Imperial College seminar, 28 March 2023

Nutritional Life Cycle Assessment: Setting a New Research Agenda

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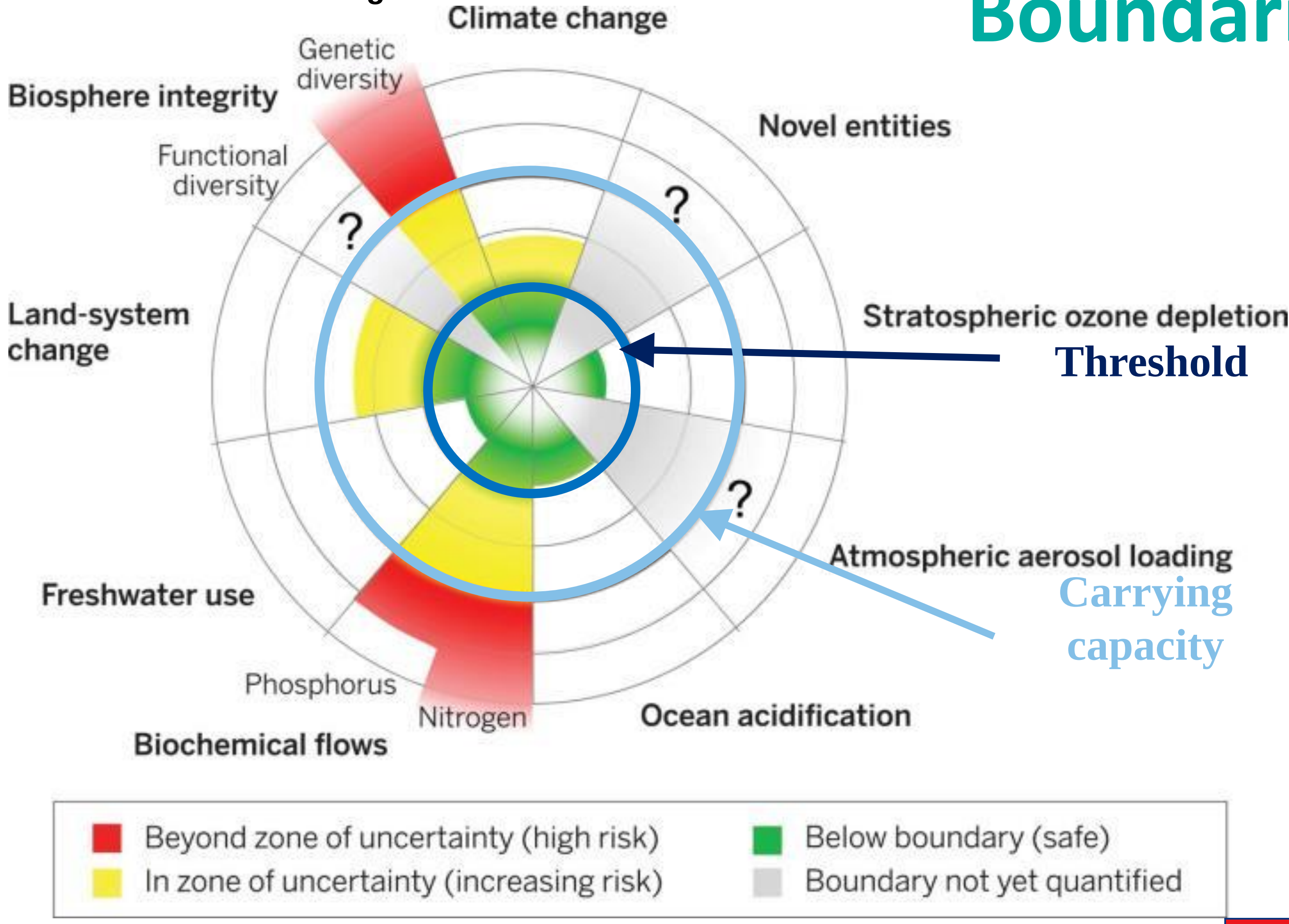
Planetary Boundaries

Current status of the control variables for seven of the planetary boundaries. The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone.



Source: Steffen et al. (2015). Science 2015;347:1259855

Science AAAS

Planetary Boundaries

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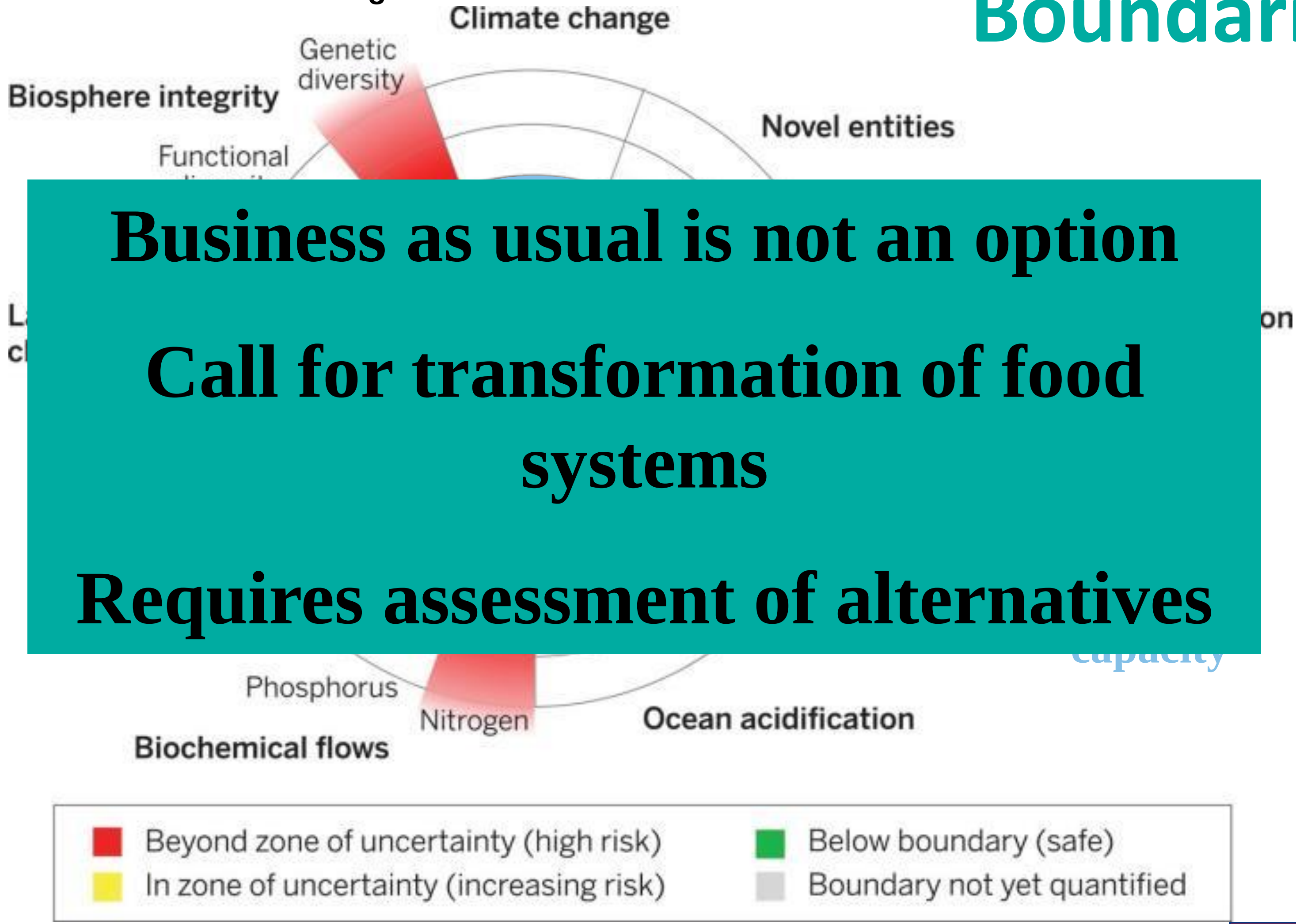

Business as usual is not an option

Call for transformation of food systems

Requires assessment of alternatives

Source: Steffen et al. (2015). Science 2015;347:1259855

Food Systems

Nearly 811 million people suffer from chronic hunger (2020)

Global prevalence of obesity increased to 13.1 **%** in 2016; 39 % of adults overweight

Micronutrient deficiencies common globally - regardless of weight

More than 3 billion people cannot afford a healthy diet: healthy diet two to five times more expensive than an energy (caloric) sufficient diet, and up to two times more expensive than a nutrient sufficient diet

By 2050, 2 billion more people than there are today, mainly in Africa (world population estimated at 9.7 billion)

Source: McLaren et al., 2021, p.99

Overview

1. Life Cycle Assessment

- Towards nutritional LCA

2. Case studies:

- Avocado LCA
- LCA of a novel protein source

3. Current research themes

- Modelling issues
- Other themes

What is nLCA?

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Functions of food:

nutritional value

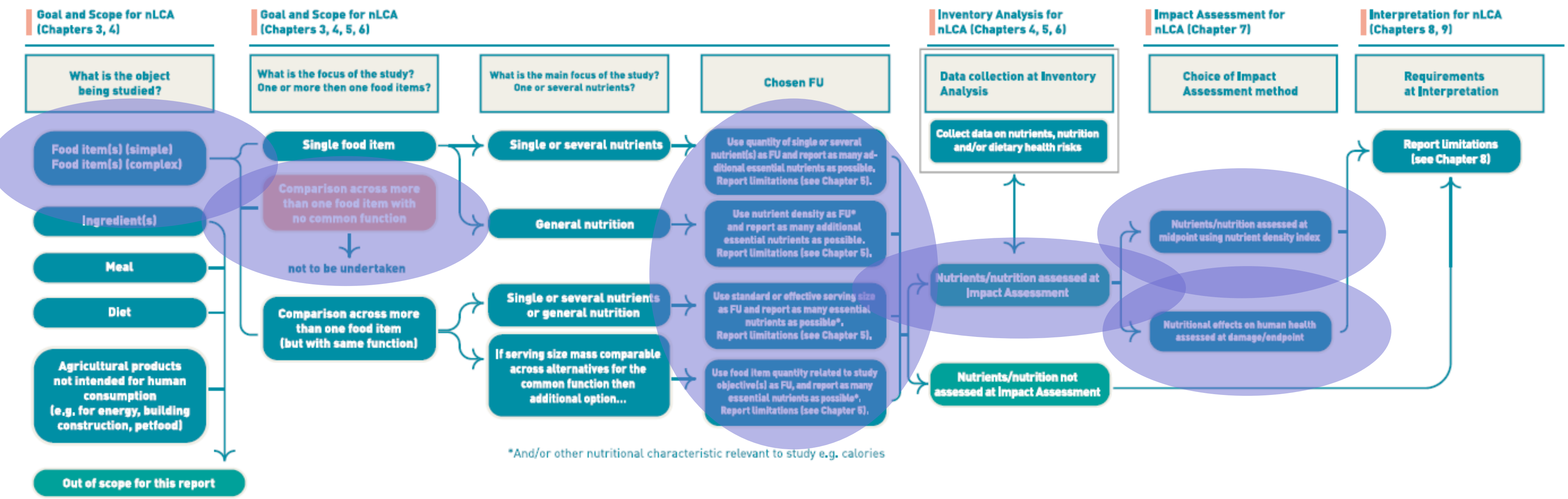
hedonic enjoyment

socio-cultural functions

monetary value

“ … nutritional LCA (nLCA), a phrase used to describe an LCA study where the provision of nutrient(s) is considered as either the main function or one of the main functions of a food item.“ (p.5, McLaren et al., 2021).

Figure 6: Decision tree to support development of a nutrition life cycle assessment study



Source: McLaren et al., 2021, p.99

Identified priorities

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Methodology issues requiring refinement of current methods:

- Is there an optimal number of nutrients to be considered in an nLCA, and should it include nutrients to be limited?
- What is the optimal use of nutrient indexes in LCA?
- How to deal with comparisons across different food groups versus only within food groups
- How to represent nutritional changes in processing that occur outside a curtailed system boundary (e.g. during preparation of meals at home)
- Representation of nutritional value using indicators that extend beyond nutrient quantities (e.g. accounting for health impacts/outcomes)
- Modelling of future scenarios (using attributional/consequential approaches)

Identified priorities

Methodology issues requiring extension beyond current methodological framework:

- Use of nLCA studies at the meal and dietary scales
- Assessing food systems within environmental limits
- Extension into food systems sustainability assessment
- Representation of multi-functionality of food items in nLCA
- Assessment of non-nutrients and anti-nutritional compounds
- Development of nutrition impact category
- How to deal with food fortification in nLCA.

[Scientific development of specific impact assessment methods is also identified in the report. However, the UNEP Life Cycle Initiative already functions as the forum for pursuing this topic.]

Identified priorities

Communication:

- How to represent unknown data in LCA e.g. on digestibility, food matrix effects
- Representation of data variability and uncertainty

Data issues (we know what we want to collect but it is not available):

- Environmental and nutritional data for developing countries
- Food loss and waste

Guidance on use of nLCA to support decision-making:

- Suitability of 'generic' LCA methodology for different application areas

Avocado supply chain

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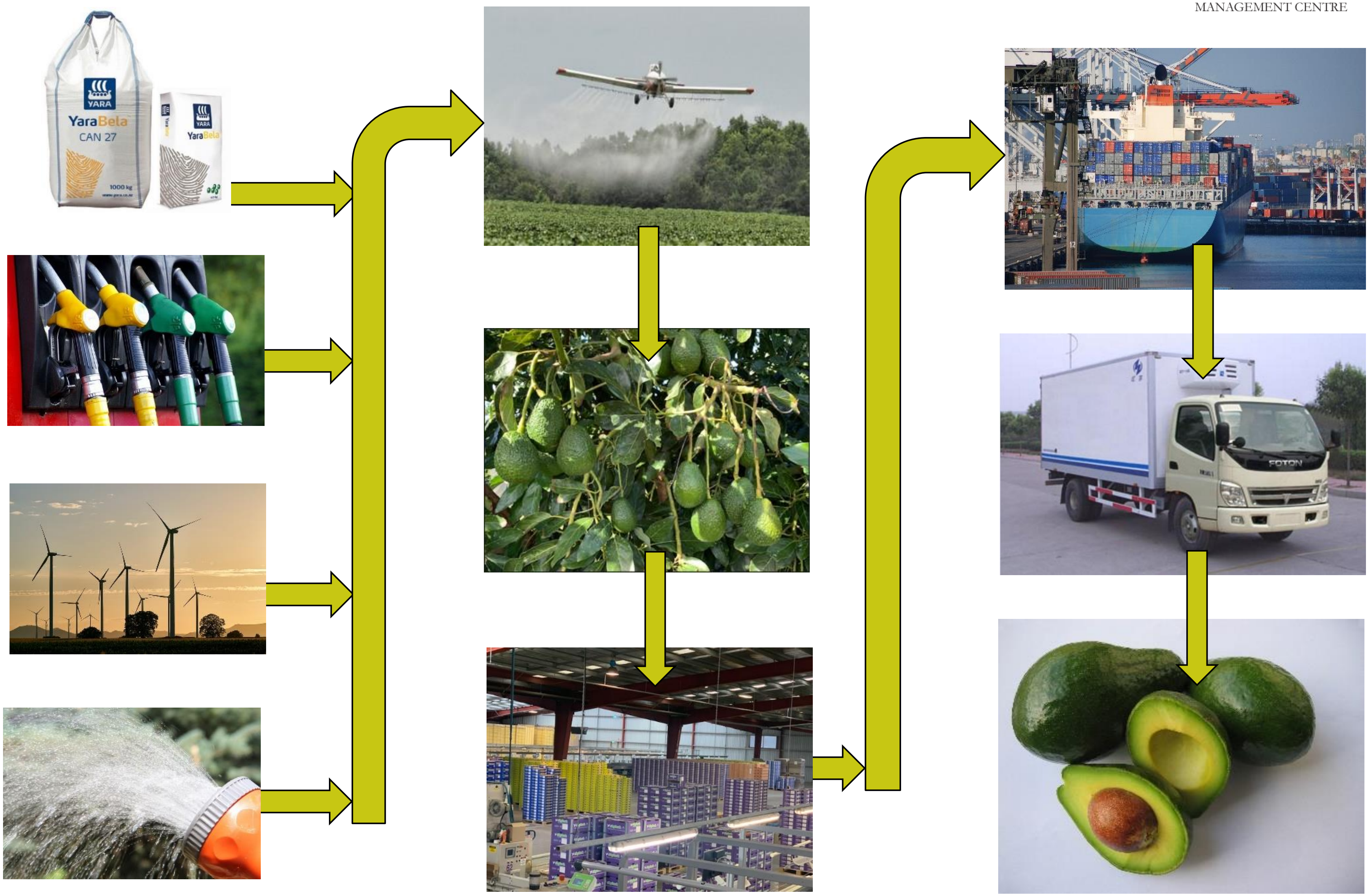


Avocado LCA results: insights (1)

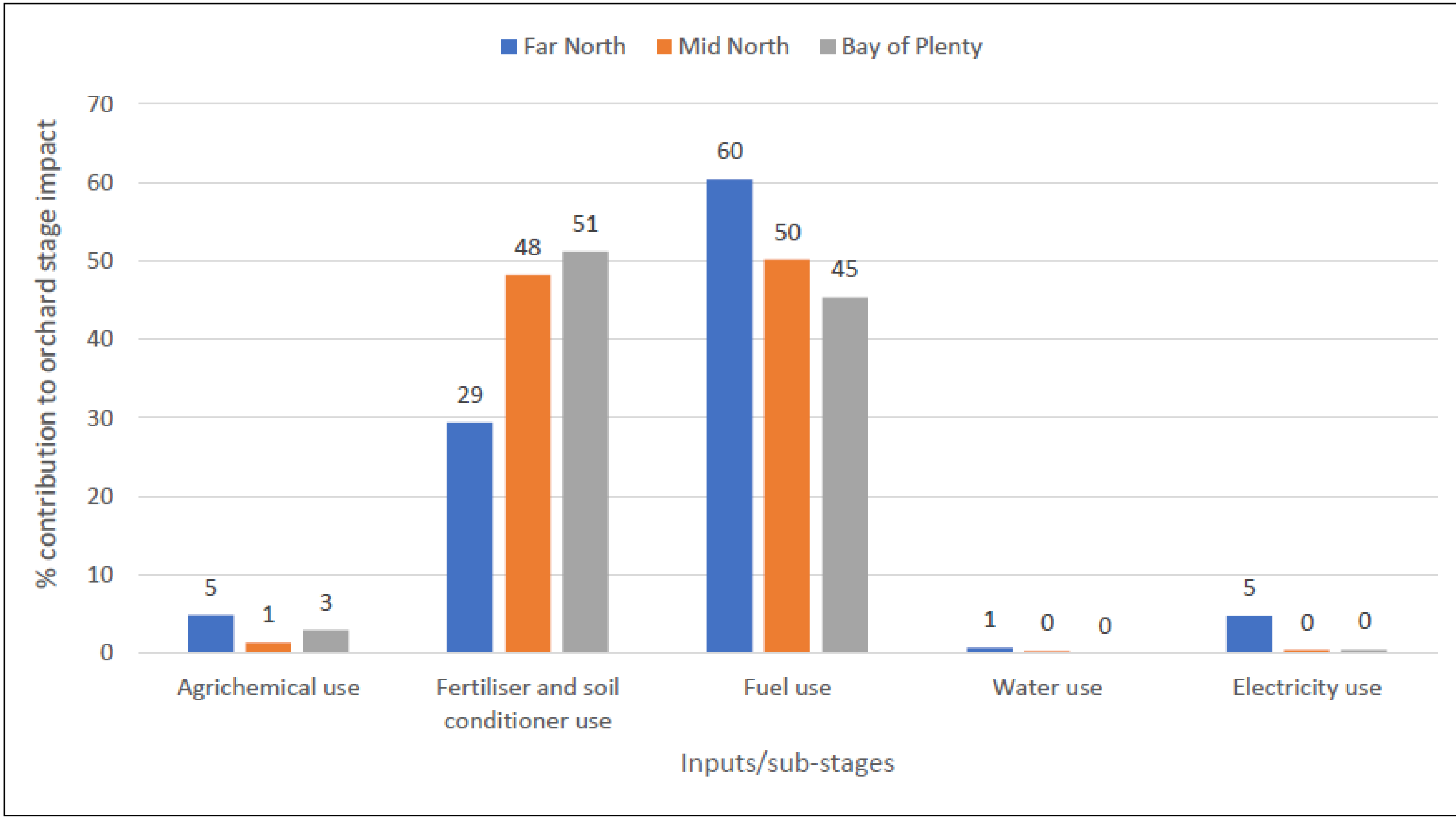
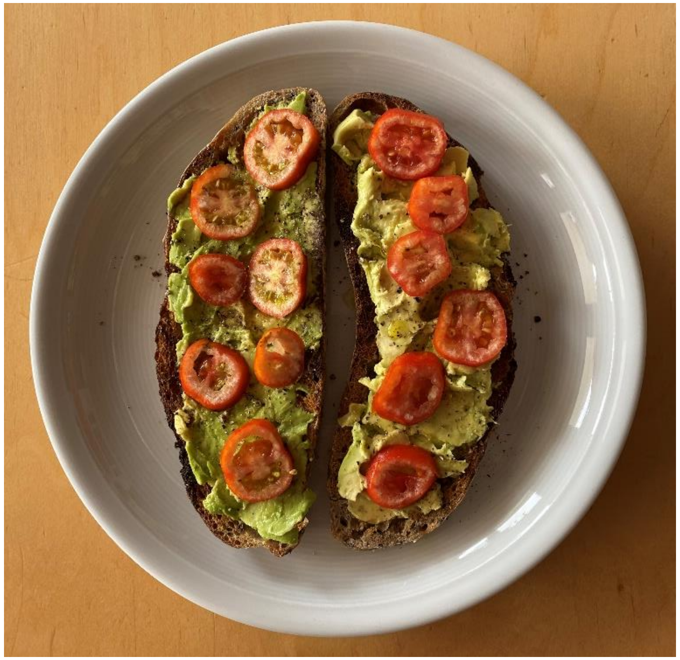


Figure 11 Contribution (%) of Inputs/sub-stages to overall climate change impact of the orchard stage

Source: "Environmental Life Cycle Assessment of NZ Avocados (Majumdar and McLaren, 2021)

From the consumption side …



- Basis for comparison
  - 100 g of different products?
  - Serving size? How typically eaten?
  - Nutritional value?

Nutritional Life Cycle Assessment?

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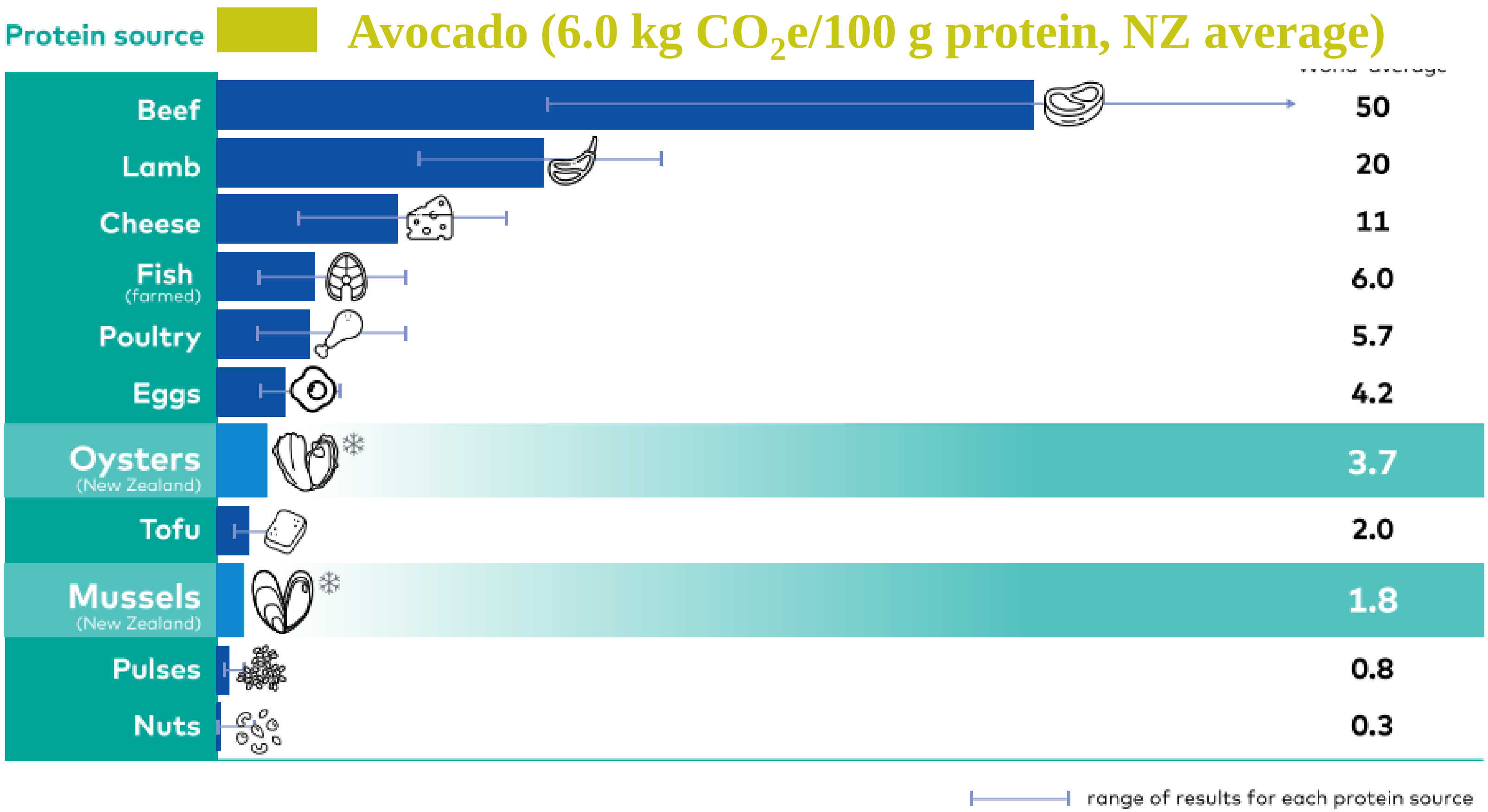

Figure 1: Carbon footprints of different dietary proteins on the global market – farming to retail only ‡

Source: "LCA of NZ Mussels and Oysters" (thinkstep ANZ, 2021)

2. Case study: novel protein

- Data from production-scale pilot scaled to industrial production
- Uncertainties calculated using (a) Monte Carlo analysis and (b) sensitivity analyses
- Baseline Finland – but model adapted for different countries

nature food

ARTICLES

https://doi.org/10.1038/s43016-021-00418-2

Check for updates

Ovalbumin production using *Trichoderma reesei* culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin

Natasha Järviö[1,2]✉, Tuure Parviainen[3,4], Netta-Leena Maljanen[1,2], Yumi Kobayashi[2,4], Lauri Kujanpää[3], Dilek Ercili-Cura[5], Christopher P. Landowski[3], Toni Ryynänen[1,2], Emilia Nordlund[3] and Hanna L. Tuomisto[2,4,6]

Ovalbumin (OVA) produced using the fungus *Trichoderma reesei* (Tr-OVA) could become a sustainable replacement for chicken egg white protein powder—a widely used ingredient in the food industry. Although the approach can generate OVA at pilot scale, the environmental impacts of industrial-scale production have not been explored. Here, we conducted an anticipatory life cycle assessment using data from a pilot study to compare the impacts of Tr-OVA production with an equivalent functional unit of dried chicken egg white protein produced in Finland, Germany and Poland. Tr-OVA production reduced most agriculture-associated impacts, such as global warming and land use. Increased impacts were mostly related to industrial inputs, such as electricity production, but were also associated with glucose consumption. Switching to low-carbon energy sources could further reduce environmental impact, demonstrating the potential benefits of cellular agriculture over livestock agriculture for OVA production.

The global growing demand for chicken egg white protein production results in many environmental impacts, such as land use, climate change, water scarcity, resource depletion and eutrophication[1–4]. Ovalbumin (OVA) is the most abundant protein in egg whites, consisting of over 50% of egg white proteins. It has been expressed in several host organisms, including *Escherichia coli* and *Pichia pastoris*, mainly in the lab[5,6]. Advances in cellular agriculture concepts have made it possible to produce recombinant or cell-cultured OVA on a large enough scale to consider it an economically feasible option to chicken-based egg white powder[7]. Using the filamentous ascomycete fungus *Trichoderma reesei*, a well-established and efficient production organism, cell-cultured OVA is now produced in a bioreactor at a pilot scale. The process is a form of acellular production where microorganisms are grown to produce an extracellular recombinant protein, in this case OVA (length: 386 amino acids)[6,8]. The coding gene in chickens (*Gallus gallus domesticus*) is *SERPINB14* (https://www.uniprot.org/uniprot/P01012). The final product of cell-based production is a protein powder that typically shows comparable functional properties to chicken egg white protein powder and can be used as a replacement in food formulations.

The purpose of this study was to assess the environmental impacts of cell-cultured OVA production in comparison to chicken-based egg white protein powder (hereafter referred to as egg white powder, unless otherwise specified) production using an anticipatory life cycle assessment (LCA) method[9,10]. Using an LCA quantifies the environmental impact of *T. reesei*-produced OVA throughout all production steps and allows for the trade-off comparison between different impact categories[11,12]. The impacts of the production process were estimated for that of an industrial level of 100,000 kg, using data from a production-scale pilot and a techno-economic assessment (TEA) produced by VTT[7]. Uncertainties were calculated using Monte Carlo (MC) analysis, while the sensitivities of the results were estimated with various sensitivity analyses. Since production of *T. reesei* OVA (Tr-OVA) mainly relies on the provision of electricity and the carbon intensity of countries varies[13], we also assess the production of Tr-OVA in various countries. The flow chart in Fig. 1 shows the assumed process steps, including the most notable inputs and outputs, and indicates the main focus of this study.

Results

Impact of Tr-OVA for different scenarios. Figure 2 shows the environmental impact of Tr-OVA production per kg of product and contribution per process for four scenarios—Finland (FI), Germany (DE), Poland (PL) and Finland using a low-carbon electricity mix (FI-LC) that includes both renewable energy sources and nuclear power (the Supplementary Data shows the full inputs of this model), which were chosen to reflect different carbon intensity levels of country electricity mixes within the European Union[13]. The largest contributor for most impact categories comes from the input of glucose with a share of 2–94%, depending on the impact category and country. For land use, the contribution of glucose most clearly dominates (86–92%), illustrating the reliance of land use of agricultural products. In addition, for water scarcity —also

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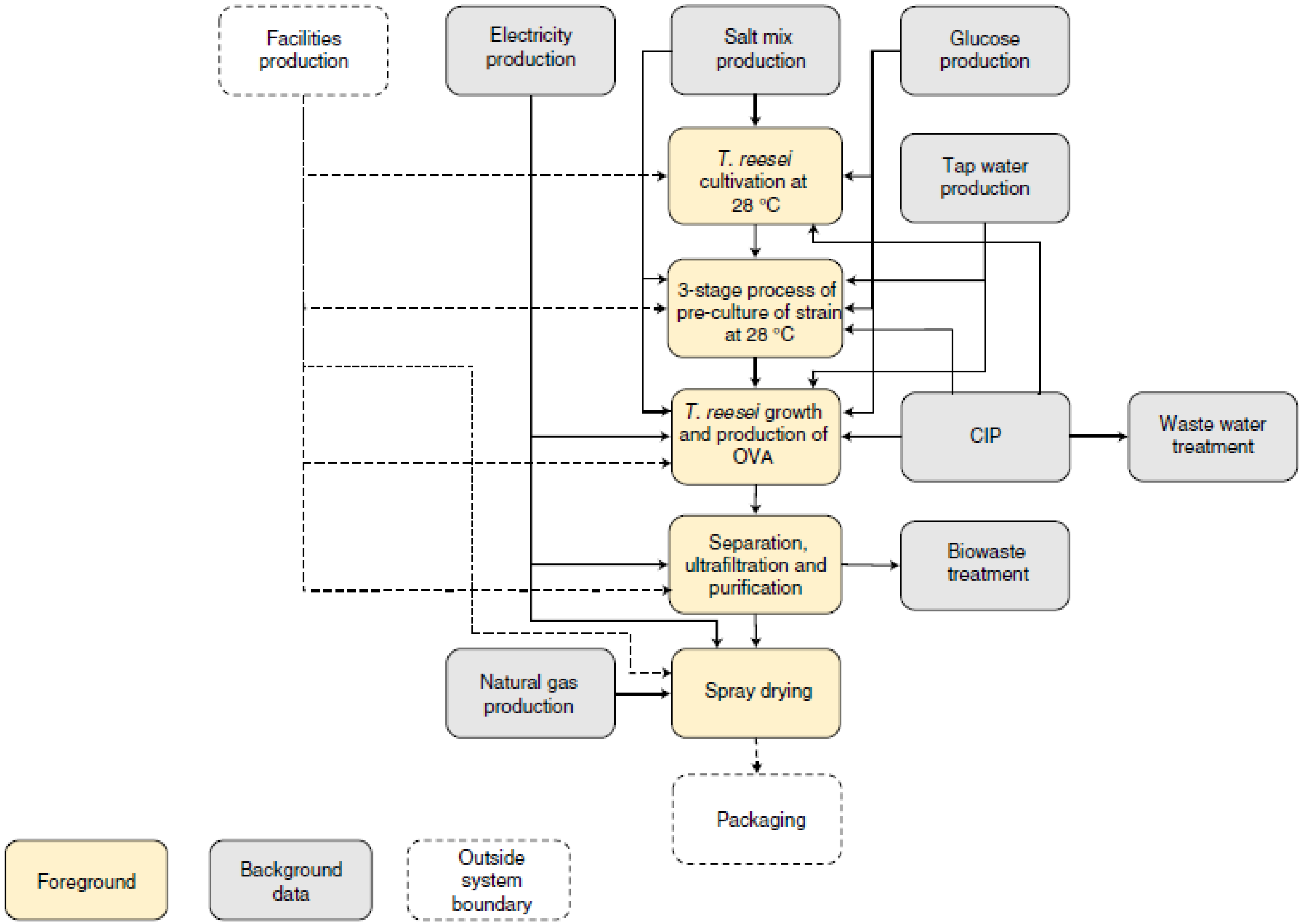
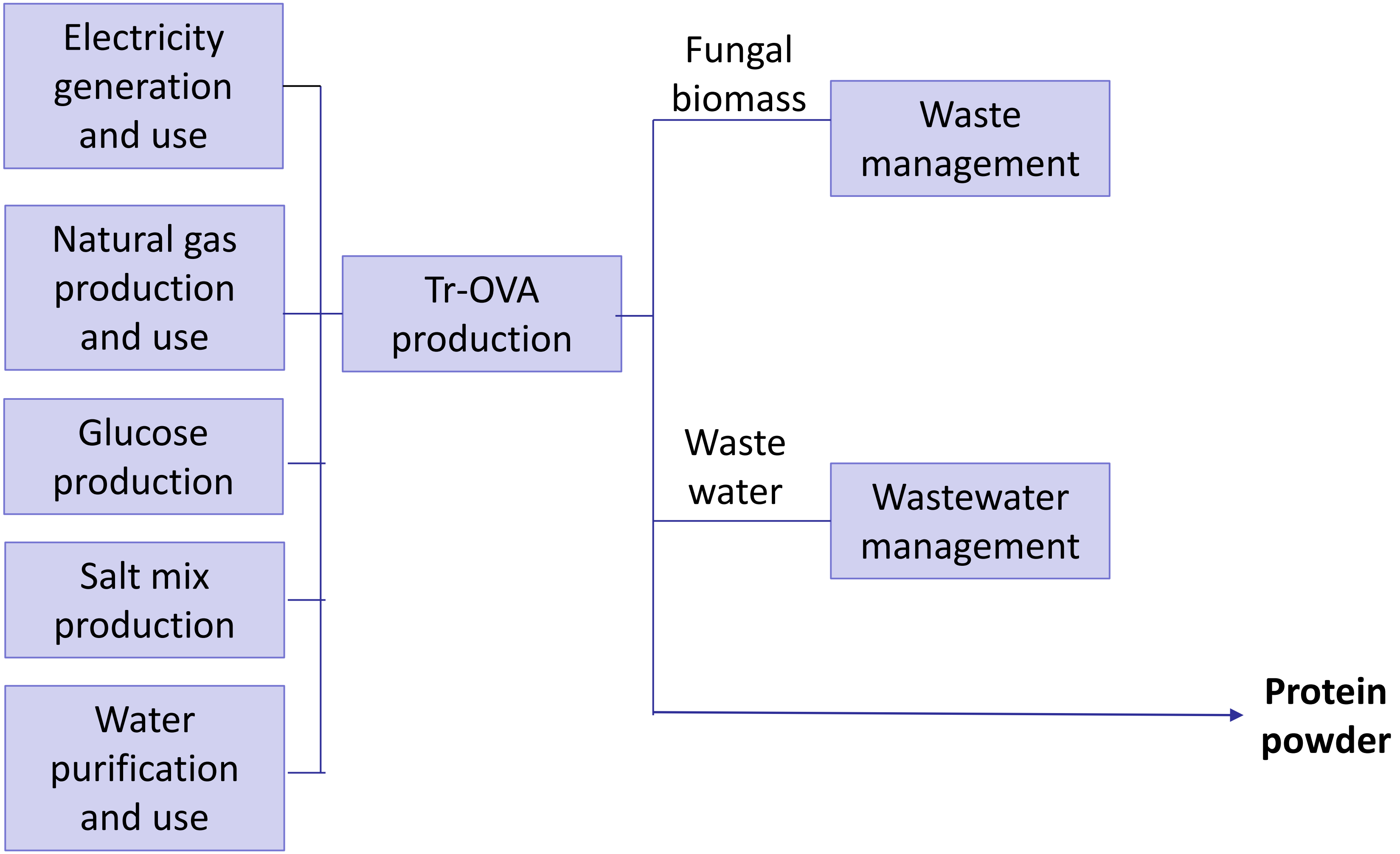


Fig. 1 | Flow chart of the processes involved in the production of Tr-OVA. Flow diagram of the input and outputs related to the production of Tr-OVA where the focus of this study was on the modelling of the environmental impacts of the foreground data (indicated with yellow boxes) while existing LCA databases were used for the background processes (in grey). Processes excluded are indicated with a dotted line.


Electricity generation and use
Natural gas production and use
Glucose production
Salt mix production
Water purification and use
Tr-OVA production
Fungal biomass
Waste management
Waste water
Wastewater management
Protein powder

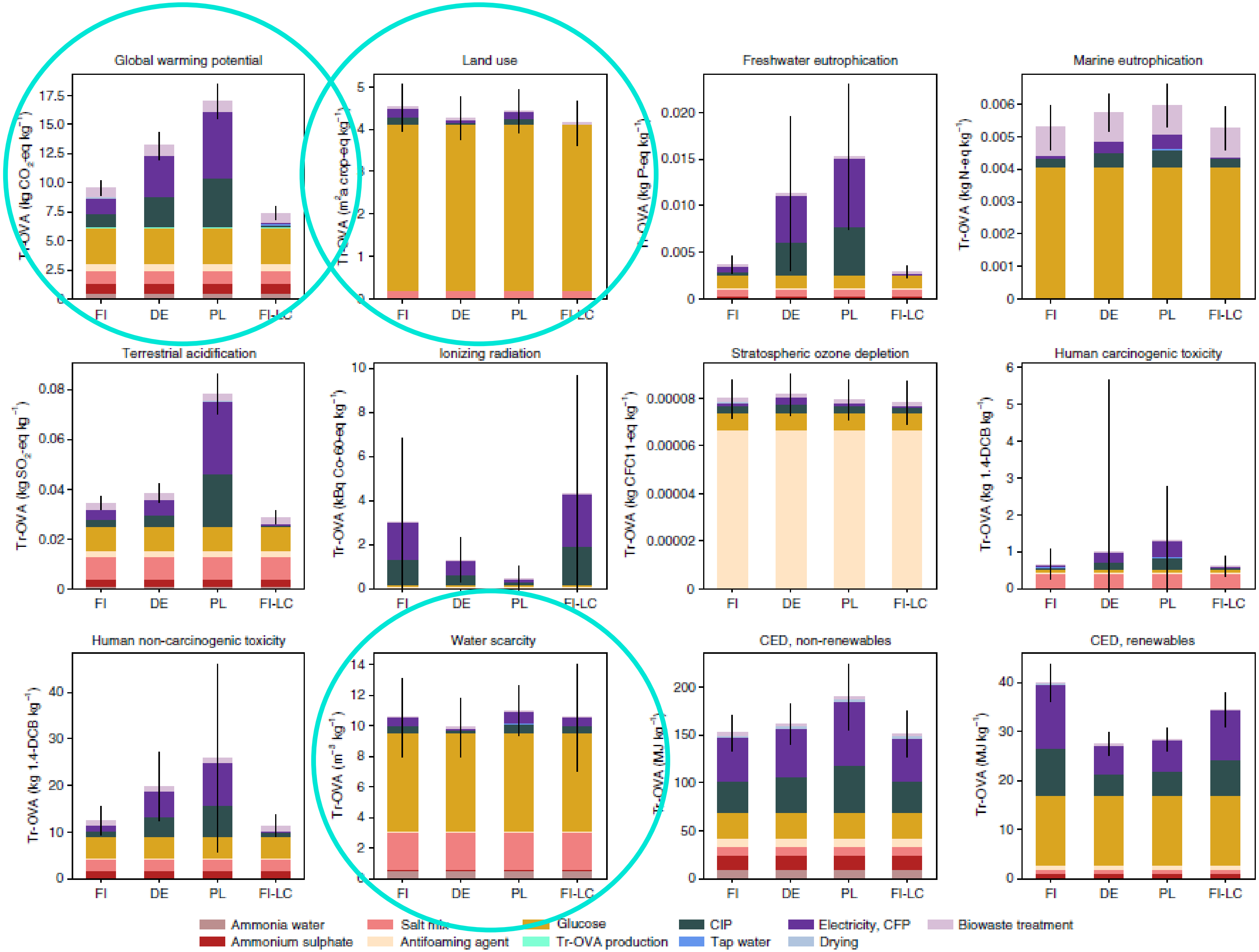
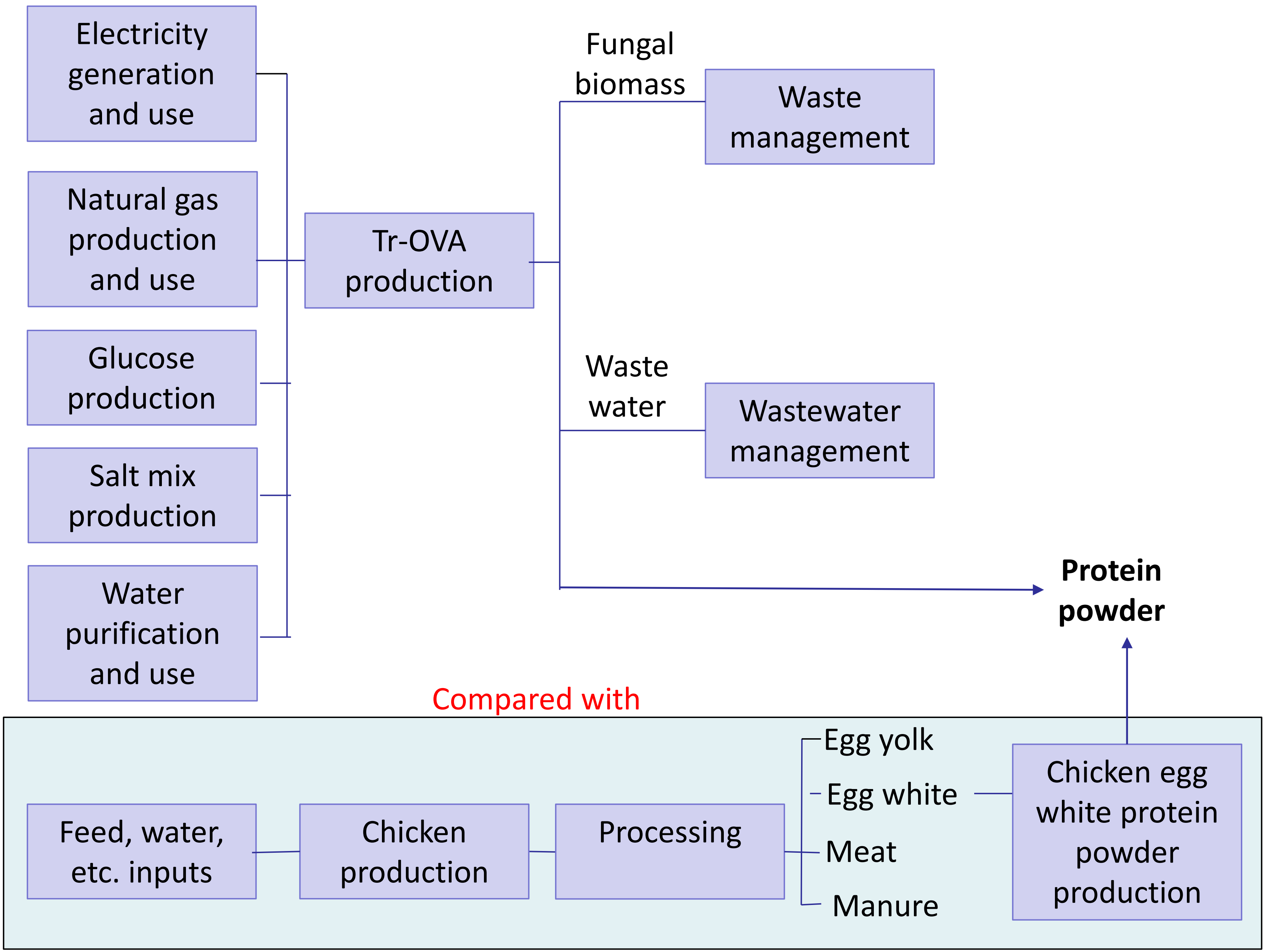


Fig. 2 | Environmental impact of Tr-OVA production per scenario. Deterministic results and process contributions in FI, DE, PL and FI-LC per kg of Tr-OVA product. Standard deviations from the MC runs ($n = 100$) are indicated by the black line. Tr-OVA production refers to direct emissions and land use caused by the Tr-OVA production system. CFP, cultivation, filtration and purification.



Electricity generation and use
Natural gas production and use
Glucose production
Salt mix production
Water purification and use
Tr-OVA production
Fungal biomass
Waste management
Waste water
Wastewater management
Protein powder
Compared with
Feed, water, etc. inputs
Chicken production
Processing
Egg yolk
Egg white
Meat
Manure
Chicken egg white protein powder production

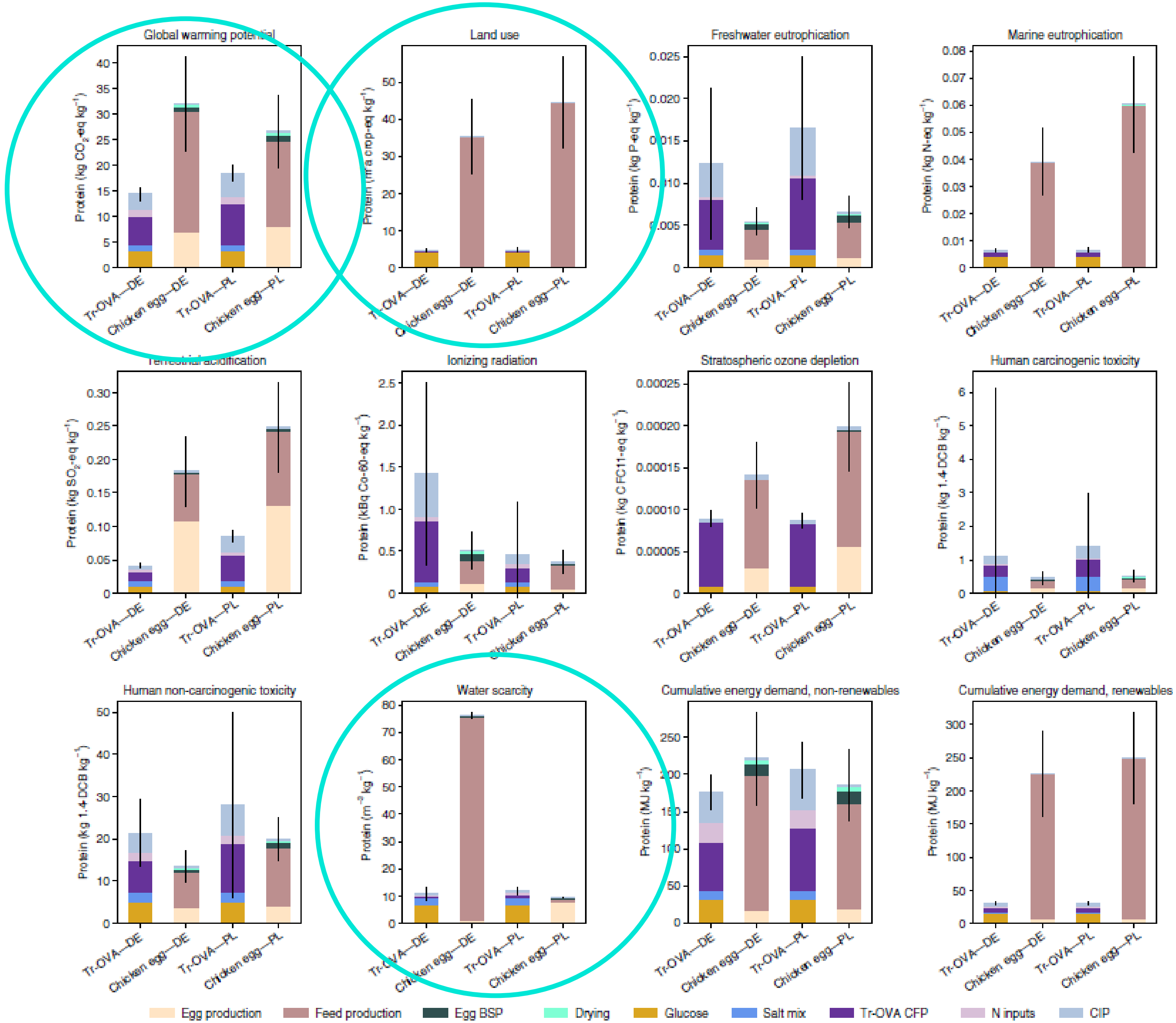
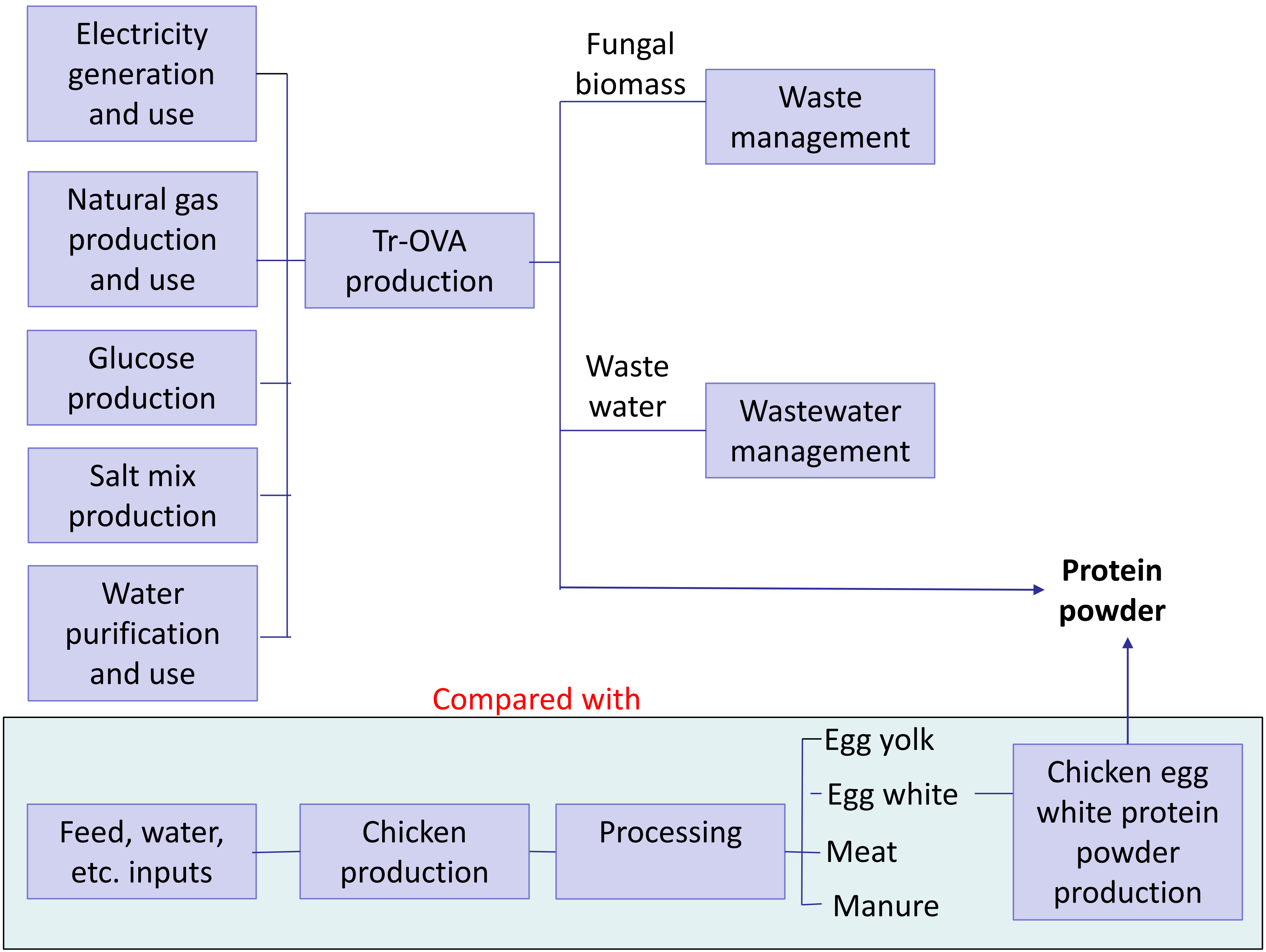


Fig. 3 | Comparison of the environmental impact of Tr-OVA with egg white powder. Deterministic results and process contributions for the production of Tr-OVA in DE and PL versus egg white powder production using chicken eggs in DE and PL per kg of protein. Standard deviations from the MC runs ($n = 100$) are indicated by the black lines.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Chicken egg white protein powder production

3. Current research themes

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Key modelling issues in nutritional LCA (nLCA):

- Nutritional assessment:
  - Functional unit
  - Nutritional value
  - Nutritional value versus human health impacts
- Represent nutritional variability:
  - Food items e.g. cut of meat, seasonal variability
  - Target population and their dietary needs

Other themes:

- Assessing sustainability: nLC**S**A
- Decision situation: general “direction of travel” versus detailed assessment
- Procedural aspects: buy-in versus confrontation
- Enabling transformative change

Food items: unit of analysis

Table 11: Examples of greenhouse gas emissions (kg CO_2e) of food items across a selection of functional units

Food item	Type of food	kg CO_2 e/ 100 g product	kg CO_2 eq/ serving size	kg CO_2 e/ 100 g dry weight	kg CO_2 e/ 100 kcal	kg CO_2 e/ 100 g protein	kg CO_2 e/ 100 mg calcium
Ham shoulder medium fat boiled	Red meat	1.08	0.16	3.95	0.81	6.60	9.04
Beef rump steak prepared	Red meat	3.13	2.35	9.01	2.15	10.70	21.46
Potatoes w/o skins boiled average	Starchy vegetables	0.09	0.05	0.42	0.11	4.86	1.24
Eggs (chicken) boiled average	Eggs	0.43	0.22	1.82	0.34	3.51	0.53
Chicken with skin prepared	Poultry	1.36	1.02	3.17	0.59	5.25	4.53
Milk whole	Dairy	0.21	0.52	1.68	0.34	6.32	0.28
Milk skimmed	Dairy	0.20	0.49	2.03	0.56	5.32	0.44
Cheese Gouda 48+ average	Dairy	1.31	0.26	2.16	0.36	5.74	0.04
Shrimps Dutch peeled boiled	Fish	1.54	0.15	6.39	1.64	7.78	1.22
Herring salted	Fish	0.28	0.21	0.84	0.16	1.59	0.32
Kale curly boiled	Vegetables	0.16	0.08	1.14	0.35	4.00	0.19
Mushrooms boiled	Vegetables	0.52	0.26	5.21	2.48	13.71	49.60
Pineapple	Fruit	0.10	0.10	0.70	0.18	20.11	1.47
Banana	Fruit	0.08	0.08	0.31	0.08	6.88	1.33
Beans French boiled	Legumes	0.11	0.05	1.34	0.42	5.89	0.79
Peas frozen boiled	Legumes	0.11	0.06	0.44	0.12	1.90	0.38
Bread wholemeal average	Cereals	0.10	0.04	0.17	0.04	0.93	0.13
Bread white water based	Cereals	0.12	0.04	0.19	0.05	1.32	0.17
Cashew nuts unsalted	Nuts	0.43	0.09	0.44	0.07	2.01	0.16
Peanuts unsalted	Nuts	0.74	0.15	0.75	0.12	2.92	0.21
Apple pie Dutch w shortbread w margarine	Sweets	0.23	0.23	0.39	0.08	6.53	0.35
Almond paste filled tarts average	Sweets	0.39	0.20	0.46	0.10	6.31	0.27
Crisps potato average	Snacks	0.48	0.05	0.49	0.09	7.67	0.33
Wine red	Alcoholic beverage	0.20	0.30	1.74	0.25	NA*	3.08
Wine white dry	Alcoholic beverage	0.23	0.34	1.64	0.34	227.67	2.83
Peanut butter	Spreads	0.87	0.13	0.88	0.13	3.87	0.26
Sauce for chips 25% oil	Spreads	0.29	0.06	0.70	0.10	58.44	1.23
Juice apple	Juice	0.15	0.22	1.31	0.33	149.50	4.06
Juice orange pasteurized	Juice	0.07	0.10	0.59	0.15	10.89	1.24
Sausage cooked	Meat	1.52	0.23	2.98	0.43	13.44	2.36
Bacon rashers streaky	Meat	1.10	0.16	2.21	0.35	7.00	4.40
Oil olive	Oils	0.72	0.07	0.72	0.08	NA*	NA*
Oil sunflower seed	Oils	0.50	0.05	0.50	0.06	167.02	NA*

* – NA – Not available as nutrient level listed as 0

Note: Values in each column are coloured based on ranking from red (highest) to green (lowest). Food composition data were obtained from the Dutch Food Composition Database (NEVO) (RIVM, 2019). These example CO_2e values for food items were published by RIVM (2021) and are calculated on a cradle-to-consumer basis.

Source: "Integration of environment and nutrition in life cycle assessment of food items: opportunities and challenges" (McLaren et al., 2021)

Towards nutritional value: use of nutritional indices

Table 1
Nutrient indices and included nutrients.

Nutrient Index[1]	Points of differentiation: included nutrients				
	Macronutrients	Vitamins	Minerals	Disqualifying nutrients	Other[2]
ONQI[3] (Katz et al., 2010)	Fiber, omega 3 (n-3) fatty acids, protein quality, fat quality	Folate, A, C, D, E, B-12, B-6	K, Ca, Zn, Mg, Fe	Saturated fat, trans fat, sodium, total/added sugar, cholesterol	Total bioflavonoids, total carotenoids
WNDS[4] (Arsenault et al., 2012)	Protein, fiber, unsaturated fat	C	Ca	Saturated fat, sodium, added sugar	None
NRF9.3[5] (Fulgoni et al., 2009)	Protein, fiber	A, C, E	Mg, Ca, Fe, K	Saturated fat, added sugars, sodium	None
NRF9[5.1]	Protein, fiber	A, C, E	Mg, Ca, Fe, K	None	None
LIM3[5.2]	None	None	None	Saturated fat, added sugars, sodium	None
NBC[6] (Fern et al., 2015)	Fiber, protein, linoleic acid, α-linolenic acid, choline	Folate, niacin, riboflavin, thiamin, pantothenic acid, A, B-12, B-6, C, D, E, K	Ca, Cu, Fe, Mg, Mn, P, K, Se, Zn	Total fat, saturated fat, trans fat, cholesterol, total sugar, sodium	Water
QI[6.1]	Fiber, protein, linoleic acid, α-linolenic acid, choline	Folate, niacin, riboflavin, thiamin, pantothenic acid, A, B-12, B-6, C, D, E, K	Ca, Cu, Fe, Mg, Mn, P, K, Se, Zn	None	Water
DI[6.2]	None	None	None	Total fat, saturated fat, trans fat, cholesterol, total sugar, sodium	None
DNS[7] (Chaudhary et al., 2018a)	None	None	None	Sugar, cholesterol, saturated fat, total fat	None

1 See sources for full information on nutrients; multiple variations of a specific index, which differ by the included nutrients, can exist.
2 E.g., other antioxidants, phytochemicals.
3 Overall Nutritional Quality Index (ONQI).
4 Weighted Nutrient Density Score (WNDS).
5 Nutrient Rich Foods Index (NRF9.3); composed of the NRF and LIM.
5.1 Nutrient Rich Foods (NRF).
5 2 Limiting Nutrient (LIM).
6 Nutrient Balance Concept (NBC); composed of the QI and DI.
6 1 Qualifying Index (QI).
6 2 Disqualifying Index (DI).
7 Disqualifying Nutrient Score (DNS).

Source: "Assessing nutritional, health, and environmental sustainability dimensions of agri-food production " (Green et al., 2020)

Nutritional value versus human health impacts

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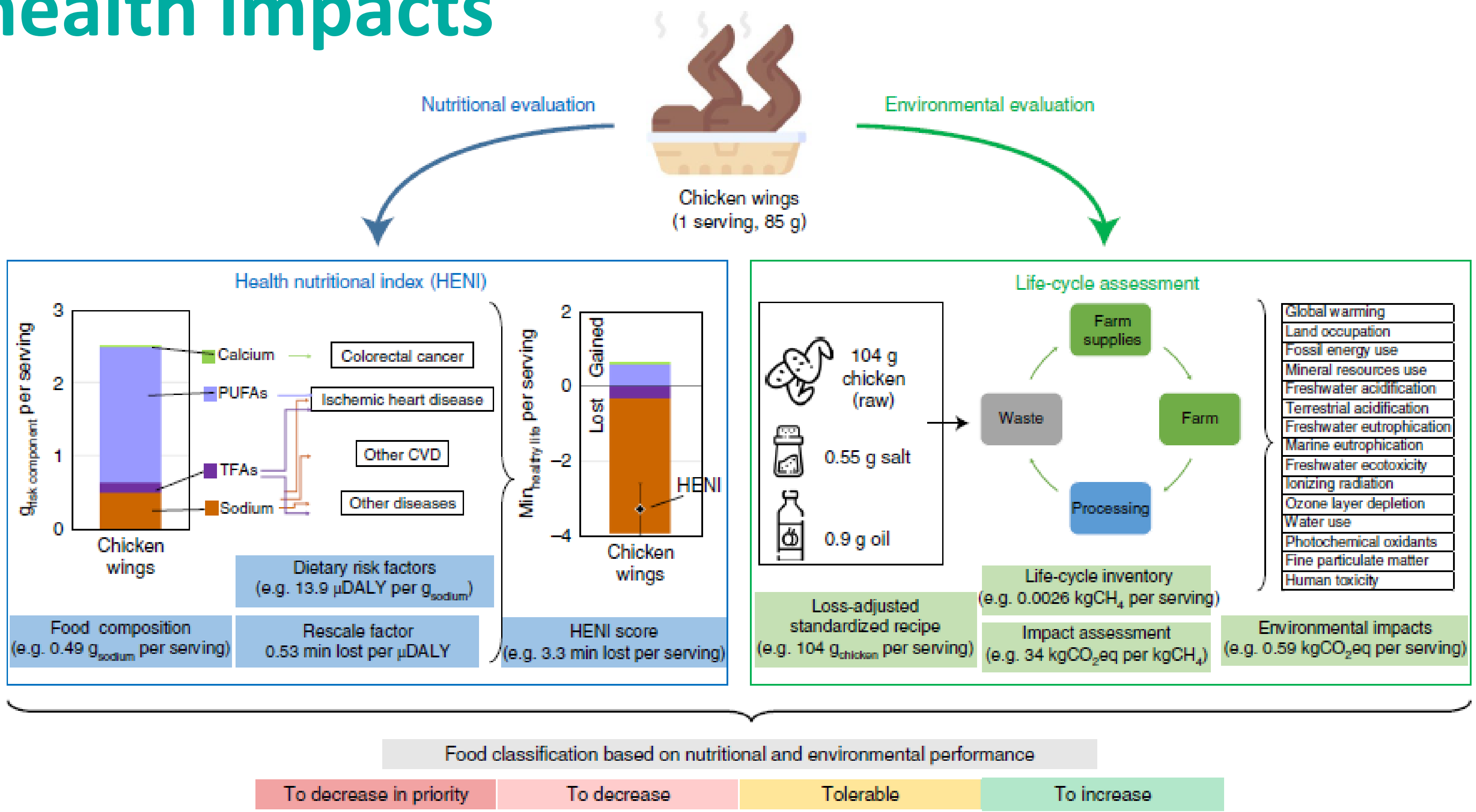

Fig. 1 | Proposed framework to evaluate and compare the nutritional and environmental performances of individual foods. This framework was used to identify, prioritize and inform dietary changes towards healthy and environmentally sustainable diets. Illustration based on a serving of chicken wings (85 g). CVD, cardiovascular disease. The icons used in the figure were made with Freepik from www.flaticon.com.

Source: "Small targeted dietary changes can yield substantial gains for human health and the environment" (Stylianou et al., 2021)

3. Current research themes

Key modelling issues in nutritional LCA (nLCA):

- Nutritional assessment:
  - Functional unit
  - Nutritional value
  - Nutritional value versus human health impacts
- ***Represent nutritional variability:***
  - ***Food items e.g. cut of meat, seasonal variability***
  - ***Target population and their dietary needs***

Other themes:

- Assessing sustainability: nLC**S**A
- Decision situation: general “direction of travel” versus detailed assessment
- Procedural aspects: buy-in versus confrontation
- Enabling transformative change

Representing nutritional variability in food items: cuts of beef

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Table 3 Ratios of protein and saturated fatty acids in various cuts of beef as per the USDA SR Legacy Database (USDA 2019)

Cut	USDA code	SFA%[a]	TP%[b]	SFA:TP
Chuck	13351	5.28	26.50	0.20
Rib	13392	9.24	24.73	0.37
Top loin	13446	5.10	28.19	0.18
Porterhouse	13463	7.04	24.47	0.29
Ground (75% lean)	23577	9.59	15.76	0.61
Ground (95% lean)	23557	2.18	21.41	0.10

[a]Saturated fatty acids

[b]Protein

Source: "Protein quality as a complementary functional unit in life cycle assessment (LCA)" (McAuliffe et al., 2023)

Representing nutritional variability in food items: seasonal variability

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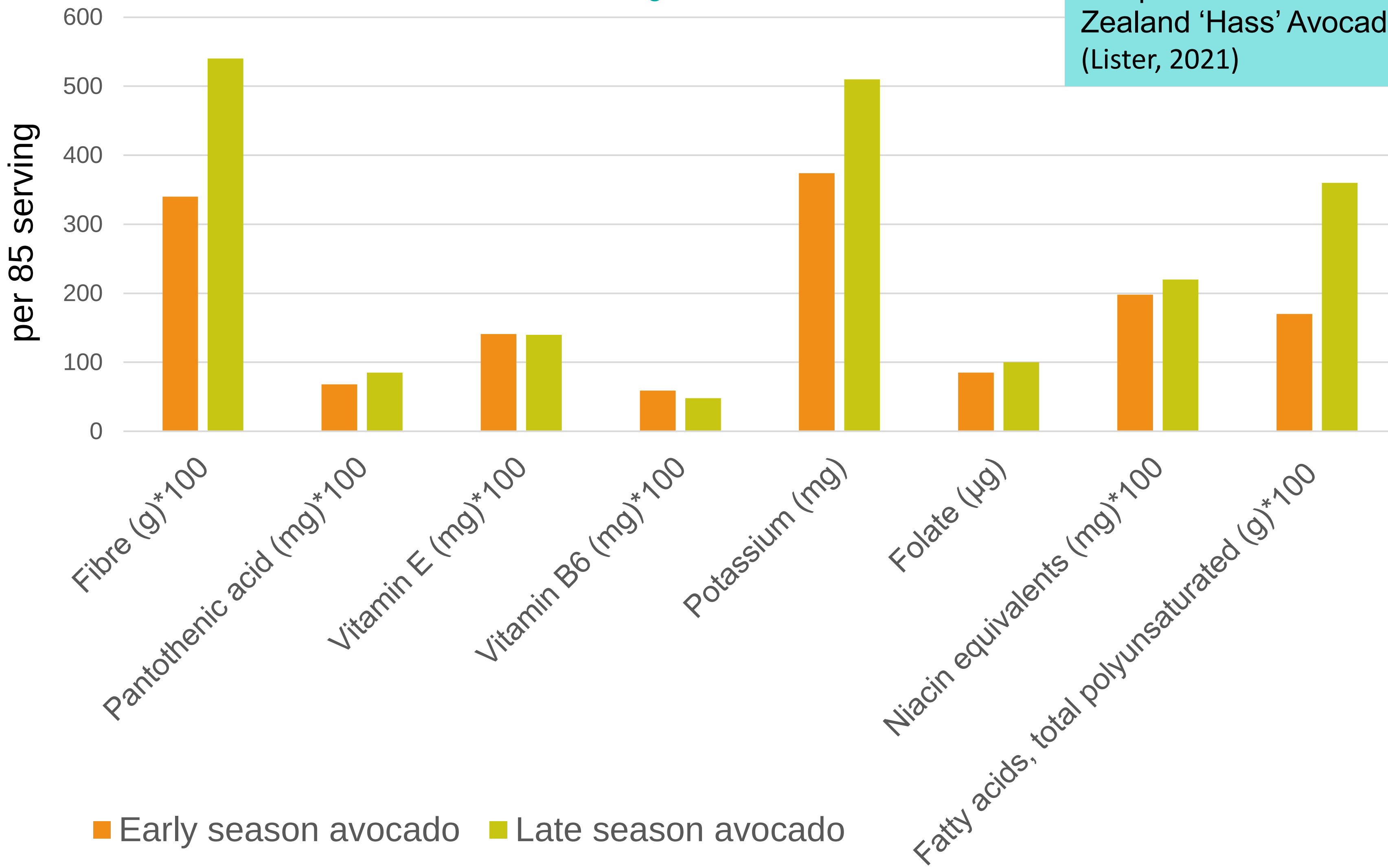
Source: "The nutritional composition of New Zealand 'Hass' Avocados" (Lister, 2021)



Target population

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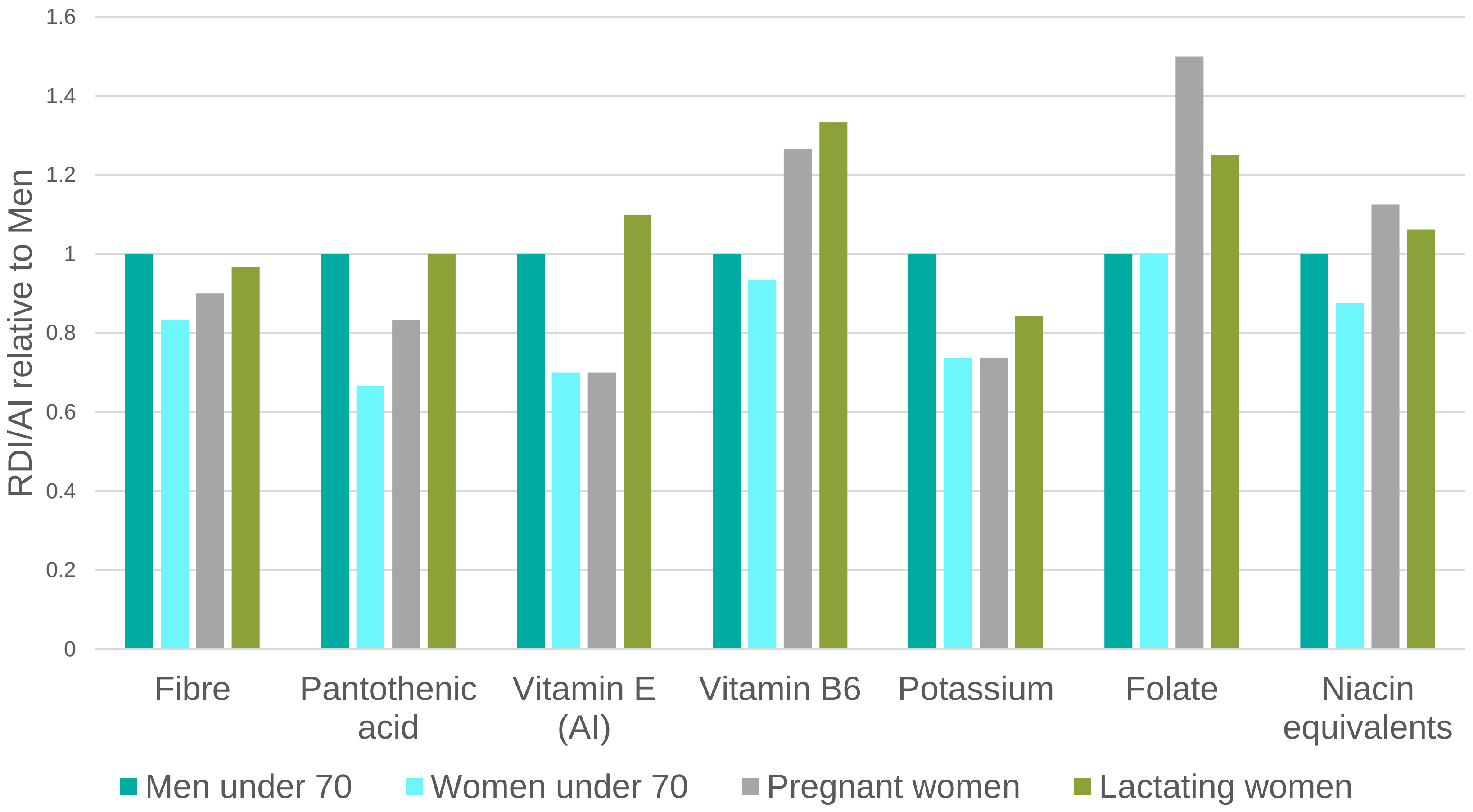

RDI= recommended dietary intake

AI= recommended average daily intake

3. Current nLC(S)A thinking

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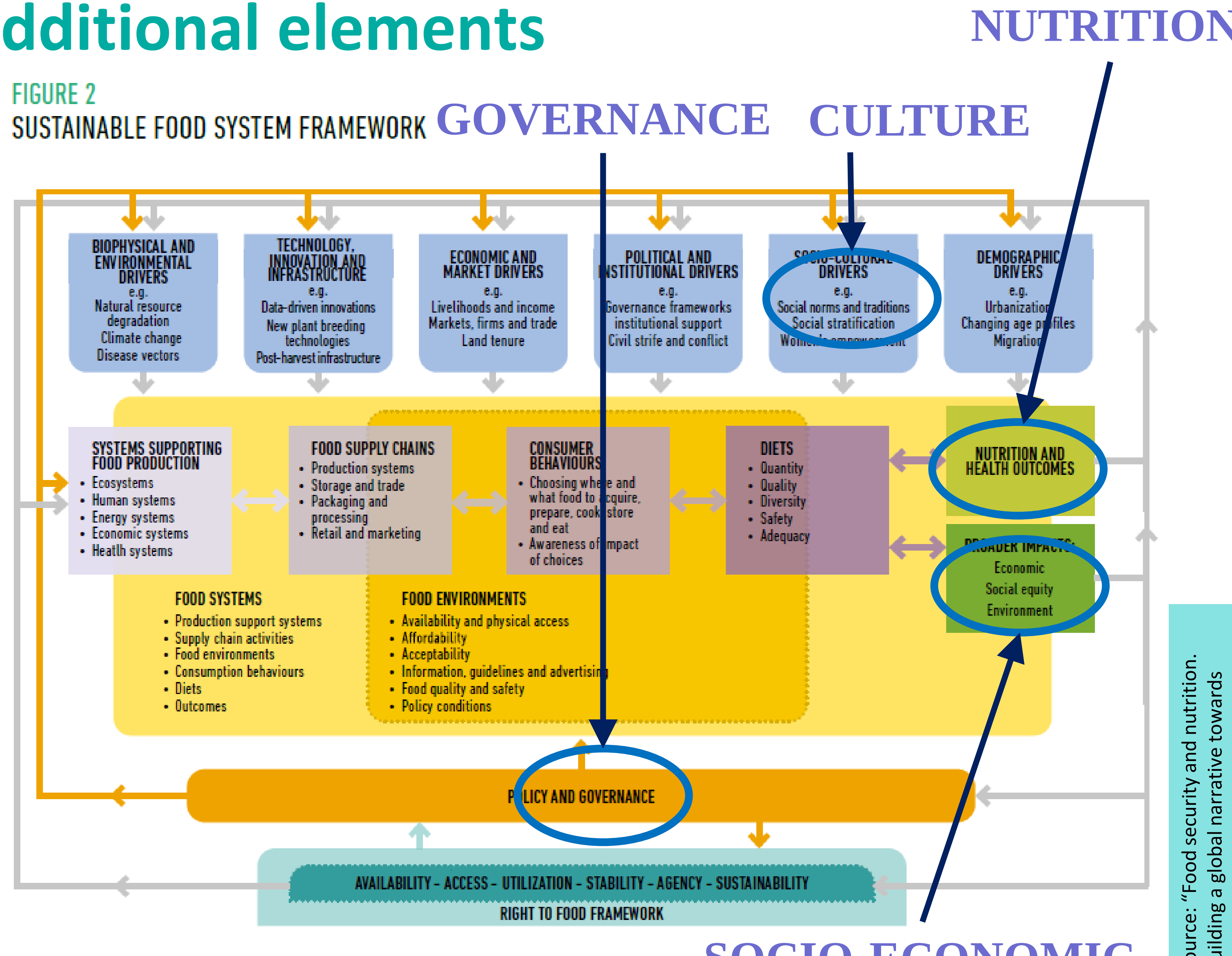
Other themes:

- ***Assessing sustainability: nLCSA***
- ***Decision situation: general "direction of travel" versus detailed assessment***
- ***Procedural aspects: buy-in versus confrontation***
- ***Enabling transformative change***

Additional elements

FIGURE 2
SUSTAINABLE FOOD SYSTEM FRAMEWORK



SOURCE: ADAPTED FROM HLPE 12, 2017

Source: "Food security and nutrition. Building a global narrative towards 2030." (HLPE, 2020)

nLCSA process

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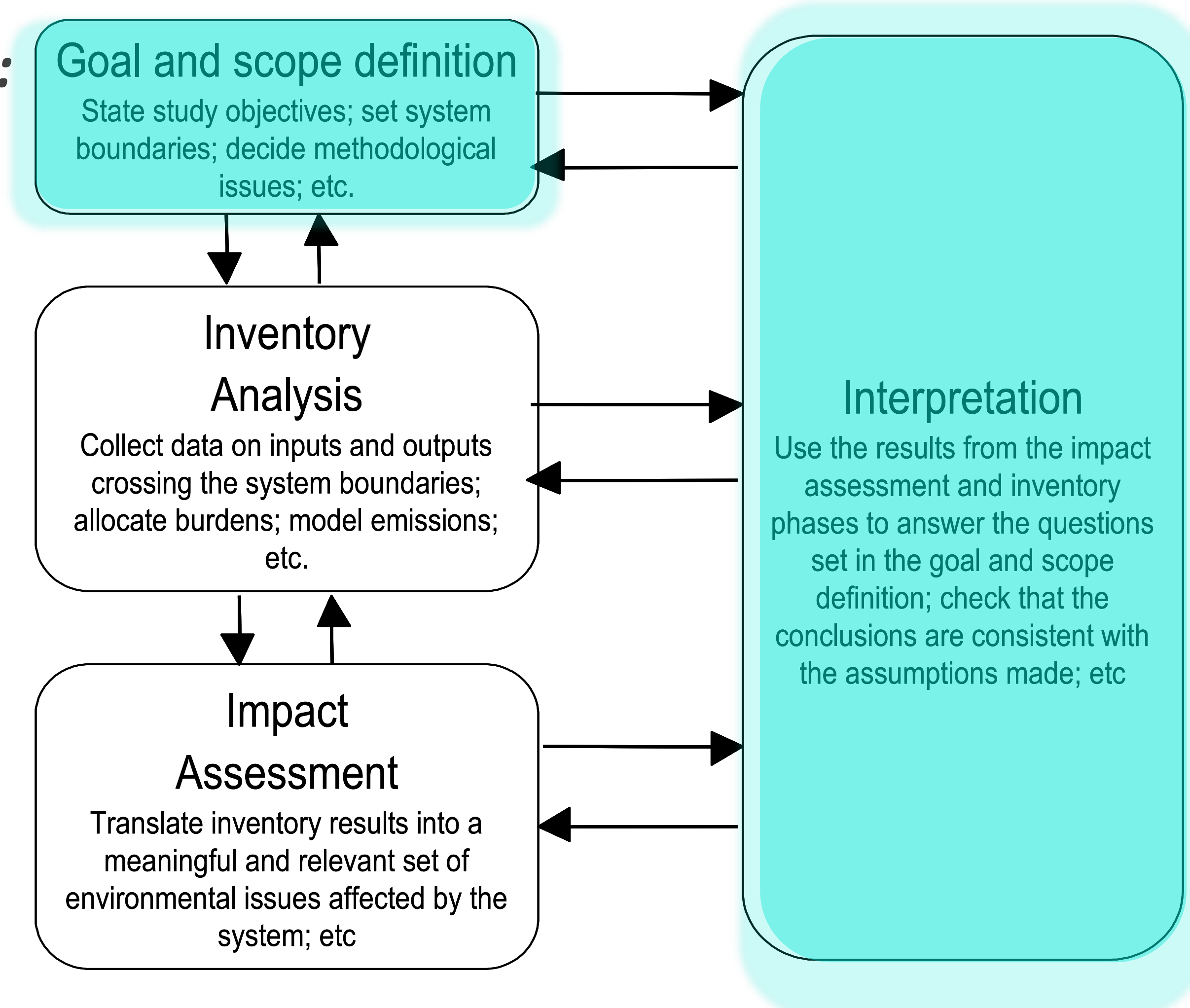
- *Decision situation: general "direction of travel" versus detailed assessment*
- *Procedural aspects: buy-in versus confrontation*
- *Enabling transformative change*



Towards Solutions

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Benefits of nLCA/nLCSA:

- Scientific evidence as basis to inform decision-making
- More holistic assessment (cf nutritional guidelines)
- Support education for transformative change

More focus needed on:

- Systems-based assessment (exploratory “what-if” LCA)
- Contextually relevant analysis
- Procedural aspects to ensure relevance and buy-in among stakeholders (for policy support)