How can we ensure enough protein for 10 billion people ?

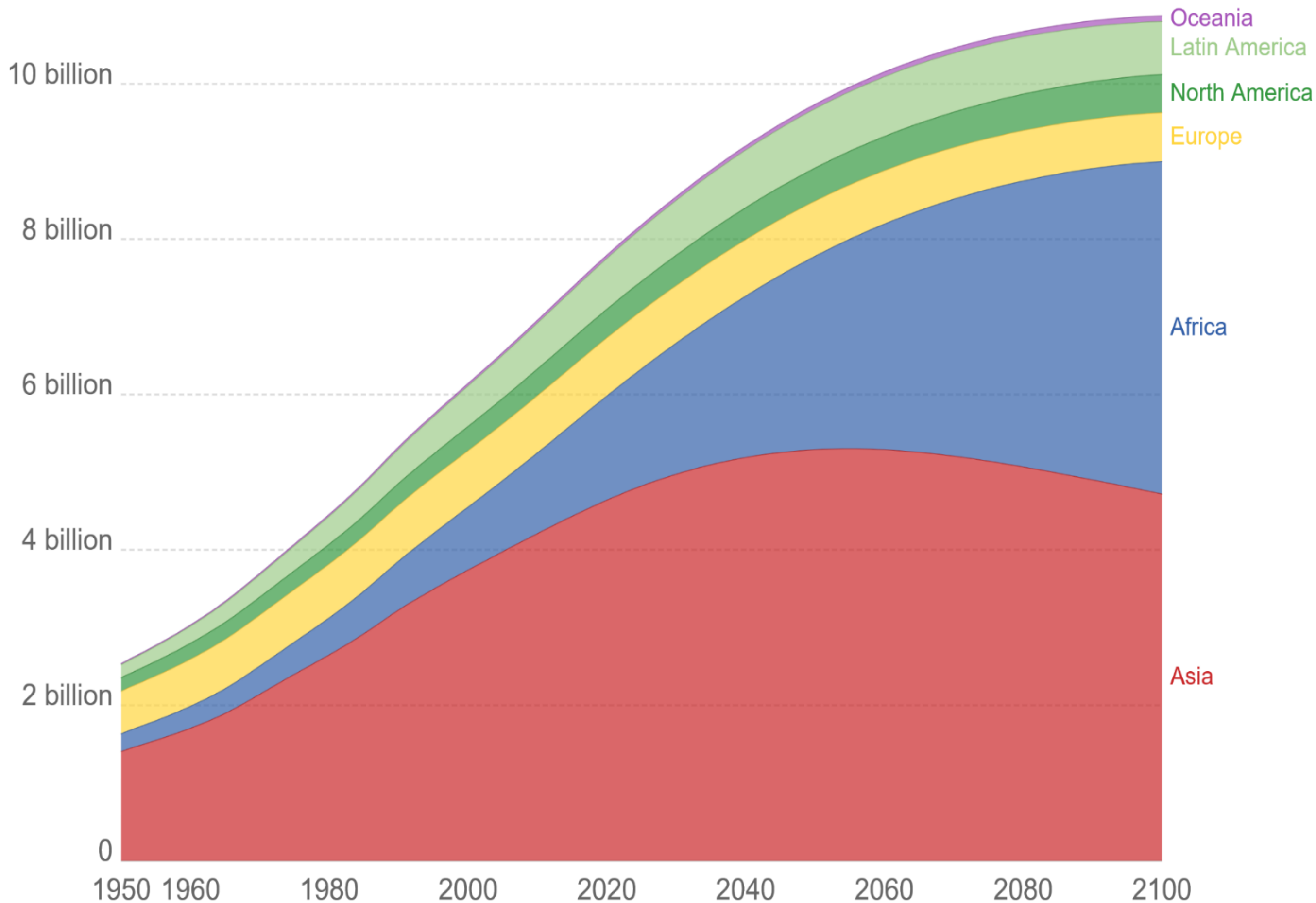
Symposium on protein supply for 10 billion people

27. August 2019, Buhler Campus

Prof. Dr.-Ing. Alexander Mathys

ETH Zurich

World population growth by region, how many people could live on our planet in a sustainable way?



Source: HYDE (2016) & UN, WPP (2019)

OurWorldInData.org/world-population-growth • CC BY

Social innovations needed, e.g.:

- **Improved health systems**
- **Empower women**
- **Better education**
- **Many more**

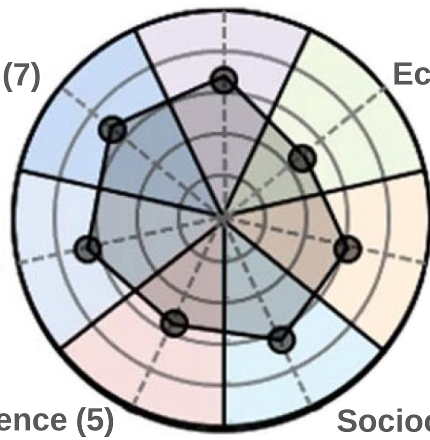
Food systems are at the heart of at least 12 of the 17 Sustainable Development Goals (SDGs)

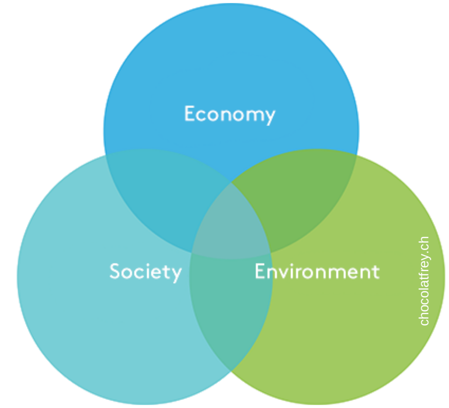
(United Nations, 2015)

Multi-indicator sustainability analysis of global food systems, the heart of at least 12 of 17 SDGs

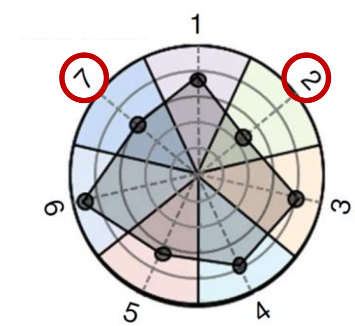
nature COMMUNICATIONS

Global food system sustainability performance





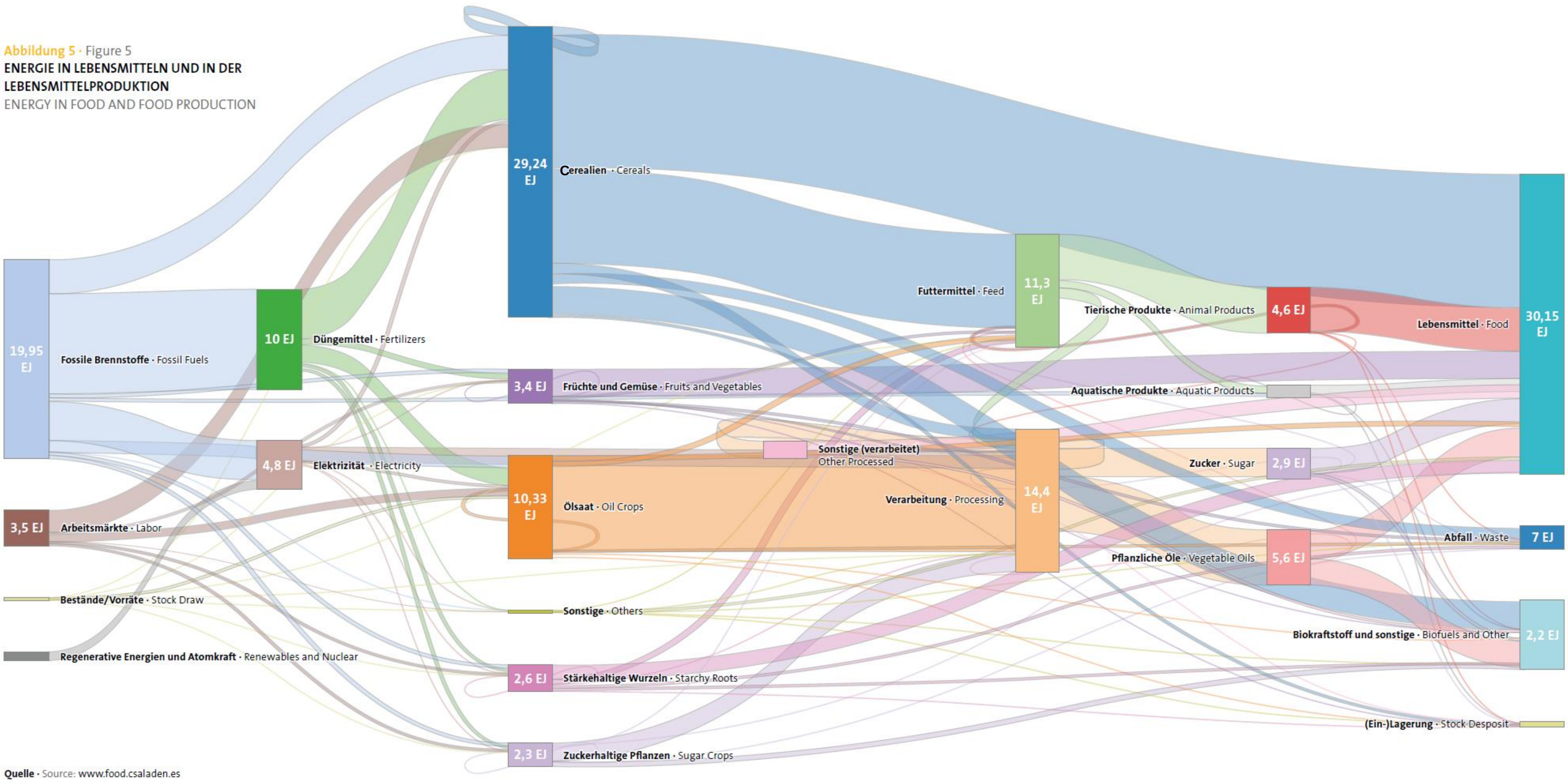
High income regions



Abhishek Chaudhary Former PostDoc | Canxi Chen, Doctoral candidate | Ashley Green, Doctoral candidate

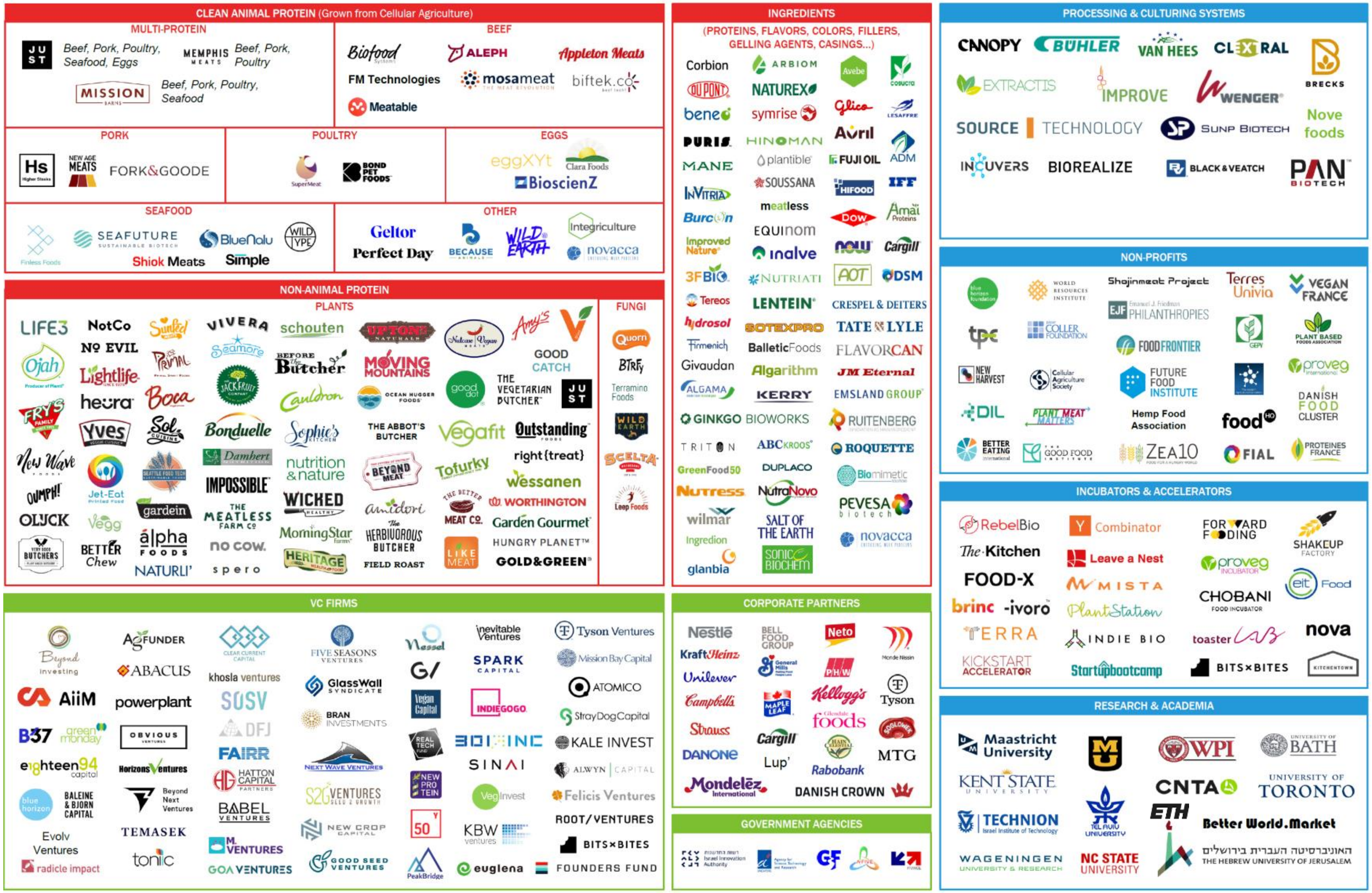
(Chaudhary, Gustafson and Mathys 2018, Nature Communications)

Energy balance in food production via Sankey diagram per year based on FAO data



(FAOSTAT database, 2015; www.food.csaladen.es; Smetana, Heinz & Mathys, 2015)

The Global Alternative Protein Ecosystem (Fox, 2019) – Great oppurtunity for collaborations!

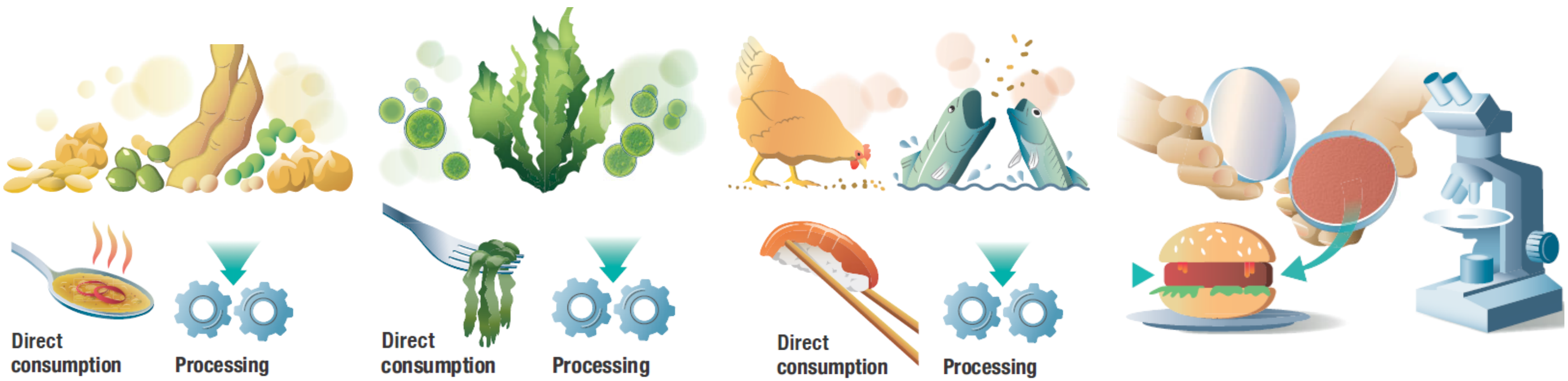


(Olivia Fox Cabane, 2019, modified)

Selected alternative protein sources with different time scales to market with large scale volumes

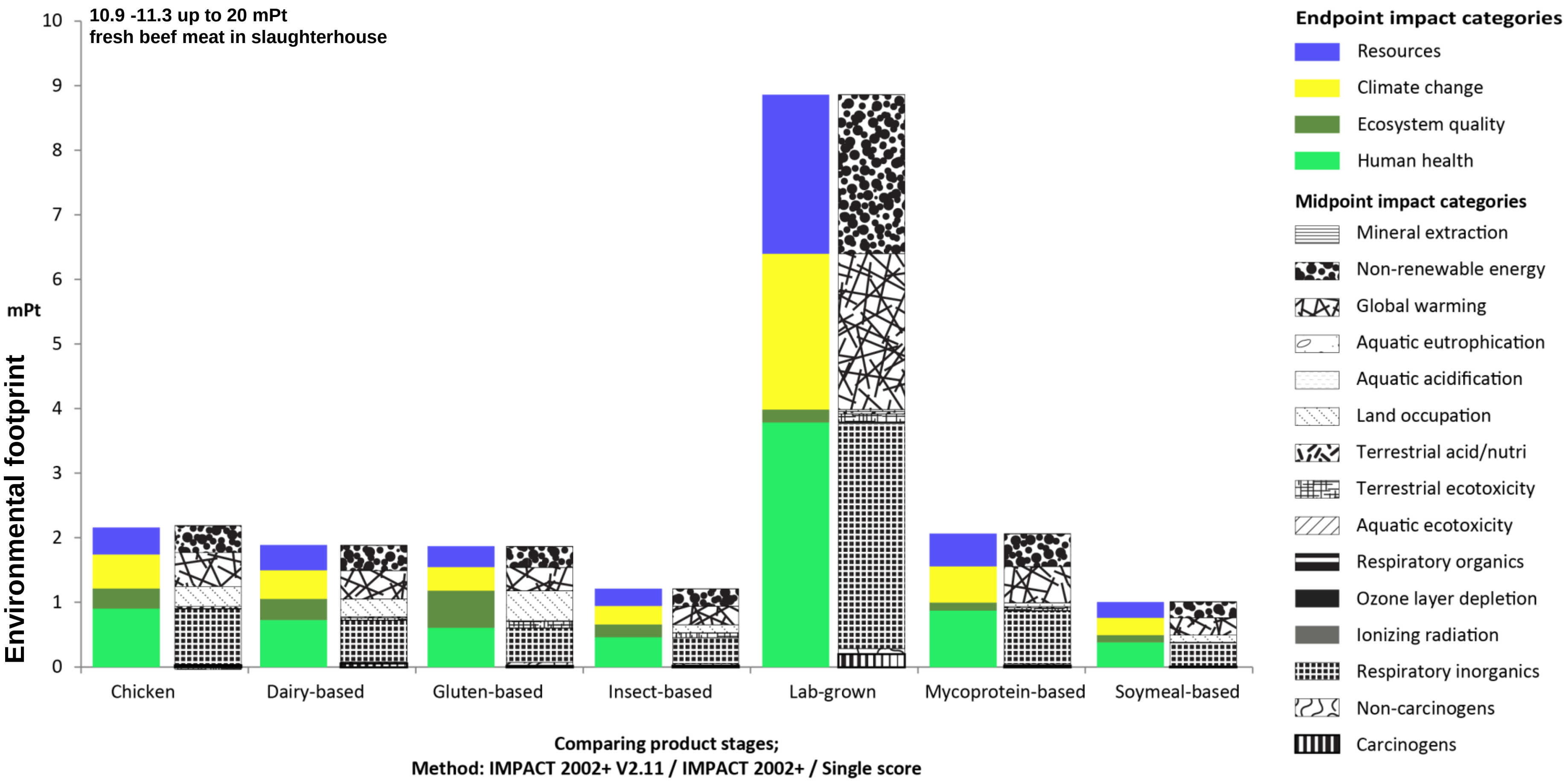
Alternatives to benchmark plant proteins | **Alternatives to benchmark animal proteins**

Pulses (short term) | **Algae (mid-long term)** | **Insects (short-mid term)** | **Lab meat (long term)**



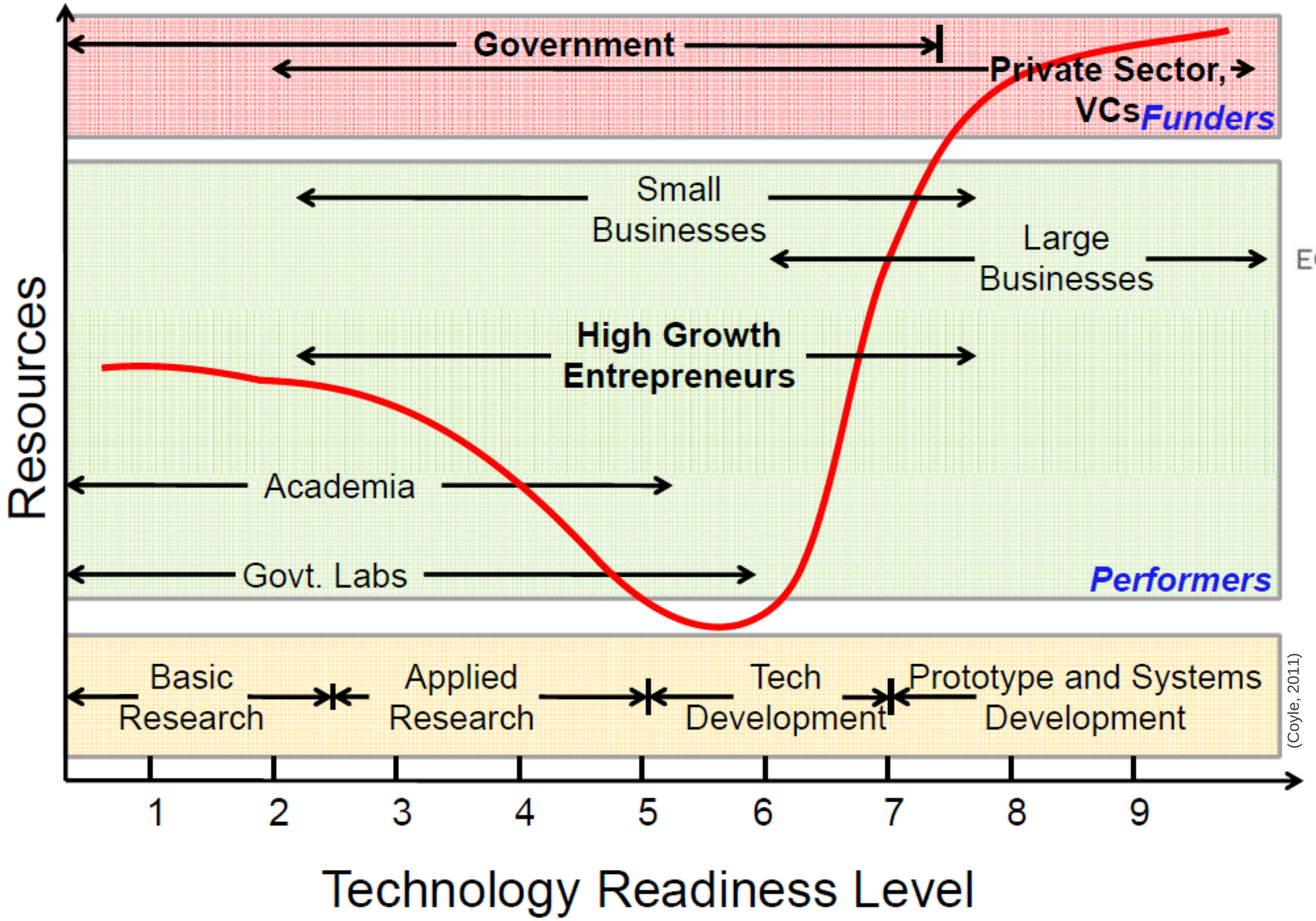
(pictures from Buhler 2018, Diagram 178)

Relevant benchmark and alternative protein sources with their respective environmental footprint

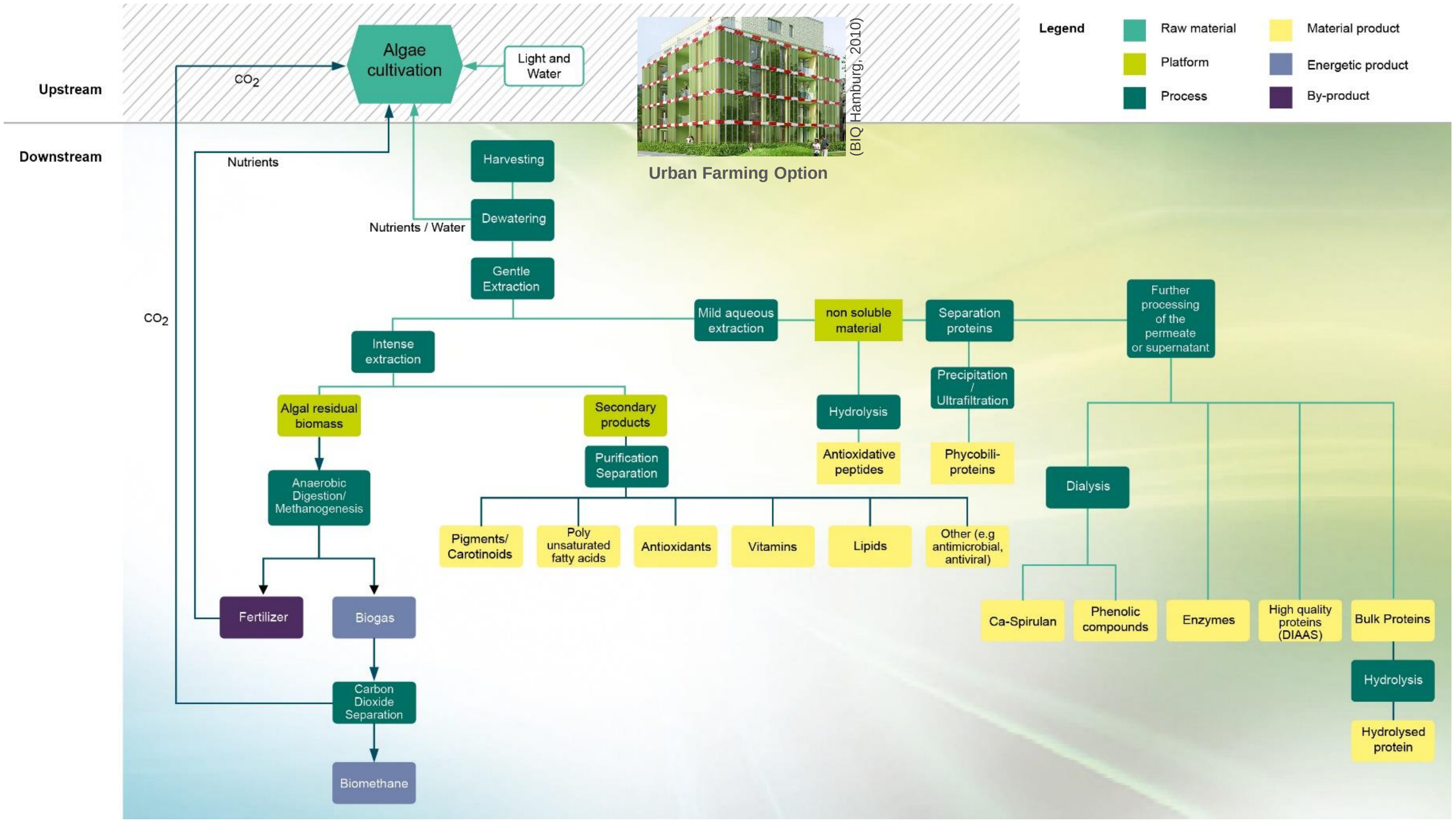


Smetana, Mathys et al. (2015). International Journal of Life Cycle Assessment

Different technology readiness level, the connected ecosystem and relevance of economies of scale



Innovative Algae Biorefinery Concept based on emerging Up- and Downstream



Martin Caporgno
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Greta Canelli
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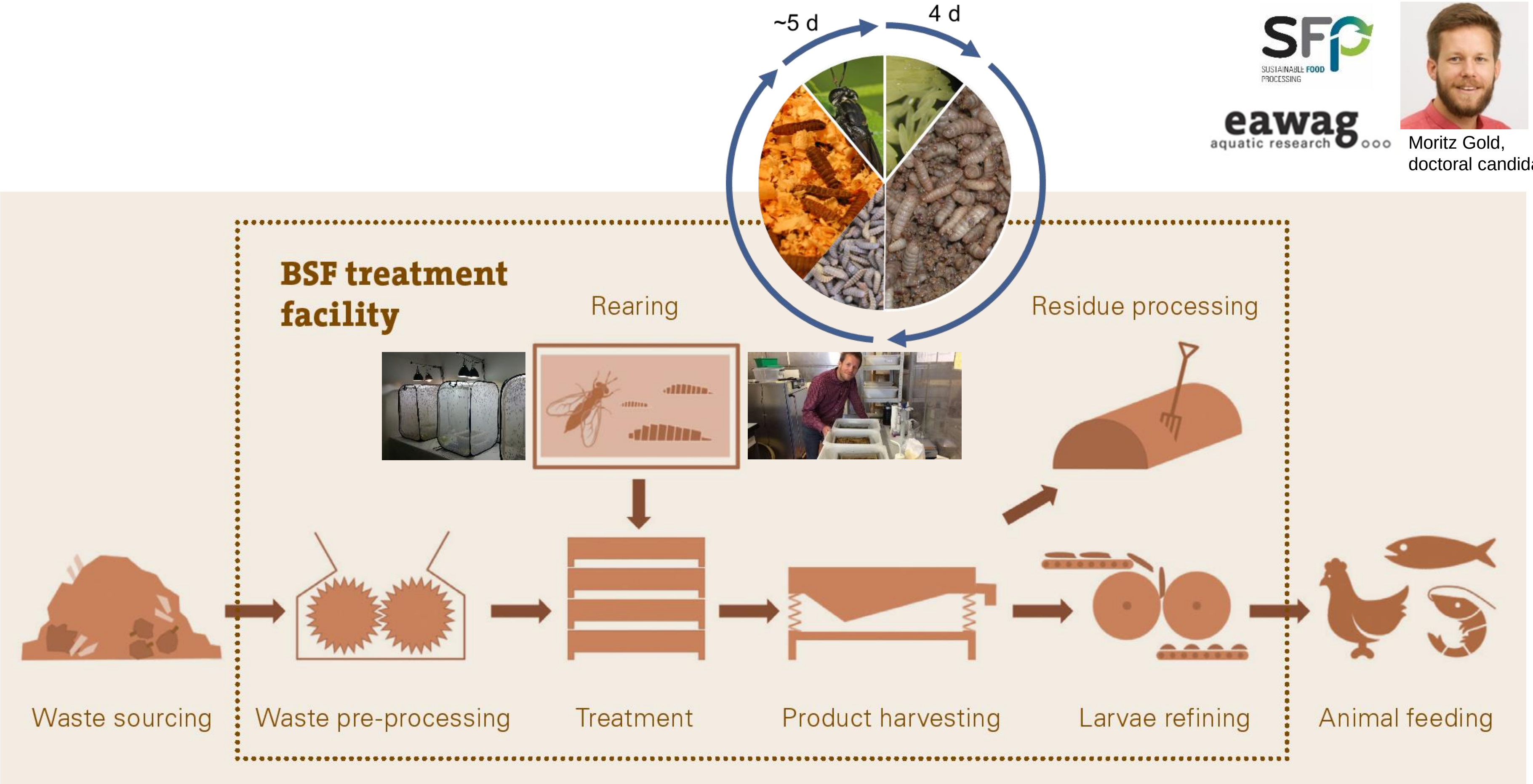
Doctoral candidate

Leandro Buchmann
Doctoral candidate

Lukas Böcker,
Doctoral candidate

1) Buchmann, Frey, Gusbeth, Ravaynia & Mathys (2019). Bioresource Technology 271, 402-408.
2) Böcker, Ortmann, Surber, Leeb, Reineke & Mathys (2019). Innovative Food Science and Emerging Technologies, 52, 116-121.
3) Buchmann, Bloch & Mathys (2018). Bioresource Technology 265, 268-274.
4) Buchmann, Böcker, Frey, Haberkorn, Nyffeler & Mathys (2018). Innovative Food Science and Emerging Technologies 47, 445-453.
5) Caporgno & Mathys (2018). Frontiers in Nutrition 5:58.
6) Caporgno, Haberkorn, Böcker & Mathys (2019). Bioresource Technology, 288, 121476.
7) Buchmann,Bertsch, Böcker, Krähenmann, Fischer & Mathys (2019). Food Hydrocolloids, 105182.
8) Haberkorn, Buchmann, Hiestand & Mathys (2019). Bioresource Technology, 122029.
9) Haberkorn, Böcker, Helisch, Belz, Schuppler, Fasoulas & Mathys (2019). (under review)
10) Böcker, et al.(2019). (under review)

Black Soldier Fly based waste utilization system for decentralized and centralized production

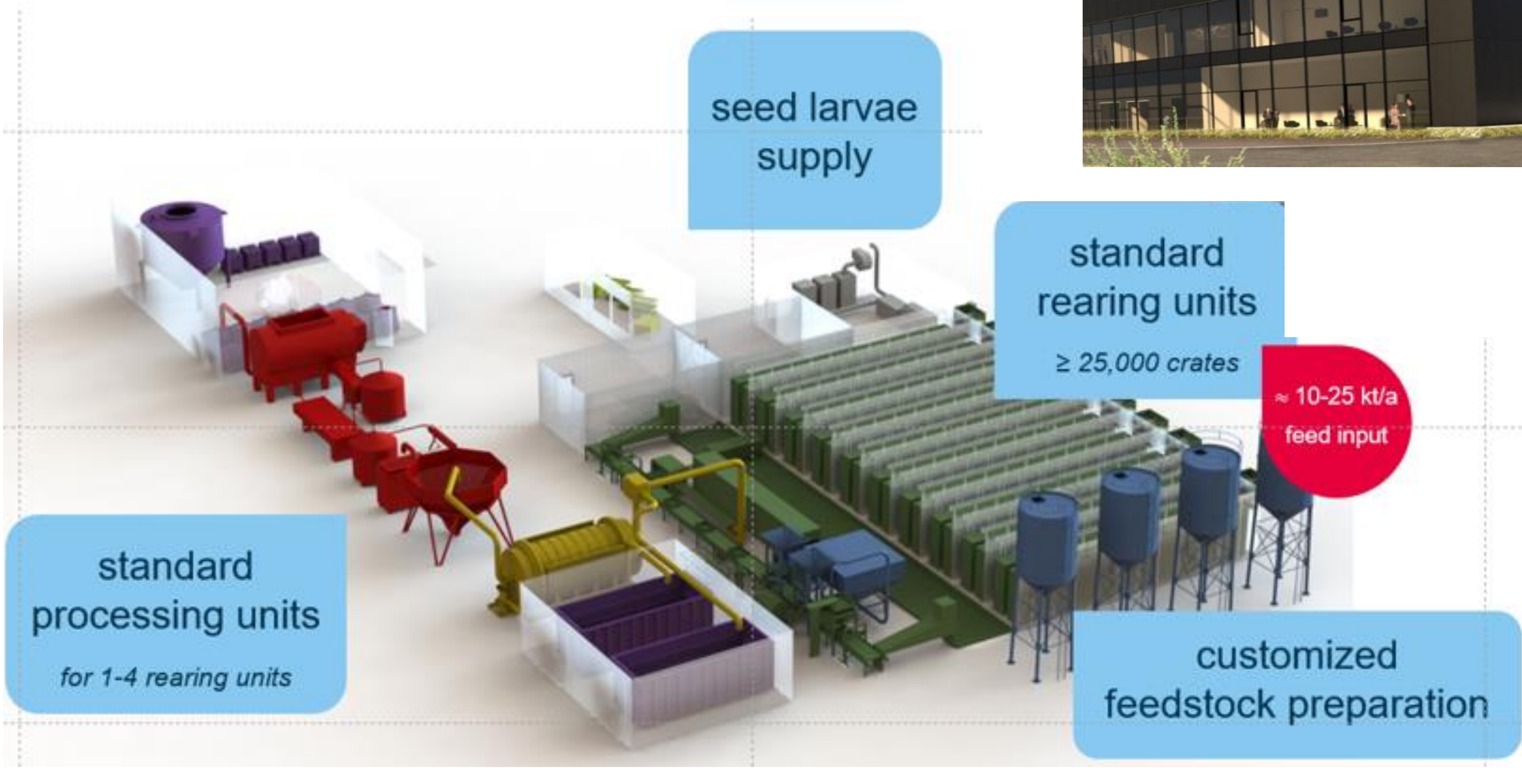


Moritz Gold, doctoral candidate

(Stefan Diener, Black Soldier Fly Biowaste Processing Manual, Sandec 2017; ETH Zurich SFP and Eawag facility in Dübendorf, CH)

1) Gold,Tomberlin, Diener, Zurbrügg, & Mathys (2018). Waste Management. 82, 302-318.
2) Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144. 285-296.
3) Soomoro , Rehman, Zheng, Cai, Xiao, Hu, Mathys, Gold, Yu & Zhang (2019). Waste Management. 86, 114-122.
4) Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.
5) Aarts, Jansen, Jacobs, Mescher, Prenter, Mathys & De Moraes (2018). Processing of insect larvae. EU patent application. Application No 18175914.3-110
6) Gold, Cassar, Zurbrügg, Kreuzer, Bolus, Diener & Mathys (2019). (under review).

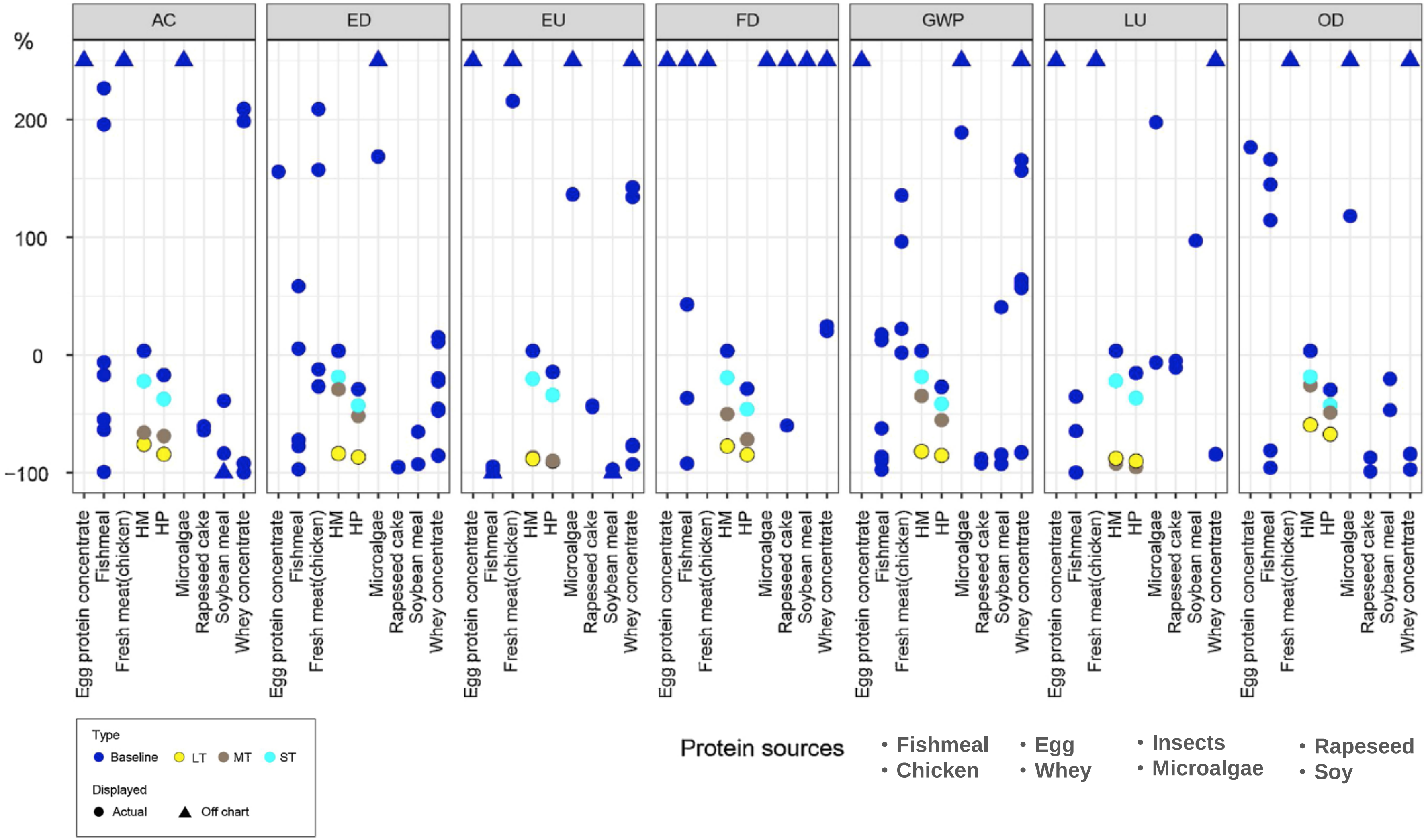
Scaling of the insect based biorefinery for the production of more sustainable food and feed



(Buhler AG & Protix, 2019)

1) Gold,Tomberlin, Diener, Zurbrügg, & Mathys (2018). Waste Management. 82, 302-318.
2) Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144. 285-296.
3) Soomoro , Rehman, Zheng, Cai, Xiao, Hu, Mathys, Gold, Yu & Zhang (2019). Waste Management. 86, 114-122.
4) Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.
5) Aarts, Jansen, Jacobs, Mescher, Prenter, Mathys & De Moraes (2018). Processing of insect larvae. EU patent application. Application No 18175914.3-110
6) Gold, Cassar, Zurbrügg, Kreuzer, Bolus, Diener & Mathys (2019). (under review).

New open environmental sustainability study of most relevant protein sources incl future scenarios



Protein sources

- Fishmeal
- Chicken
- Egg
- Whey
- Insects
- Microalgae
- Rapeseed
- Soy

Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.

Thank you very much to the whole ETH Sustainable Food Processing Group

Acknowledgement

ETH; Department of Health Sciences and Technology & Institute of Food, Nutrition and Health

ETH Sustainable Food Processing & Food Process Engineering Teams

Donors Buhler AG & Migros Industry Support, ETH Foundation, SNF

Partners

SUSTAINABLE FOOD PROCESSING

?

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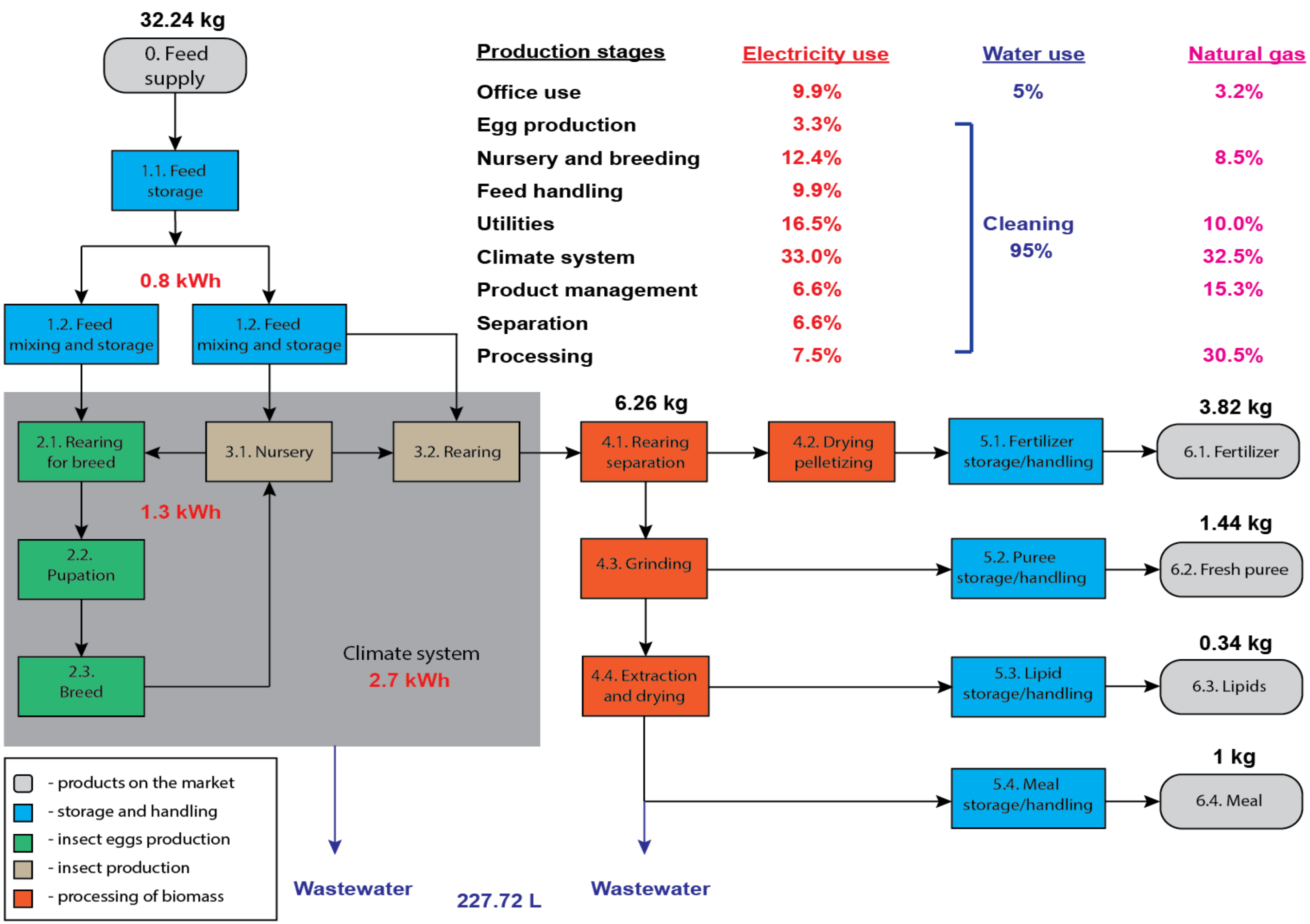
SUSTAINABLE FOOD PROCESSING

New sustainability study of the most advanced Black Soldier Fly factory, Protix, Dongen, Netherlands

Production stages	Electricity use	Water use	Natural gas
Office use	9.9%	5%	3.2%
Egg production	3.3%	Cleaning 95%	
Nursery and breeding	12.4%		8.5%
Feed handling	9.9%		
Utilities	16.5%		10.0%
Climate system	33.0%		32.5%
Product management	6.6%		15.3%
Separation	6.6%		
Processing	7.5%		30.5%



Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.

Table 1 Main inputs in the production of meals used in the study (from cradle to plate)

Product	Resources used per FU (1 kg of ready-to-eat product)				
	Main ingredients	Electricity, MJ[d,g]	Tap water, kg[d]	Transport, kgkm[d,h]	Other[p]
(1) Chicken	1 kg chicken[a]	49.78*	16.3*	850*	–
(2) Dairy based[k]	6 kg skimmed milk[b]	12.27*	4.2*	360*	0.84 kg oat hull fiber[c]
(3) Lab grown[l]	1 kg urea[d]	103.5	420	110	–
(4) Insect based[m]	0.8 kg carrots[d]	10.762[f]	1.34[f]	128.5	0.57 kg grain mix (rye, wheat, barley)[d] 0.048 kg oat hull fiber[c]
(5) Gluten based[e]	1.622 kg wheat grain[d]	8.94	0.954	141.1	0.15 kg oat hull fiber[c]
(6) Soy meal based[n]	0.27 kg soy meal[d]	10.002[f]	0.73[f]	2791*	0.15 kg oat hull fiber[c]
(7) Mycoprotein based[o]	3 kg molasses from sugar beet[d]	21.32	40	215.45	0.069 kg nitrogen fertilizer[d] 0.04 kg egg white

[a] From a supermarket (LCA Food DK), based on live chicken for slaughterhouse (Ecoinvent 3 database)

[b] From dairy (LCA Food DK), water, electricity, and heat inputs are changed (Ecoinvent 3 database)

[c] By-product of oat cereals production, includes 2.3 m^2 of arable land occupation, use of 0.023 kg of nitrogen, 0.0048 kg of phosphate, and 0.0143 kg of potassium fertilizers, and 0.95 MJ of energy for 1 kg production (LCA Food DK, and Ecoinvent 3 database)

[d] Based on a product from Ecoinvent 3 database

[e] van Zeist et al. (2012) and Deng et al. (2013)

[f] Data from DIL e.V. are included

[g] Foster et al. (2006)

[h] Assumed resources transported 50 km to assembly and supermarket, 10 km from a supermarket to the consumer (McEachern and Warnaby 2006)

[i] Assumed, 20 g of oil needed to fry 0.5 kg of product

[j] PYR Ltd (2014)

[k] Berlin (2002), Blonk et al. (2008), and Head et al. (2011)

[l] Tuomisto and De Mattos (2010) and Tuomisto and Roy (2012)

[m] Oonincx and de Boer (2012) and Van Huis et al. (2013)

[n] Berk (1992) and Dalgaard et al. (2008)

[o] Raats (2007) and Finnigan et al. (2010)

[p] Table 1 does not include the data similar for all scenarios

(Smetana, Mathys, Knoch and Heinz, 2015)

LCA of meat and meat substitutes, 1kg of ready to eat product, from cradle to plate

Table 2 The comparison of main characterization results of the study with literature data

Product	Climate change, kg CO_2eq./1 kg (FU)			Land use/occupation, m^2/1 kg (FU)			Non-renewable energy use, MJ/1 kg (FU)		
	This study	Literature data		This study	Literature data		This study	Literature data	
(1) Chicken	5.2–5.82	1.3–1.4	(Katajajuuri et al. 2008; Pelletier 2008; Cederberg et al. 2009)	3.85–3.89	2.1–5.0	(Alig et al. 2012)	51.64–63.4	1.3–14.9	(Williams et al. 2006a, b; Katajajuuri et al. 2008; Pelletier 2008)
		1.6–2.4	(Alig et al. 2012; Wiedemann et al. 2012)					12.8–20.4	At processing gate (Wiedemann et al. 2012)
		1.5–5.5	(Williams et al. 2006a, b)		2.2–7.3	(Williams et al. 2006a, b)		17.3–26.9	(Alig et al. 2012)
								54	(Ellingsen and Aanondsen 2006)
(2) Dairy based	4.38–4.95	3.79–6.2	(Blonk et al. 2008; Head et al. 2011)	3.32–3.41	2.94–3.1	(Blonk et al. 2008; Head et al. 2011)	48.79–59.1	55.5	(Blonk et al. 2008)
(3) Lab grown	23.9–24.64	1.8–2.3	(Tuomisto and de Mattos 2011; Tuomisto and Roy 2012)	0.39–0.77	0.18–0.23	(Tuomisto and de Mattos 2011; Tuomisto and Roy 2012)	290.7–373	25.2–31.8	(Tuomisto and de Mattos 2011)
		10	Proteins (Tuomisto and Roy 2012)					31,700	(Tuomisto and Roy 2012)
(4) Insect based	2.84–3.02	2.7	Fresh insects (Oonincx and de Boer 2012);	1.5–1.52	3.6	Fresh insects (Oonincx and de Boer 2012)	32.0–40.4	34	Fresh insects (Oonincx and de Boer 2012)
		20	Proteins (Van Huis et al. 2013)		18	Proteins (Van Huis et al. 2013)		170	Proteins (Van Huis et al. 2013)
(5) Gluten based	3.59–4.03	1.55	Gluten powder (Deng et al. 2013)	5.5–5.82	2.07	Gluten powder (Deng et al. 2013)	39.7–49.2	1.4–1.7	Wheat (Nemecek et al. 2001)
								2500	Edible wheat (Tuomisto and Roy 2012)
(6) Soy meal based	2.65–2.78	2.54–3.72	Tofu (Head et al. 2011)	1.06–1.44	1.95–2.49	Tofu (Head et al. 2011)	27.78–36.9	1.5–2.3	Soy (Pelletier et al. 2008)
		0.34–0.9	Soy meal (Dalgaard et al. 2008)		3.0–3.6	Soy meal (Dalgaard et al. 2008)		3000	Edible soy (Tuomisto and Roy 2012)
(7) Mycoprotein based	5.55–6.15	2.4–2.6	(Blonk et al. 2008; Head et al. 2011)	0.79–0.84	0.41–1.2	(Blonk et al. 2008; Head et al. 2011)	60.07-76.8	38.0	(Blonk et al. 2008)

(Smetana, Mathys, Knoch and Heinz, 2015)

Sustainability metrics for nutrition with the example of LCA of bread/pasta with pulses

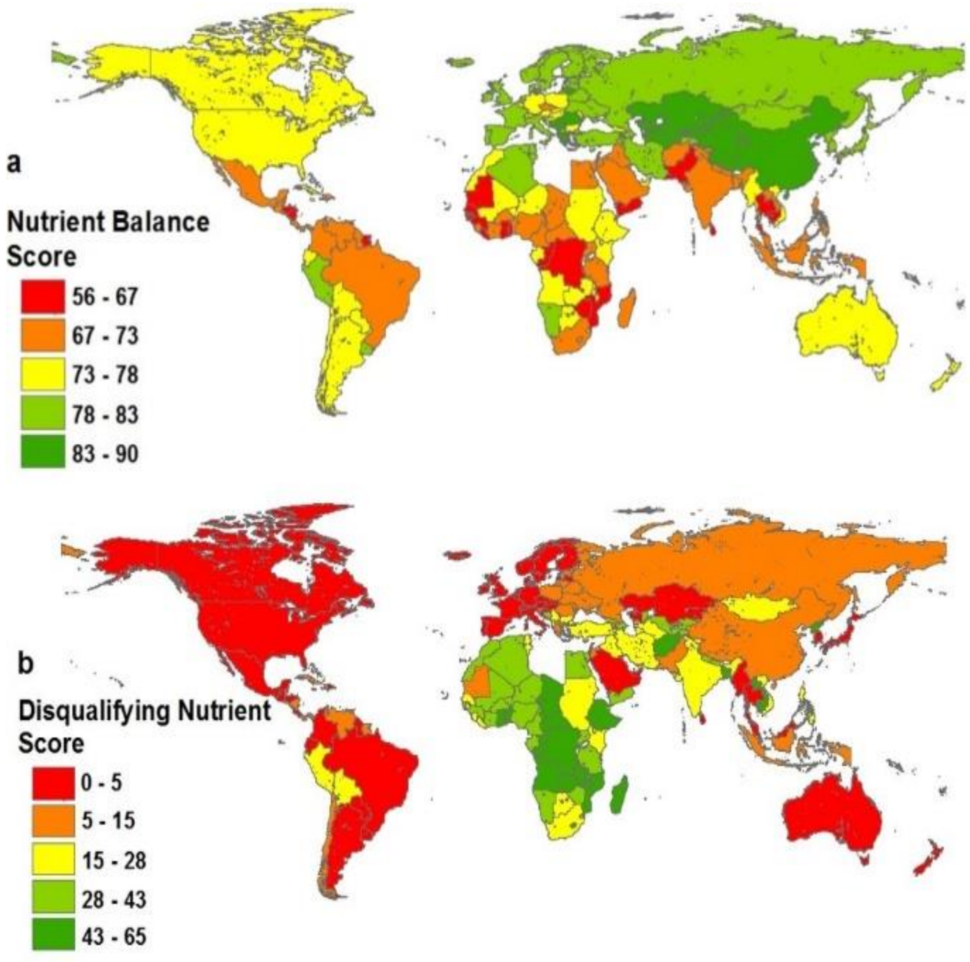
Breakout session “Sustainable Nutrition“

27. August 2019, Buhler Campus

Prof. Dr.-Ing. Alexander Mathys

ETH Zurich

Multi Indicator Sustainability Assessment - Nutrient Balance Score and Disqualifying Nutrient Score



Nutrient Balance Score NBS

$$\mathrm{QI}_{q,k} = \frac{2000}{E_k} \cdot \frac{a_{q,k}}{\mathrm{DRI}_q}$$

$$\mathrm{NB}_k = 100 \cdot \left(\frac{\sum_{q=1}^{25} \mathrm{QI}_{q,k}}{N_q} \right)$$

where: $QI_{q,k}$ is the value for the Qualifying Index (QI) of an individual nutrient q in the country k and N_q is the number of qualifying nutrients considered (=25), Daily Reference Intakes DRI, E_k is the total daily caloric intake for country k, $a_{q,k}$ is the daily intake amount of a qualifying or disqualifying food nutrient q in country k

Disqualifying Nutrient Score DNS

$$\mathrm{DI}_{d,k} = 100 \cdot \left(\frac{2000}{E_k} \cdot \frac{a_{d,k}}{\mathrm{MRV}_d} \right)$$

$$\mathrm{DNS}_k = 100 \cdot \left[1 - \left(\frac{\sum_{d=1}^{4} \mathrm{DI}_{d,k}}{N_d} \right) \right]$$

Disqualifying Index DI for each of the four public health-sensitive nutrients d(sugar, cholesterol, saturated fat,& total fat) as the ratio of their amounts contained in 2000 kcal of a given country’s diet, and their MRV for those nutrients

(Chaudhary, Gustafson and Mathys 2018, Nature Communications)

Multi Indicator Sustainability Assessment - A case study on pulse integration into food commodities

Pulse Canada

nutrients

MDPI

Article

Nutritional Combined Greenhouse Gas Life Cycle Analysis for Incorporating Canadian Yellow Pea into Cereal-Based Food Products

Abhishek Chaudhary [1,*], Christopher P. F. Marinangeli [2], Denis Tremorin [2] and Alexander Mathys [1]

- Incorporating low cost pulses, such as yellow peas, that are rich in nutrients and low in fertilizer requirements, into daily food items, can improve the nutritional and sustainability profile of national diets.
- Results showed that partial replacement of refined wheat flour with yellow pea flour increased the nutrient balance score (NBS, 27 macro- and micronutrients) of pan bread, breakfast cereal, and pasta by 11%, 70%, and 18%, and decreased the life cycle carbon footprint (kg CO2 eq/kg) by 4%, 11%, and 13%, respectively.
- The nutritional and greenhouse gas (GHG) data were combined as the nutrition carbon footprint score (NCFS) (NBS/g CO2 per serving), a novel indicator that reflects product-level nutritional quality per unit environmental impact.
- Results showed that yellow pea flour increased the NCFS by 15% for pan bread, 90% for breakfast cereal, and 35% for pasta.

(Chaudhary, Marinangeli, Tremorin and Mathys 2018)

Multi Indicator Sustainability Assessment - A case study on pulse integration into food commodities

Table 3. The effect of reformulation with whole yellow pea flour on the nutritional profile and carbon footprint of pan bread, breakfast cereals, and pasta.

Product	% of Total Flour per Formulation *		Indices of Nutritional Quality			Carbon Footprint		NCFS
	Wheat Flour	Yellow Pea Flour	QI	DI	NBS (%)	kg CO_2 eq/kg Food	g CO_2 eq/Serving †	(NBS/ g CO_2 eq/Serving)
Pan Bread								
Traditional *	100	0	0.62	0.40	47	0.405	31.70	1.49
Reformulated	85	15	0.70	0.40	52	0.389	30.43	1.72
Breakfast Cereal								
Traditional	100	0	0.40	0.17	30	0.979	32.99	0.91
Reformulated	47	53	0.76	0.20	51	0.875	29.47	1.73
Pasta								
Traditional	100	0	0.57	0.03	43	0.610	65.20	0.67
Reformulated	70	30	0.74	0.04	51	0.532	56.85	0.90

CO_2 eq: carbon dioxide equivalents; DI: disqualifying index; NBS: nutrient balance score; NCFS: nutrition carbon footprint score; QI: qualifying index. * Traditional formulations contain refined wheat flour (see Table 1). In reformulated foods, a proportion of refined wheat flour was replaced by whole yellow pea flour (15% for pan bread, 53% for the breakfast cereal, and 30% for the pasta). † Serving sizes correspond to the Reference Amounts outlined by the Government of Canada [29]: pan bread, 75 g; breakfast cereal (low density: 20 g to 42 g per 250 mL; without milk), 30 g; pasta (dry), 85 g.

(Chaudhary, Marinangeli, Tremorin and Mathys 2018)

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Multi Indicator Sustainability Assessment - A case study on pulse integration into food commodities

Table 4. Greenhouse gas emissions associated with each stage of the production of 1 kg of traditional and reformulated bread, breakfast cereals, and pasta.

Food	Formulation *	Cultivation Stage		Milling Stage		Manufacturing Stage		Total	
		kg CO_2 eq	% of Total	kg CO_2 eq	% of Total	kg CO_2 eq	% of Total	kg CO_2 eq	% Difference
Pan Bread	Traditional	0.242	60	0.022	5	0.141	35	0.405	
	Reformulated	0.224	58	0.024	6	0.141	36	0.389	−4%
Breakfast Cereal	Traditional	0.440	45	0.040	4	0.498	51	0.979	
	Reformulated	0.322	37	0.052	6	0.498	57	0.873	−11%
Pasta	Traditional	0.518	85	0.025	4	0.068	11	0.610	
	Reformulated	0.427	80	0.036	7	0.068	13	0.531	−13%

* Traditional formulations contain refined wheat flour (Table 1). In the reformulated foods, a proportion of the total flour was whole yellow pea flour (pan bread: 15%; breakfast cereal, 53%; pasta: 30%). CO_2 eq, carbon dioxide equivalents.

(Chaudhary, Marinangeli, Tremorin and Mathys 2018)

Including nutrition quality in food LCA or sustainability assessment

Nutrient Balance Score (NBS). The Nutrient Balance Score (0<NB<100) of each country's daily diet is:

$$NB_k = 100 \cdot \left(\frac{\sum_{q=1}^{25} QI_{q,k}}{N_q} \right) \qquad \text{Eq. 1}$$

where: $QI_{q,k}$ is the value for the Qualifying Index (QI) of an individual nutrient *q* in the country *k* and *Nq* is the number of qualifying nutrients considered (=25).

A NB score of 100 is achieved a diet satisfies at least 100% of the daily dietary requirement for every qualifying nutrient. Conversely, a value of 0 implies that none of the qualifying nutrients are contained in the diet.

(Fern et al. 2014, PLoS ONE; Chaudhary, Gustafson and Mathys 2018, Nature Communications

Including nutrition quality in food LCA or sustainability assessment

The **Qualifying Index** is defined as the ratio of a particular nutrient's amount contained in 2000 kcal of a given food/meal/diet relative to the Reference Daily Intakes for those nutrients:

$$QI_{q,k} = \frac{2000}{E_k} \cdot \frac{a_{q,k}}{DRI_q}$$

Eq. 2

Here E_k is the total daily caloric intake for country *k* (in kcal capita^{-1} day^{-1}) and $a_{q,k}$ is the daily intake amount of a qualifying food nutrient *q* in country *k* (in g capita^{-1} day^{-1}).

If the QI for a given nutrient is > 1, then the value is truncated to 1 on the rationale that once the requirement for a specific qualifying nutrient is met ($QI_{q,k}$ = 1.0) any further provision of that nutrient does not serves additional nutrition function.

following 25 essential (qualifying) food nutrients: Folate, Niacin, Pantothenic acid, Riboflavin, Thiamin, Calcium, Copper, Iron, Mg, Mn, P, K, Se, Zn, Linoleic acid, Choline, Dietary Fiber, Protein, and Vitamins A, B-6, B-12, C, D, E, and K.

The four nutrients of concern (disqualifying nutrients) included in this analysis and recognized as potentially having adverse effects on health and for which necessary data are available were as follows: sugar, total fats, saturated fats, and cholesterol.

(Fern et al. 2014, PLoS ONE; Chaudhary, Gustafson and Mathys 2018, Nature Communications