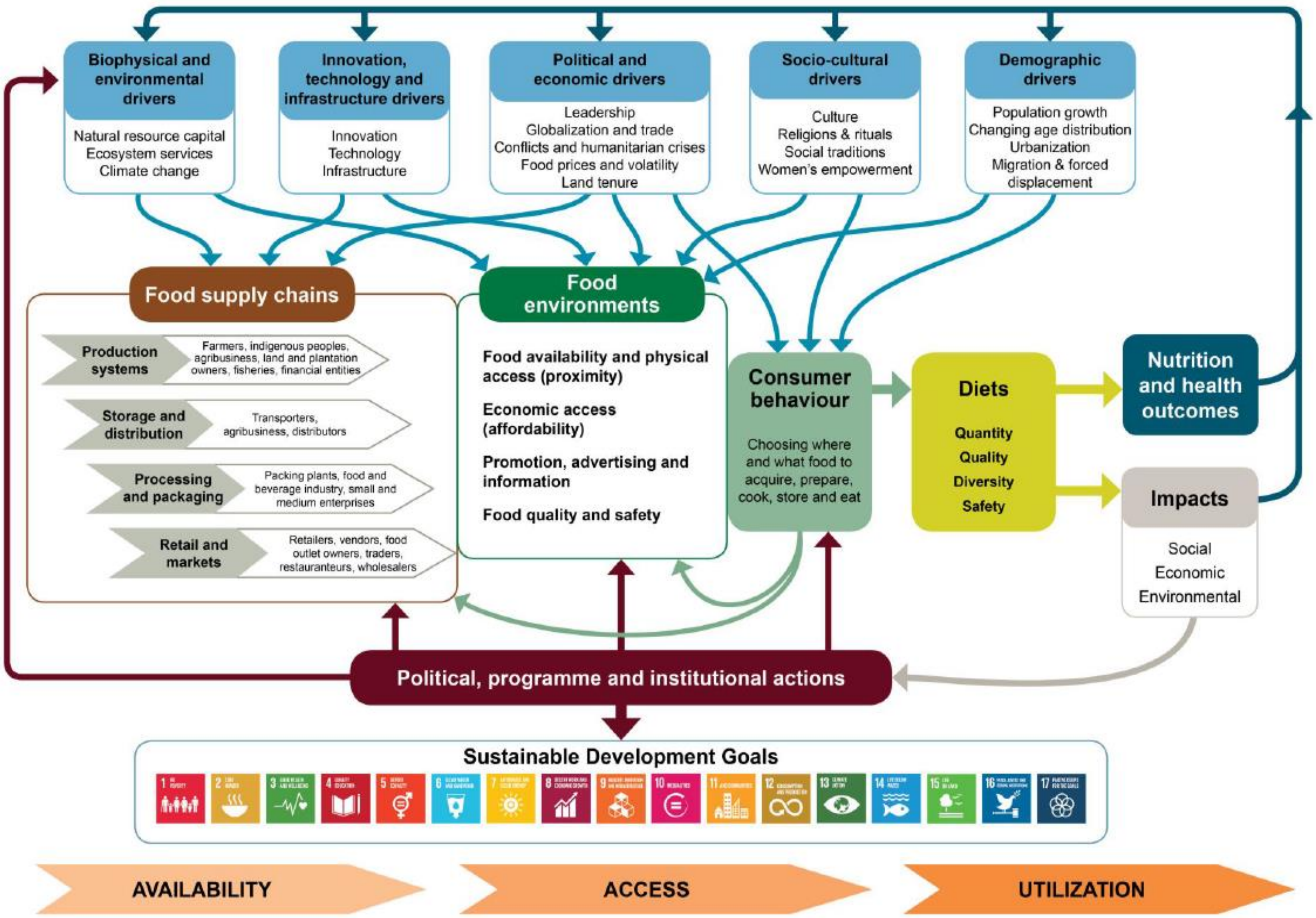


Figure 1 Stock-and-flow diagram of the world system



Source: HLPE, 2017

sustainability

MDPI

Article

Development of Organic Farming in Europe at the Crossroads: Looking for the Way Forward through System Archetypes Lenses

Natalia Brzezina [1,*], Katharina Biely [2], Ariella Helfgott [3,4], Birgit Kopainsky [5], Joost Vervoort [3,4] and Erik Mathijs [1]

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Evaluating patterns rather than just indicators

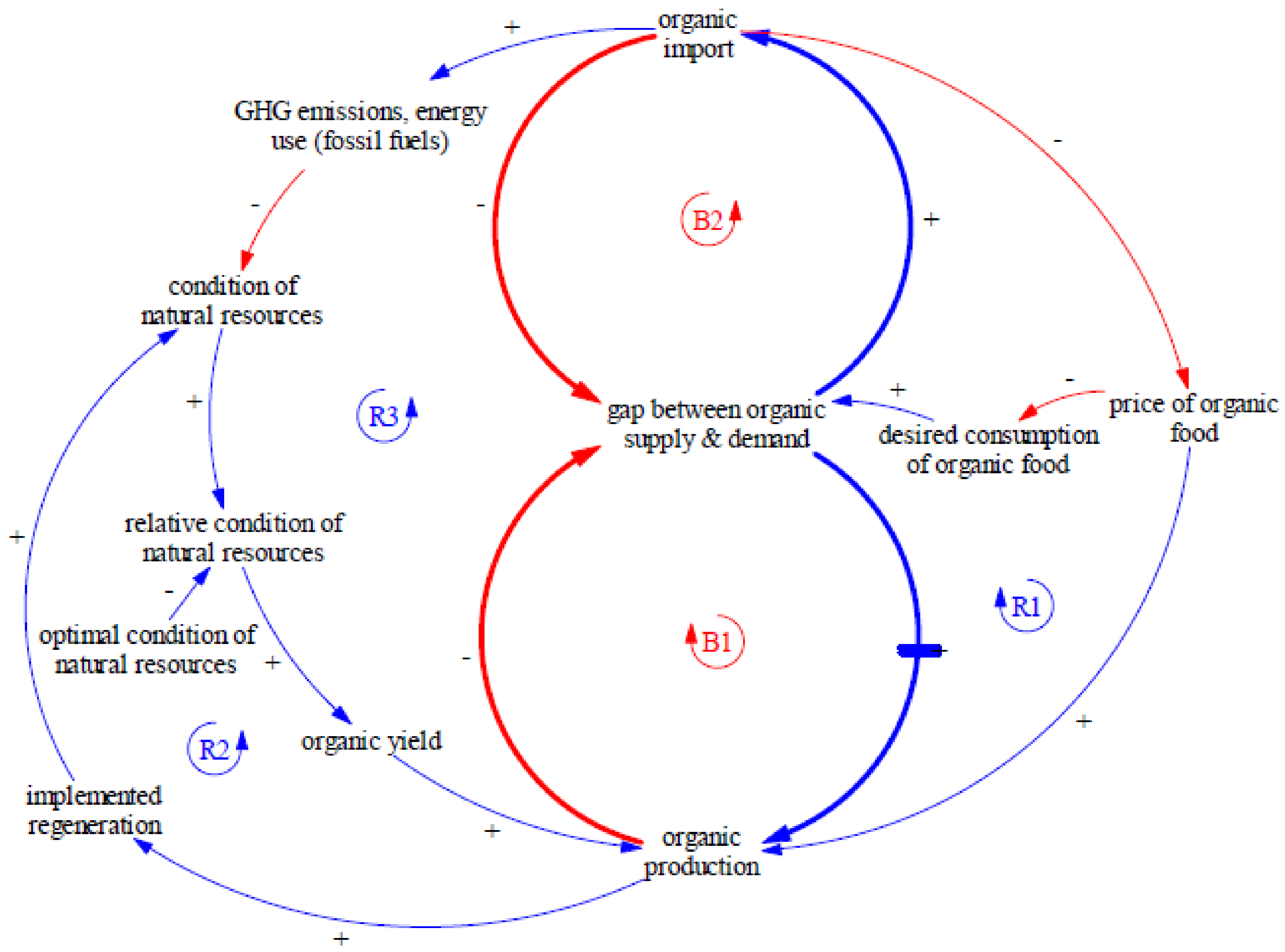


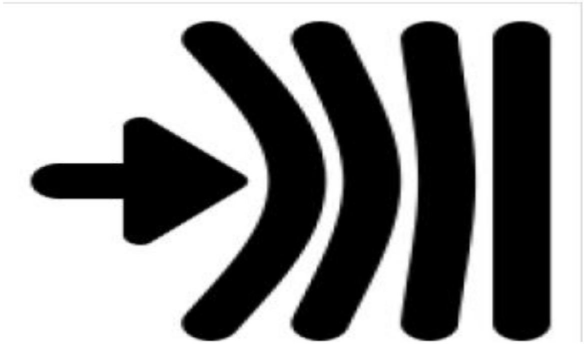
Figure 9. Shifting the Burden: fundamental solution (B1) and quick fix (B2) to the problem of widening gap between organic domestic production and desired consumption of organic food along with unintended reinforcing processes related to price squeeze (R1), decline in implementation of practices regenerating natural resources (R2), and degradation of natural resources (R3).

Beyond sustainability: resilience

- Increasing risks and uncertainty: shocks and trends
- Vulnerability and resilience
- Relationship between sustainability and resilience?

What is resilience?

- The capacity of individuals, businesses, communities, or systems
- to respond to perturbations (shocks or persistent stress, natural or anthropogenic origin),
- that can push a system towards a tipping point where it can no longer maintain its previous state and fulfil its functions (collapse).



This project has received funds from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 727520

Three dimensions of resilience

Robustness: the capacity of a system to resist/withstand perturbations and to maintain previous levels of functionality without major changes to its internal elements and processes

Adaptability: the capacity of a system to change internal elements and processes in response to changing external circumstances and thereby to continue its development along the previous trajectory while maintaining functionalities

Transformability: the capacity of a system to radically change, including its identity, paradigms and logics

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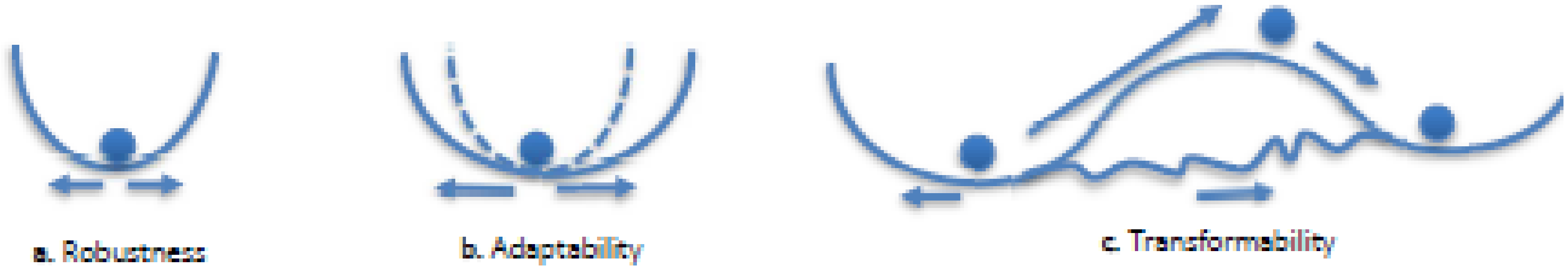
SURE Farm



Source: Meuwissen et al. (2018) based on Holling (2002)

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SURE Farm

Beyond sustainability: resilience

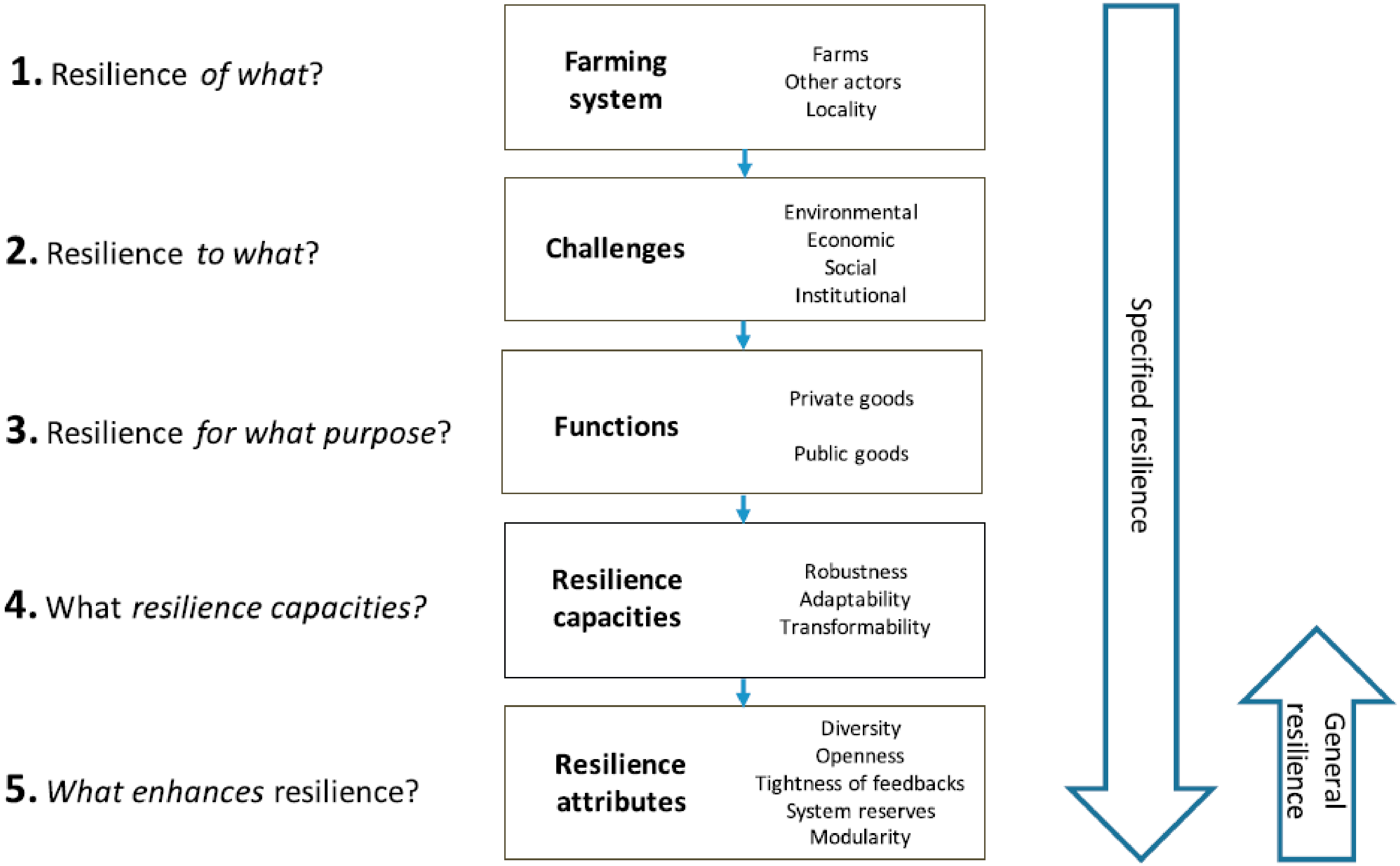

Fig. 2. Framework to assess resilience of farming systems.

Source: Meuwissen et al. (2018)

Indicator	What to look for
Socially self-organized	Farmers and consumers are able to organize into grassroots networks and institutions such as co-ops, farmer's markets, community sustainability associations, community gardens, and advisory networks
Ecologically self-regulated	Farms maintain plant cover and incorporate more perennials, provide habitat for predators and parasitoids, use ecosystem engineers, and align production with local ecological parameters
Appropriately connected	Collaborating with multiple suppliers, outlets, and fellow farmers; crops planted in polycultures that encourage symbiosis and mutualism
Functional and response diversity	Heterogeneity of features within the landscape and on the farm; diversity of inputs, outputs, income sources, markets, pest controls, etc.
Optimally redundant	Planting multiple varieties of crops rather than one, keeping equipment for various crops, getting nutrients from multiple sources, capturing water from multiple sources
Spatial and temporal heterogeneity	Patchiness on the farm and across the landscape, mosaic pattern of managed and unmanaged land, diverse cultivation practices, crop rotations
Exposed to disturbance	Pest management that allows a certain controlled amount of invasion followed by selection of plants that fared well and exhibit signs of resistance
Coupled with local natural capital	Builds (not deplete) soil organic matter, recharges water, little need to import nutrients or export waste
Reflective and shared learning	Extension and advisory services for farmers; collaboration between universities, research centers, and farmers; record keeping; baseline knowledge about the state of the agroecosystem
Globally autonomous and locally interdependent	Less reliance on commodity markets and reduced external inputs; more sales to local markets, reliance on local resources; farmer co-ops, close relationships producer - consumer, shared resources (equipment)
Honors legacy	Maintenance of heirloom seeds and engagement of elders, incorporation of traditional cultivation techniques with modern knowledge
Builds human capital	Investment in infrastructure and institutions for the education of children and adults, support for social events in farming communities, programs for preservation of local knowledge
Reasonably profitable	Farmers and farm workers earn a livable wage; agriculture sector does not rely on distortionary subsidies

Cabell & Oelofse, 2012,
Ecologyand Society

Concluding remarks

- Indicators measure **impact** on a set of human and non-human categories
- Sustainability metrics should go beyond impact indicators taking into account underlying **structures**
- Relationship between impact and structures is not straightforward and e.g. scale dependent