UNIVERSITY OF STIRLING

Protein Sustainability in Aquafeeds Workshop

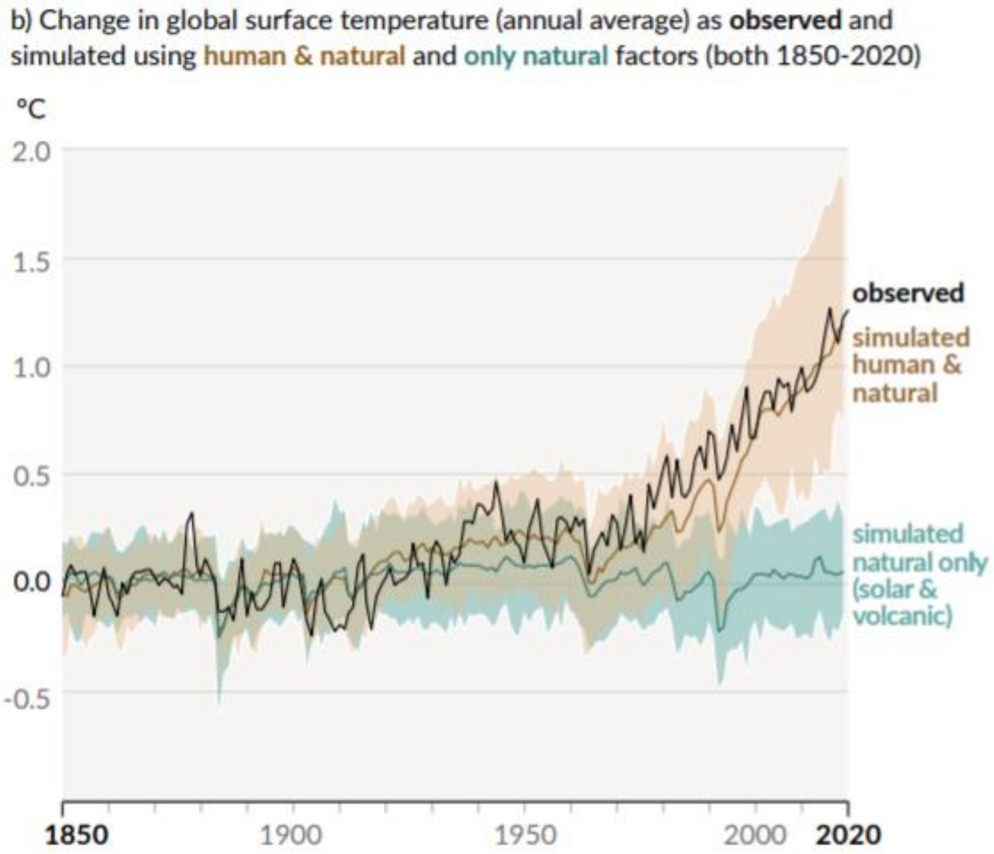
Sorrento, 5th June 2022

How to Assess Ingredient Sustainability

Richard Newton, University of Stirling

Why measure sustainability?

- Environmental impact high in consumer consciousness
- Retail and consumer organisations want more transparency over responsible sourcing of products
- EU looking to benchmark products – Product Environmental Footprint (PEF) “Single market for green products”
- Certification bodies want to develop more harmonised sustainability metrics
- Value chain actors want more traceability concerning sustainability

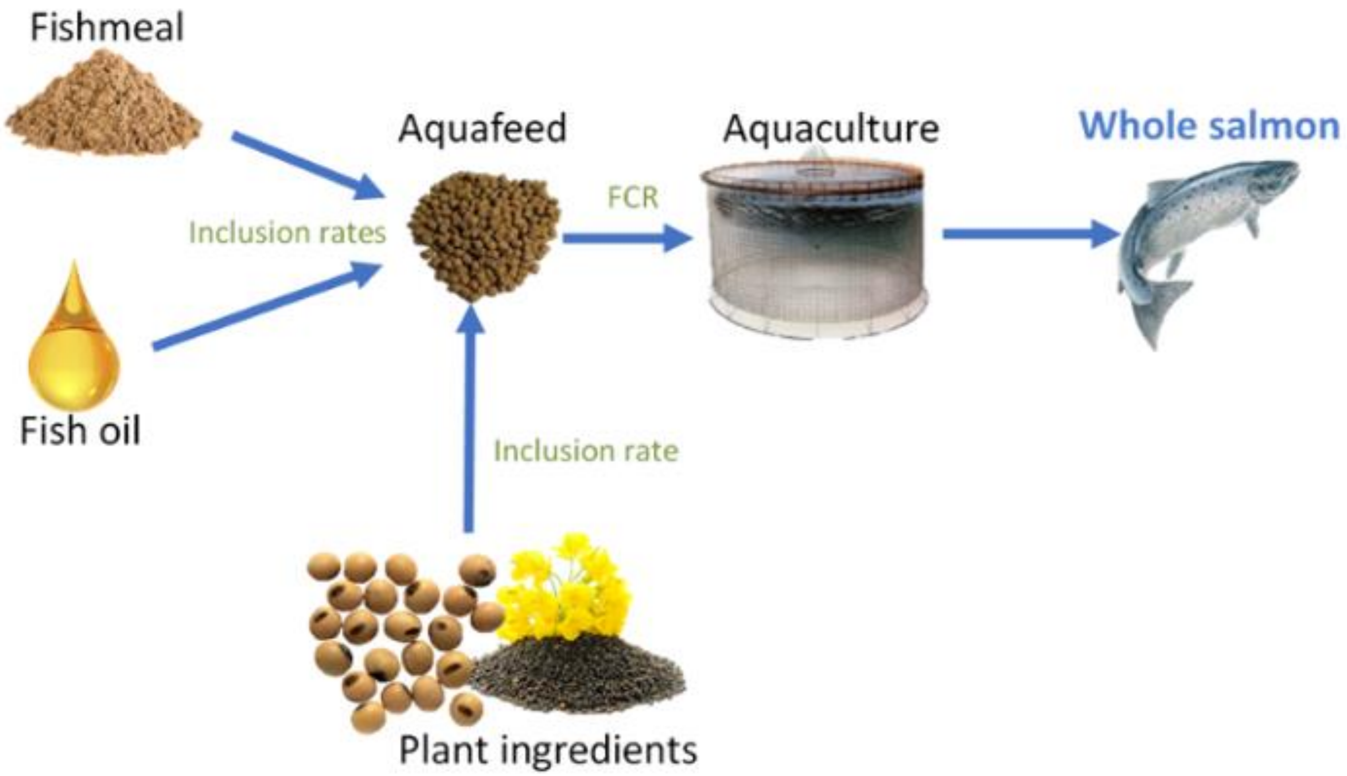


IPCC 2021 – Climate Change Report

Aquafeeds sustainability journey

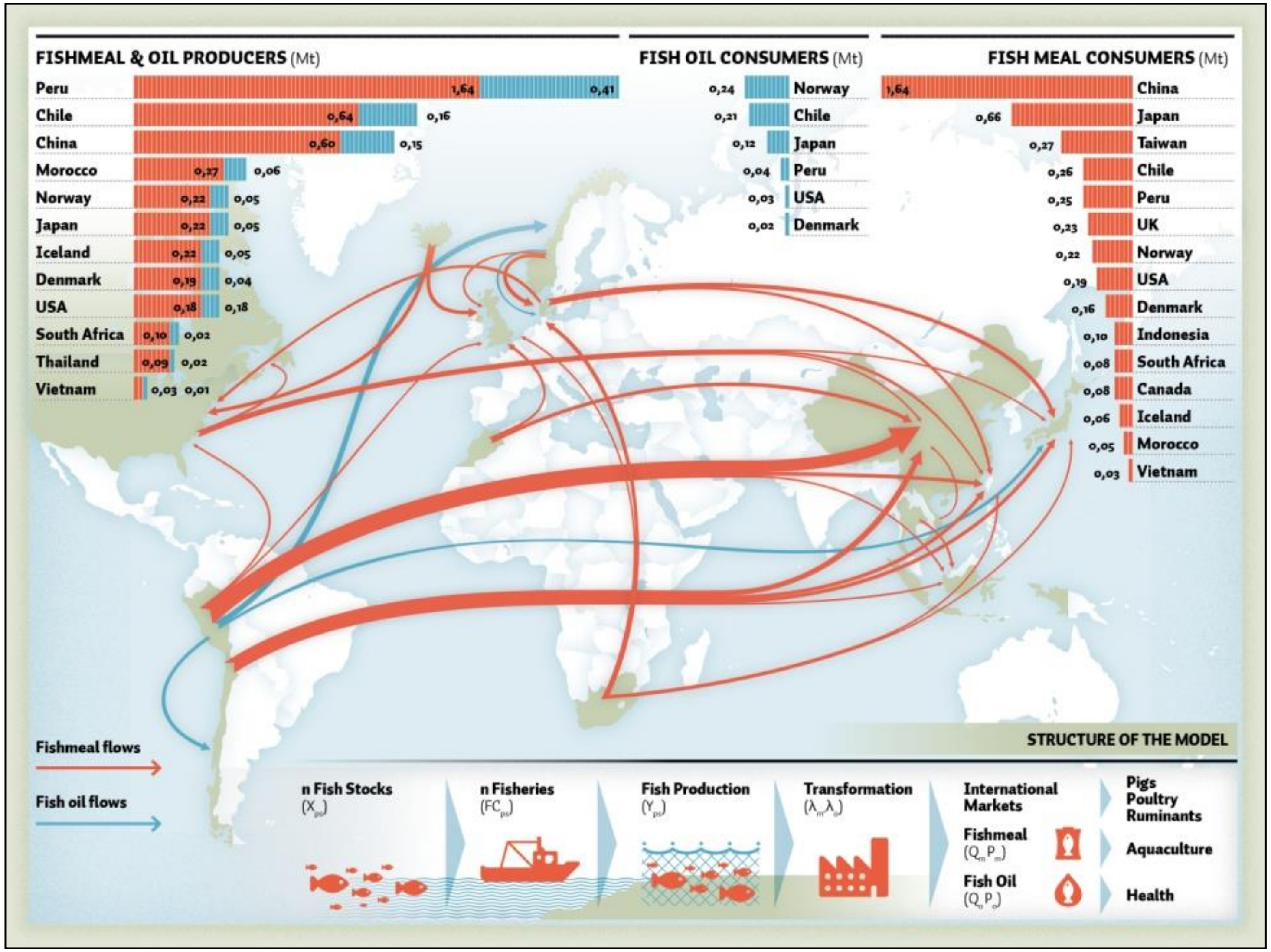
- Early days of carnivorous fish feeds largely made from marine ingredients (MIs)
- Low volumes of plant ingredients for binders

- Growth in aquaculture led to pressures on MI supply



Aquafeeds sustainability journey

- Rapid expansion of aquaculture across the world
- Carnivorous species dependent on MIs
- Large volumes of species with low MI inclusion added to pressure



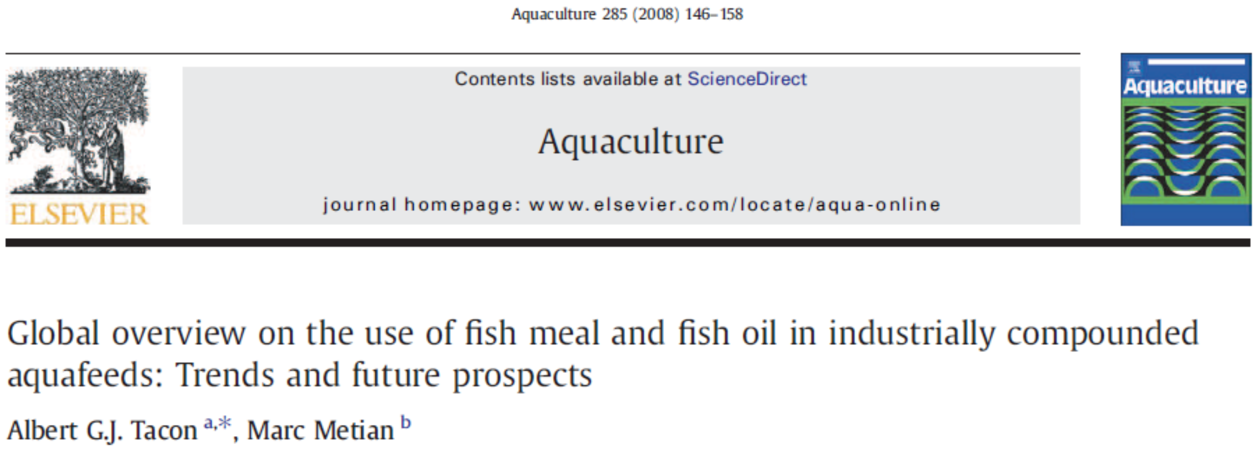
Merino *et al* 2010

Growing concerns over marine ingredients in aquafeed

Effect of aquaculture on world fish supplies

Rosamond L. Naylor[*], Rebecca J. Goldburg[†], Jurgenne H. Primavera[‡], Nils Kautsky[§||], Malcolm C. M. Beveridge[¶], Jason Clay[#], Carl Folke[§||], Jane Lubchenco[☆], Harold Mooney[*] & Max Troell[§||]

NATURE | VOL 405 | 29 JUNE 2000 | www.nature.com



Aquaculture 285 (2008) 146–158

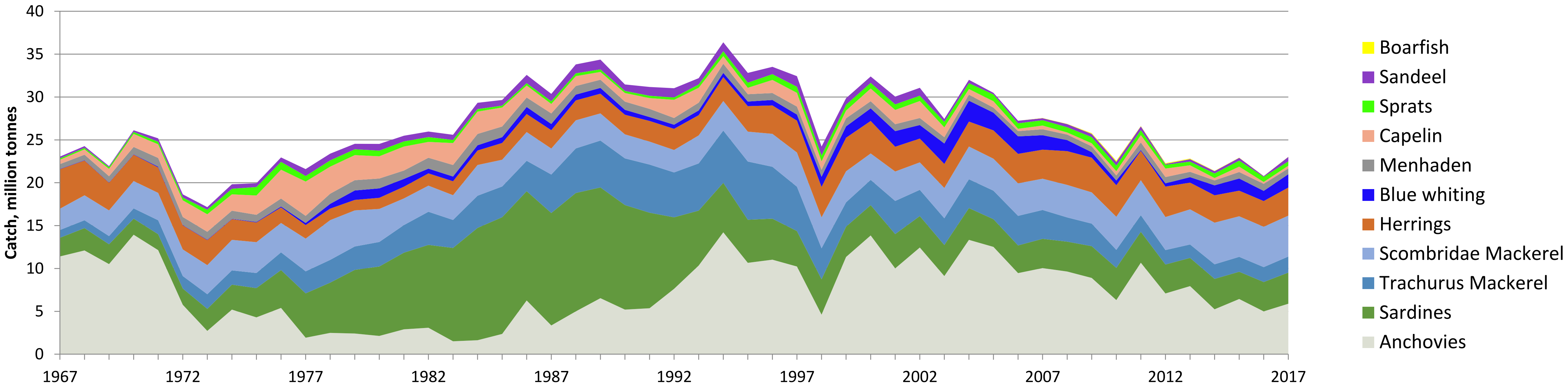
Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

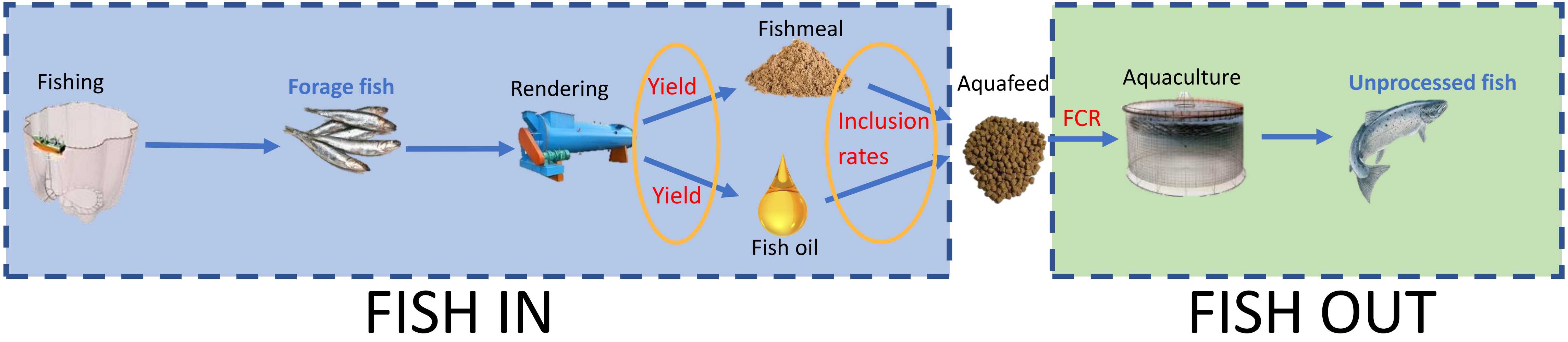
Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects

Albert G.J. Tacon [a,*], Marc Metian [b]



- Growing number of studies measuring wild fish needed to produce aquaculture species
- The birth of the Fish In: Fish Out ratio

What is FIFO?



- FIFO is a ratio between the amount of wild fish required to make the marine ingredients in the aquafeed required to grow fish from aquaculture
- It is a function of the yields of fishmeal and oil from wild fish, their inclusion rates and the Feed Conversion Ratio
- There are several versions of the FIFO ratio that have been used
- A key point of contention is that the Yields are not in the same proportion to the Inclusion rates for most aquaculture species

Fishmeal and fish oil yields

Meal and oils	Source	Meal yield,%	Oil yield,%
Whole fish			
Anchoveta (Engraulis ringens)	Fréon et al. 2017	23.8	4.5
Blue whiting (Micromesistius poutassou)	Cashion et al. 2017	19.7	1.9
Capelin (Mallotus villosus)	Cashion et al. 2017	16.6	7.7
Atlantic herring (Clupea harengus)	Cashion et al. 2016	22.1	11.5
Atlantic mackerel (Scomber scombrus)	Cashion et al. 2016	19.4	18.6
Norway Pout (Trisopterus esmarkii)	Cashion et al. 2016	20.4	11.5
Sandeel (Ammodytes marinus)	Danish Food LCA	21.5	4.5
California pilchard (Sardinops sagax)	Cashion et al. 2017	23.0	18.0
Gulf Menhaden (Brevoortia patronus)	Cashion et al. 2017	21.0	16.0
Atlantic horse mackerel (Trachurus trachurus)	Tacon et al. 2006	23.0	6.0
European sprat (Sprattus sprattus)	Cashion et al. 2017	18.8	7.9
Sardine (Sardina pilchardus)	Cashion et al. 2017	23.0	18.0
Krill (Euphausia superba)	Parker and Tyedmers 2012	14.4	0.07
Indian Oil Sardine (Sardinella longiceps)	Sanaputi et al. 2017, Pravinkumar et al. 2015	25.7	15.4
Byproducts			
White fish (Gadus morhua, Melanogrammus aeglefinus)	Cashion et al. 2017	17.0	1.7
Pelagics (Clupea harengus, Scomber scombrus)	Hilmarsdottir et al. 2020	22.5	17.0

FFDR and FIFO

- Forage Fish Dependency Ratio (FFDR) separates fish meal and fish oil into separate equations

$$\mathrm{FFDR}_{\mathrm{fm}} \frac{Fishmeal\ inclusion\%}{Fishmeal\ yield\%} \times \mathrm{FCR}$$

- Early FIFO used similar equations to FFDR so that the limiting ingredient dictates the FIFO
- E.g. Using anchovy as an example, a feed with 45% meal and 25% oil, FCR of 1.25
- $\mathrm{FFDR}_{\mathrm{fm}} = \frac{45}{23.8} \times 1.25 = \mathbf{2.36}$ $\mathrm{FFDR}_{\mathrm{fo}} = \frac{25}{4.5} \times 1.25 = \mathbf{6.94}$

- Early FIFOs presented the larger figure and didn’t account for the “spare” fish
- Aquaculture is “dependent” on 6.94 kg of forage fish for every kg produced

FFDR and FIFO

- FIFO method introduced by Andy Jackson to account for “spare fish”
- Merges the requirement for meal and oil

$$\frac{Fishmeal\ inclusion\%+Fish\ oil\ inclusion\%}{Fishmeal\ yield\%+fish\ oil\ yield\%} \text{ x FCR}$$

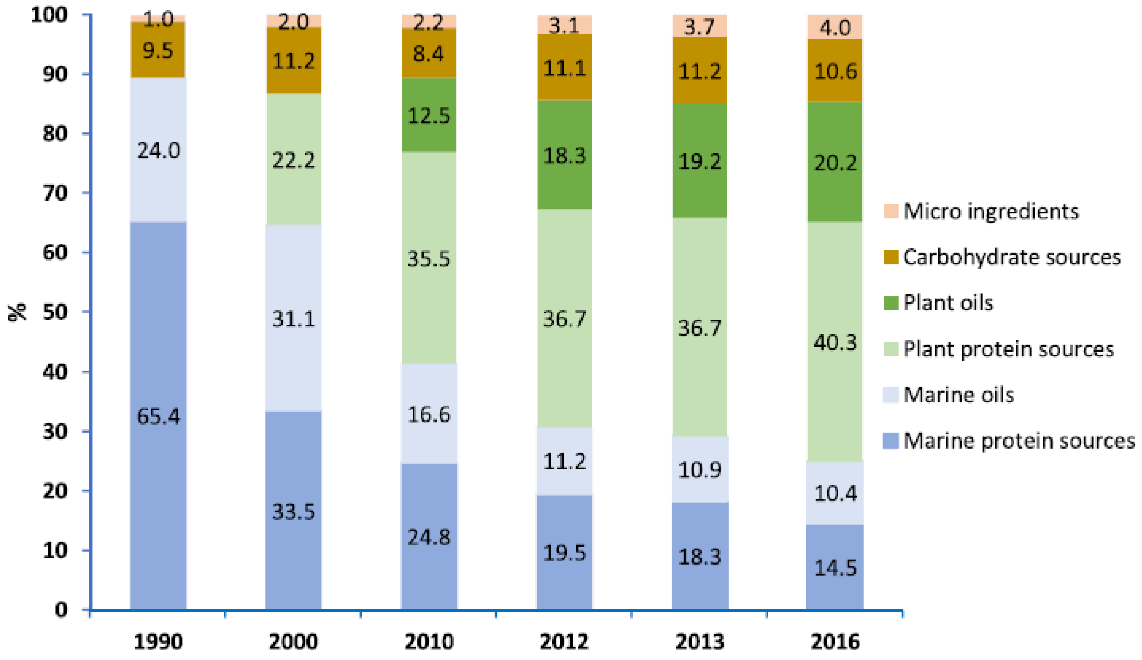
- E.g. Using anchovy as an example, a feed with 45% meal and 25% oil, FCR of 1.25

$$\frac{45+25}{23.8+4.5} \text{ x } 1.25 = \mathbf{3.09}$$

- A measure of “efficiency” rather than dependence
- But does not include the increasing contribution from by-products

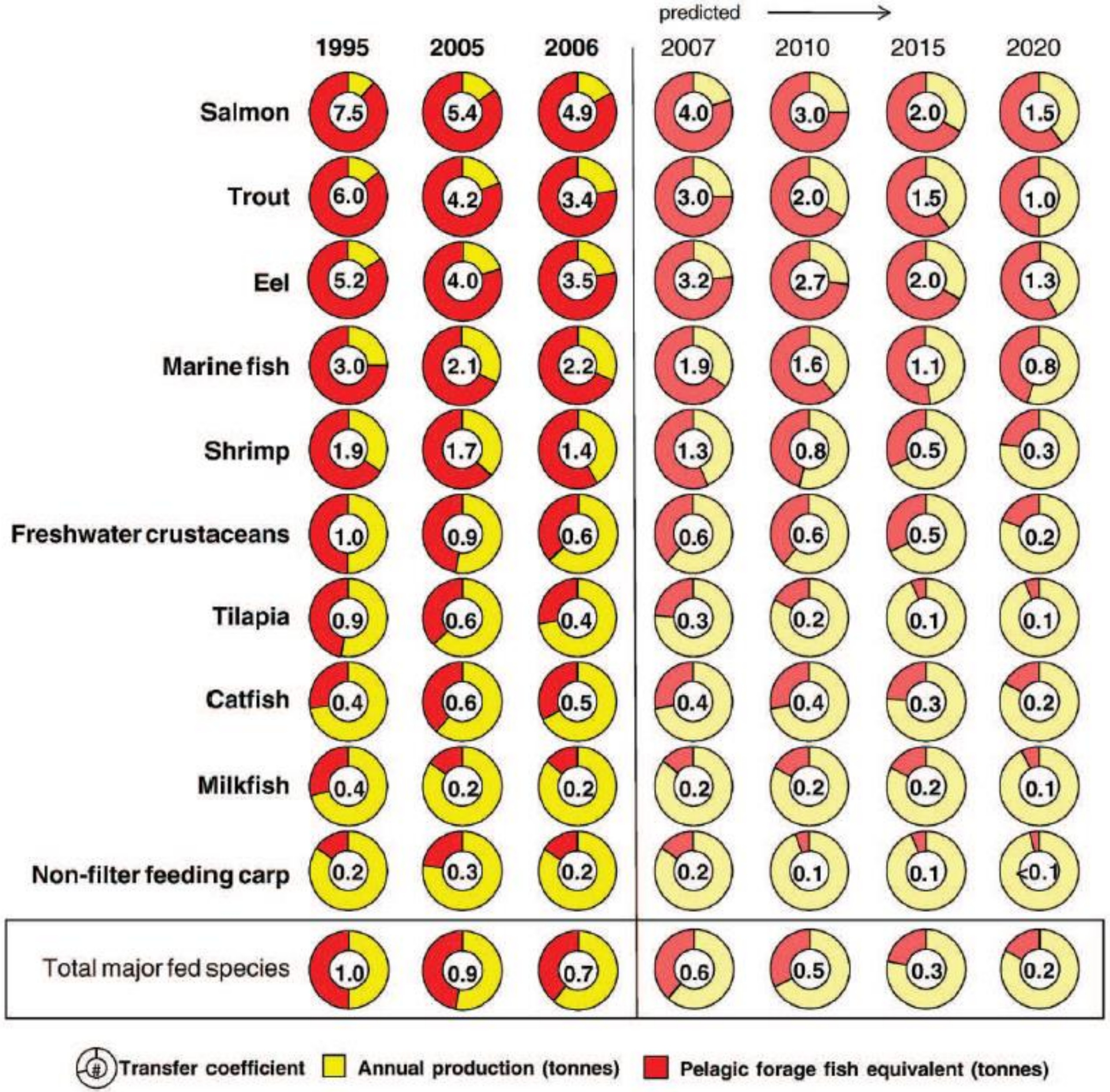
Long term trends

- Growing aquaculture industry
- Static/reducing MI supply
- Higher costs of MI
- Poor public perception
- Reduced inclusion rates



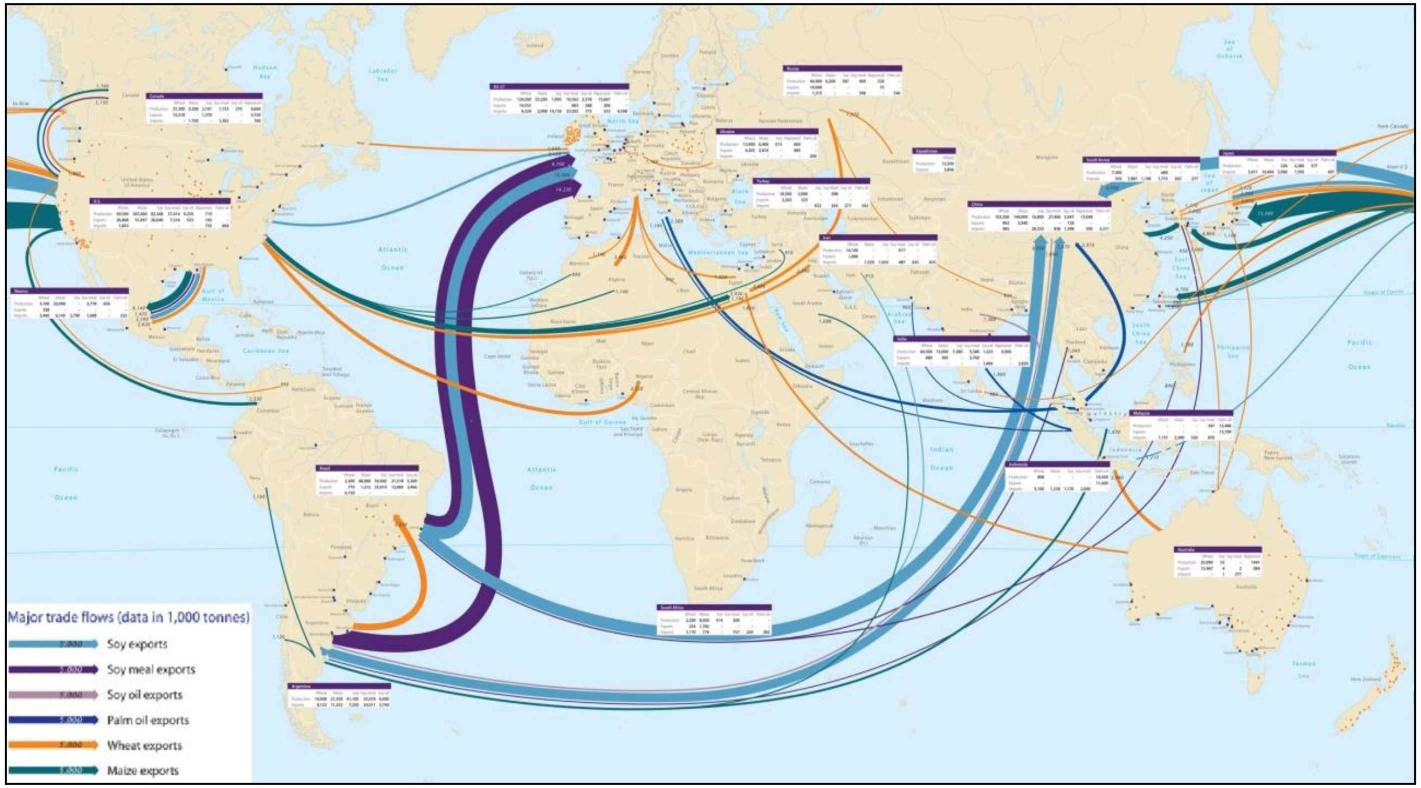
Aas et al 2019

FIFOs of major aquaculture species

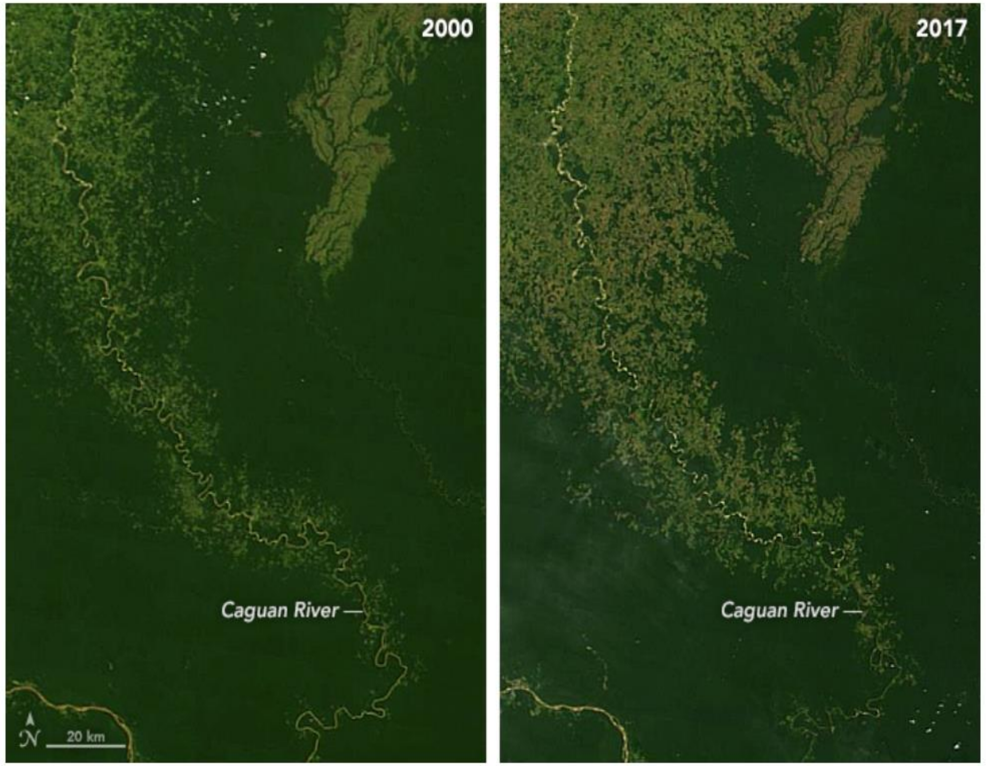


Tacon and Metian 2008

Fine, so what about the substitutes??



http://www.rabobank.com/content/research/FoodAndAgriResearch/grains_and_oilseeds/tab4.jsp 2014

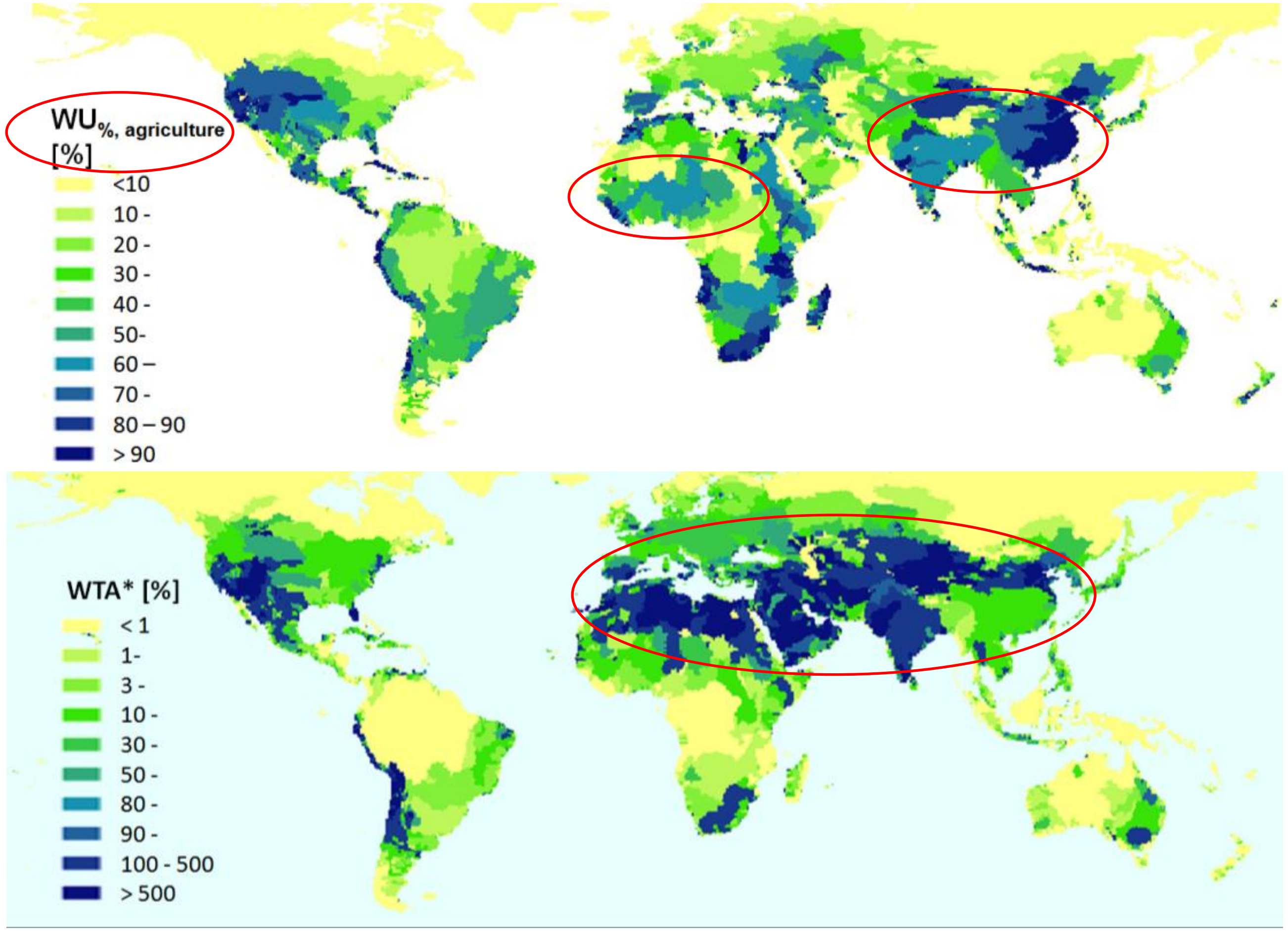


Land use change in Brazil from 2000 to 2017 linked to soyabean and cattle ranching (source: Nasa accessed 8/5/21)

- Habitat loss, loss of CO_2 sequestration, GHG emissions through mineralisation of organic matter, application of fertilisers etc.
- Land use is the amount of land used per year in m^2
- LUC is the effect on C footprint caused by forest clearance etc.

Fresh water use

- Leads to salinisation, sanitation problems, drought, other environmental and public health issues
- Many areas extracting more water than is recharged
- Mostly used for agriculture



a) % Water used for agriculture, b) Global water scarcity factor (WTA*); extraction to availability.
Source: Pfister *et al* 2011

We need a broader measure of sustainability than just FIFO! - LCA

Carbon Footprint and much more!

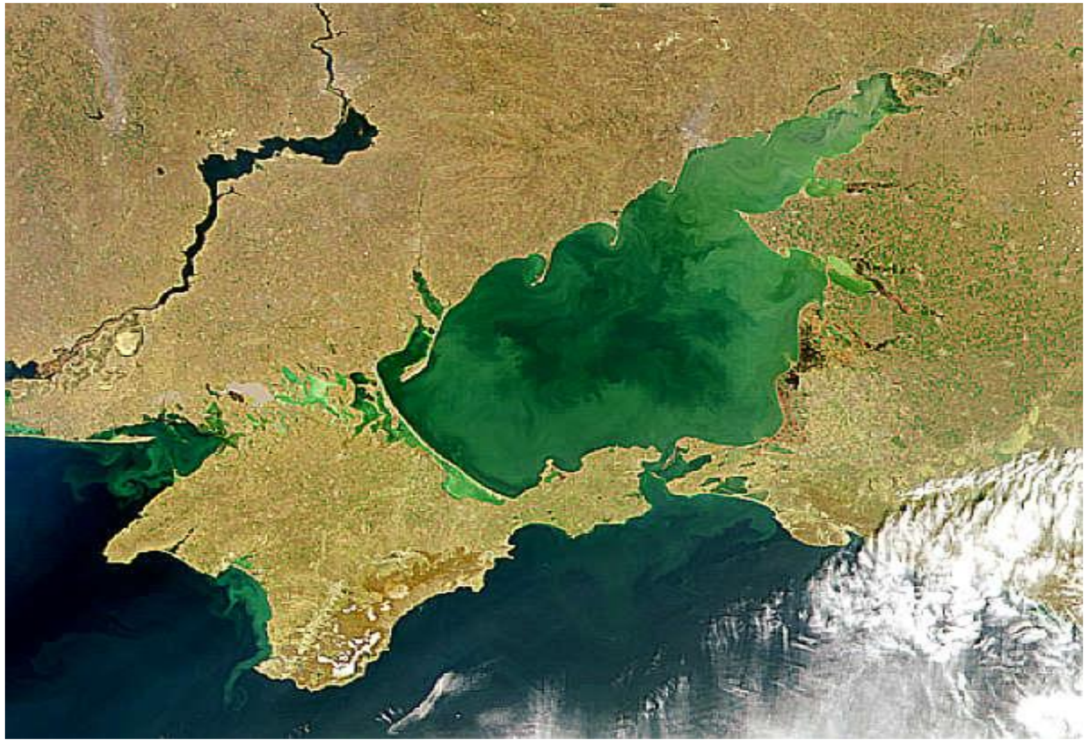
- Global Warming Potential (carbon footprint)

LCA impact categories

- Acidification Potential

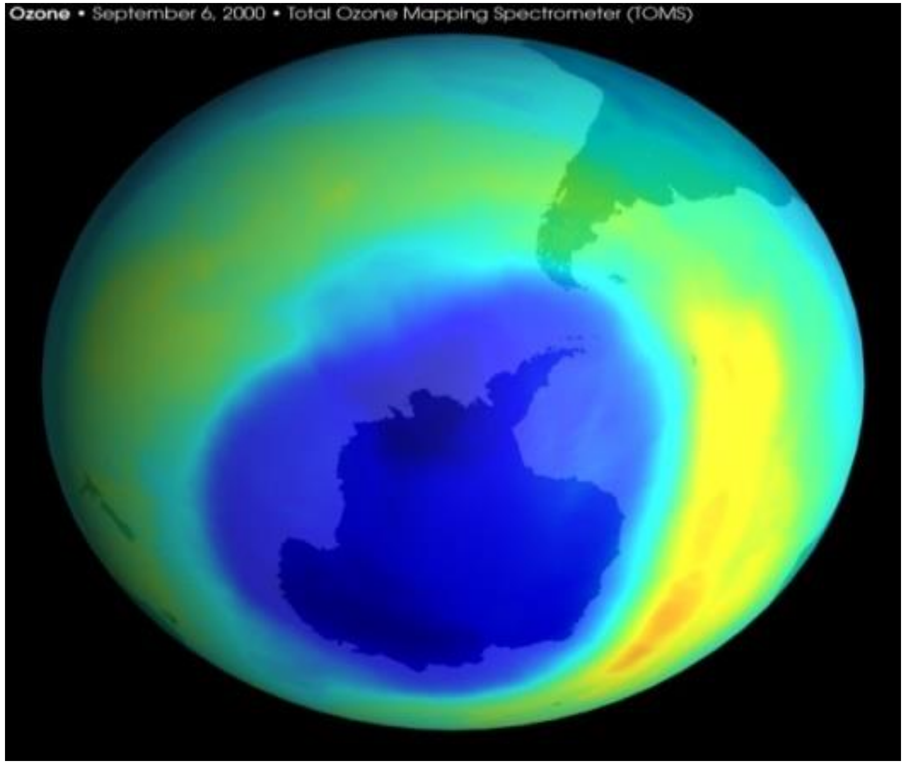
LCA impact categories

- Eutrophication Potential



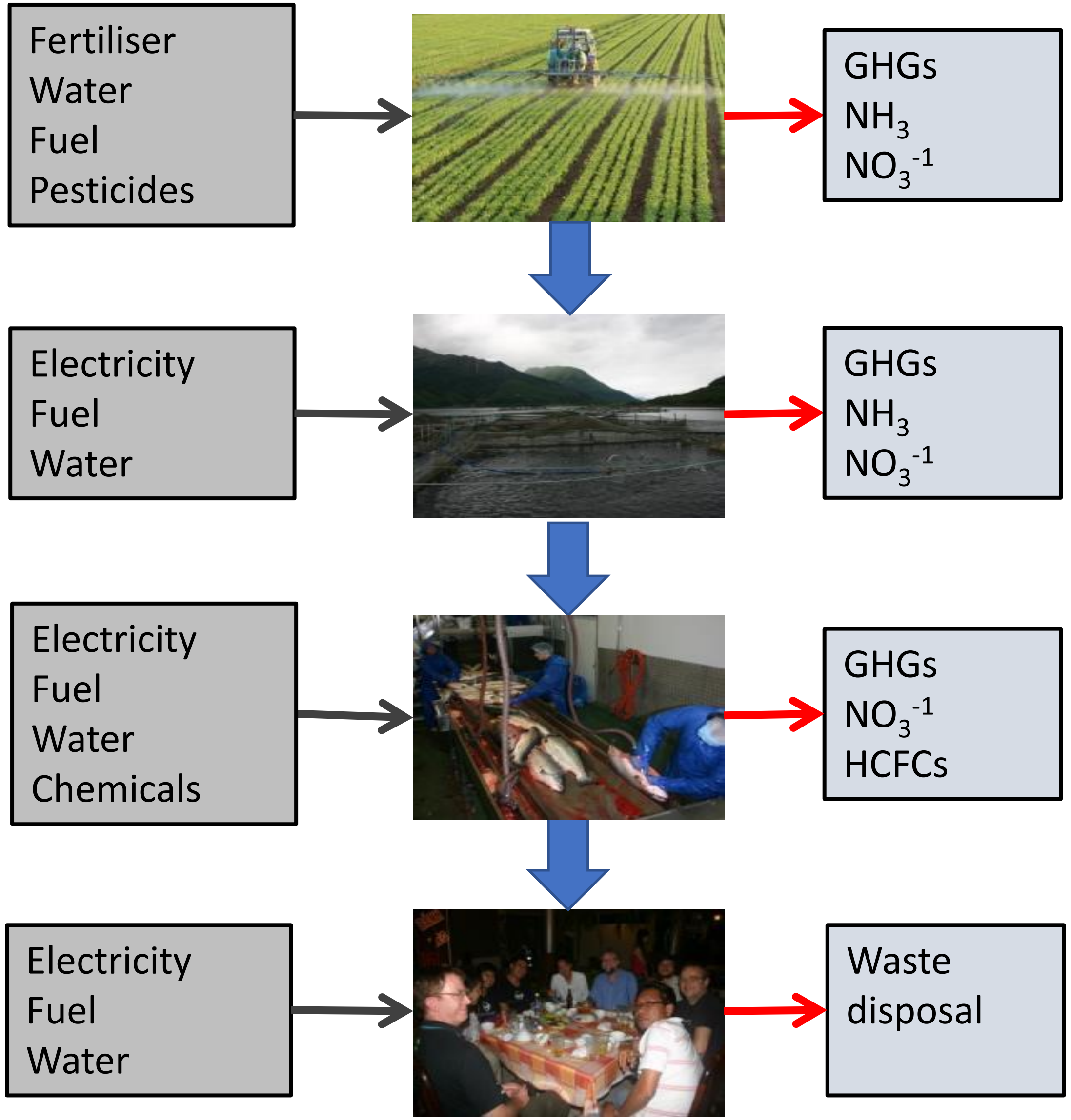
LCA impact categories

- Ozone Depletion Potential



Life cycle approach to impact assessment - LCA

- Environmental impacts do not just occur on the production unit
    - Feed ingredients
    - Feed processing
    - On farm production
    - Processing
    - Distribution
    - Consumption
    - Waste disposal
- All require land, water, raw materials and energy, and can lead to harmful emissions



Fertiliser
Water
Fuel
Pesticides

GHGs
NH_3
NO_3^{-1}

Electricity
Fuel
Water

GHGs
NH_3
NO_3^{-1}

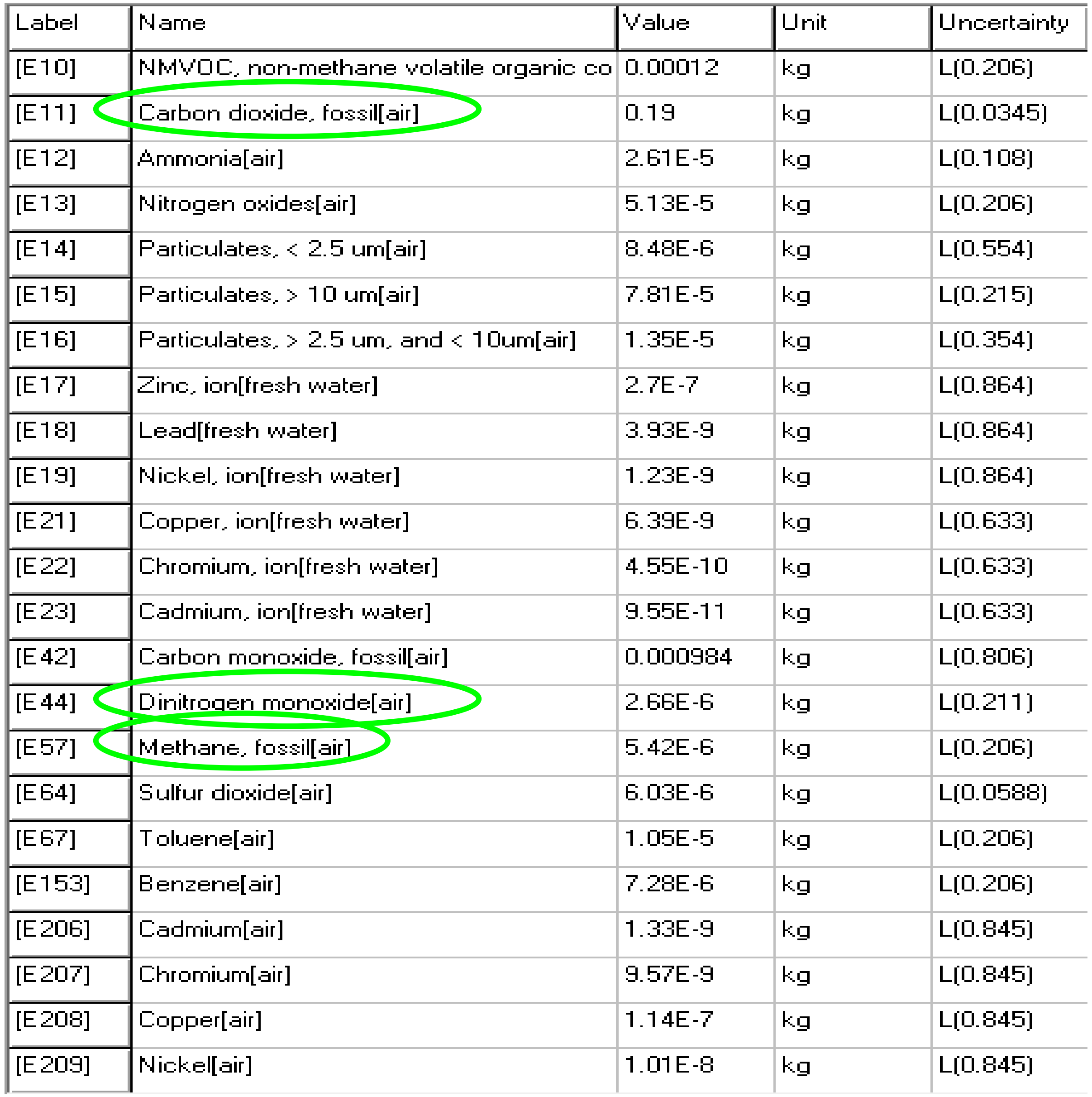
Electricity
Fuel
Water
Chemicals

GHGs
NO_3^{-1}
HCFCs

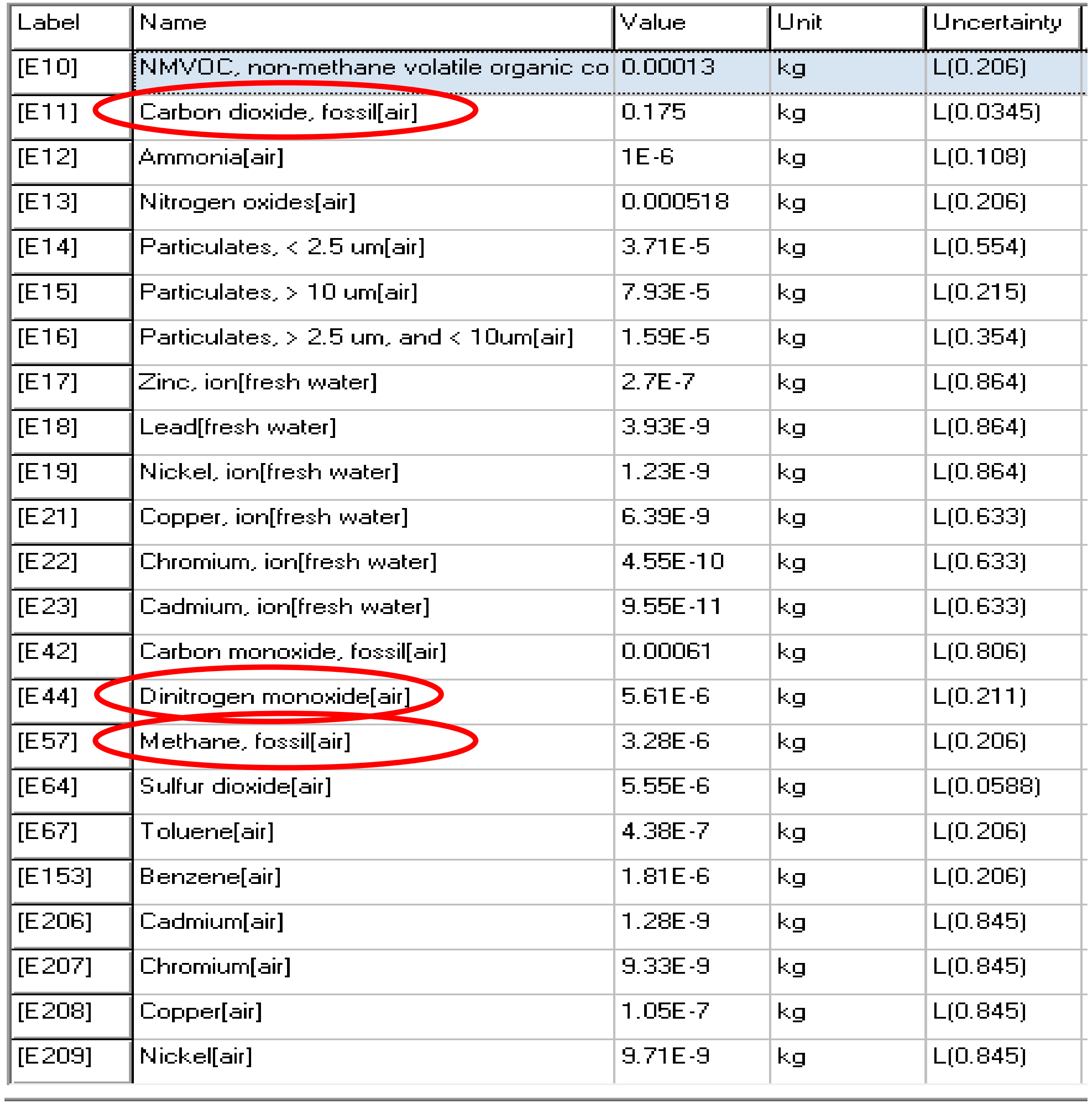
Electricity
Fuel
Water

Waste disposal

Life Cycle Inventories – only part of the story



Label	Name	Value	Unit	Uncertainty
[E10]	NMVOC, non-methane volatile organic co	0.00012	kg	L(0.206)
[E11]	Carbon dioxide, fossil[air]	0.19	kg	L(0.0345)
[E12]	Ammonia[air]	2.61E-5	kg	L(0.108)
[E13]	Nitrogen oxides[air]	5.13E-5	kg	L(0.206)
[E14]	Particulates, < 2.5 um[air]	8.48E-6	kg	L(0.554)
[E15]	Particulates, > 10 um[air]	7.81E-5	kg	L(0.215)
[E16]	Particulates, > 2.5 um, and < 10um[air]	1.35E-5	kg	L(0.354)
[E17]	Zinc, ion[fresh water]	2.7E-7	kg	L(0.864)
[E18]	Lead[fresh water]	3.93E-9	kg	L(0.864)
[E19]	Nickel, ion[fresh water]	1.23E-9	kg	L(0.864)
[E21]	Copper, ion[fresh water]	6.39E-9	kg	L(0.633)
[E22]	Chromium, ion[fresh water]	4.55E-10	kg	L(0.633)
[E23]	Cadmium, ion[fresh water]	9.55E-11	kg	L(0.633)
[E42]	Carbon monoxide, fossil[air]	0.000984	kg	L(0.806)
[E44]	Dinitrogen monoxide[air]	2.66E-6	kg	L(0.211)
[E57]	Methane, fossil[air]	5.42E-6	kg	L(0.206)
[E64]	Sulfur dioxide[air]	6.03E-6	kg	L(0.0588)
[E67]	Toluene[air]	1.05E-5	kg	L(0.206)
[E153]	Benzene[air]	7.28E-6	kg	L(0.206)
[E206]	Cadmium[air]	1.33E-9	kg	L(0.845)
[E207]	Chromium[air]	9.57E-9	kg	L(0.845)
[E208]	Copper[air]	1.14E-7	kg	L(0.845)
[E209]	Nickel[air]	1.01E-8	kg	L(0.845)



Label	Name	Value	Unit	Uncertainty
[E10]	NMVOC, non-methane volatile organic co	0.00013	kg	L(0.206)
[E11]	Carbon dioxide, fossil[air]	0.175	kg	L(0.0345)
[E12]	Ammonia[air]	1E-6	kg	L(0.108)
[E13]	Nitrogen oxides[air]	0.000518	kg	L(0.206)
[E14]	Particulates, < 2.5 um[air]	3.71E-5	kg	L(0.554)
[E15]	Particulates, > 10 um[air]	7.93E-5	kg	L(0.215)
[E16]	Particulates, > 2.5 um, and < 10um[air]	1.59E-5	kg	L(0.354)
[E17]	Zinc, ion[fresh water]	2.7E-7	kg	L(0.864)
[E18]	Lead[fresh water]	3.93E-9	kg	L(0.864)
[E19]	Nickel, ion[fresh water]	1.23E-9	kg	L(0.864)
[E21]	Copper, ion[fresh water]	6.39E-9	kg	L(0.633)
[E22]	Chromium, ion[fresh water]	4.55E-10	kg	L(0.633)
[E23]	Cadmium, ion[fresh water]	9.55E-11	kg	L(0.633)
[E42]	Carbon monoxide, fossil[air]	0.00061	kg	L(0.806)
[E44]	Dinitrogen monoxide[air]	5.61E-6	kg	L(0.211)
[E57]	Methane, fossil[air]	3.28E-6	kg	L(0.206)
[E64]	Sulfur dioxide[air]	5.55E-6	kg	L(0.0588)
[E67]	Toluene[air]	4.38E-7	kg	L(0.206)
[E153]	Benzene[air]	1.81E-6	kg	L(0.206)
[E206]	Cadmium[air]	1.28E-9	kg	L(0.845)
[E207]	Chromium[air]	9.33E-9	kg	L(0.845)
[E208]	Copper[air]	1.05E-7	kg	L(0.845)
[E209]	Nickel[air]	9.71E-9	kg	L(0.845)

Characterisation – making sense of the emissions

- How do we make sense of the long list of emissions?
- Characterisation compares the effect of an emission to a reference compound e.g. Global Warming Potential (GWP) to carbon dioxide

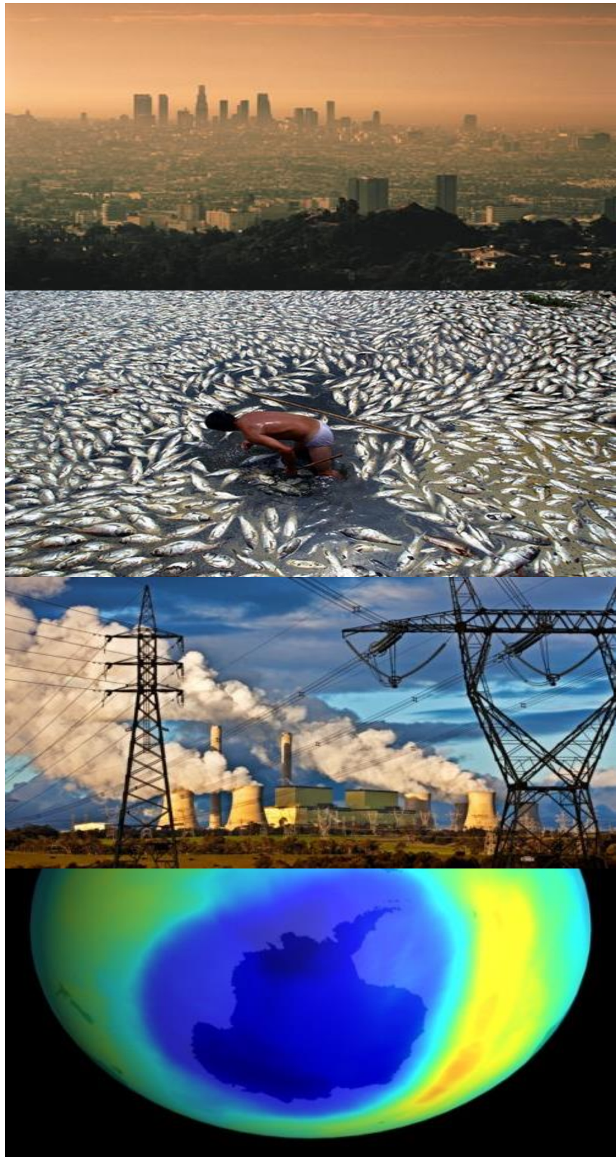
Compound	CO_2 eq.
CO_2	1
CH_4	25
N_2O	298
CHF_3	14800
CCl_3F	4750

- Use standardise “characterisation factors” for each emission – e.g. CO_2eq
- Every kg of methane released has the same effect as 25kg of CO_2 etc.
- Other emissions can be characterised to other “impact categories”

LCA impact categories

- Typically:
  - Global warming potential
  - Acidification potential
  - Eutrophication potential
  - Photochemical oxidant formation
  - Aquatic/terrestrial/human toxicity potential
  - Cumulative energy use
  - Abiotic resource use
  - Biotic resource use
  - Ozone depletion potential
  - Consumptive water use
  - Land use

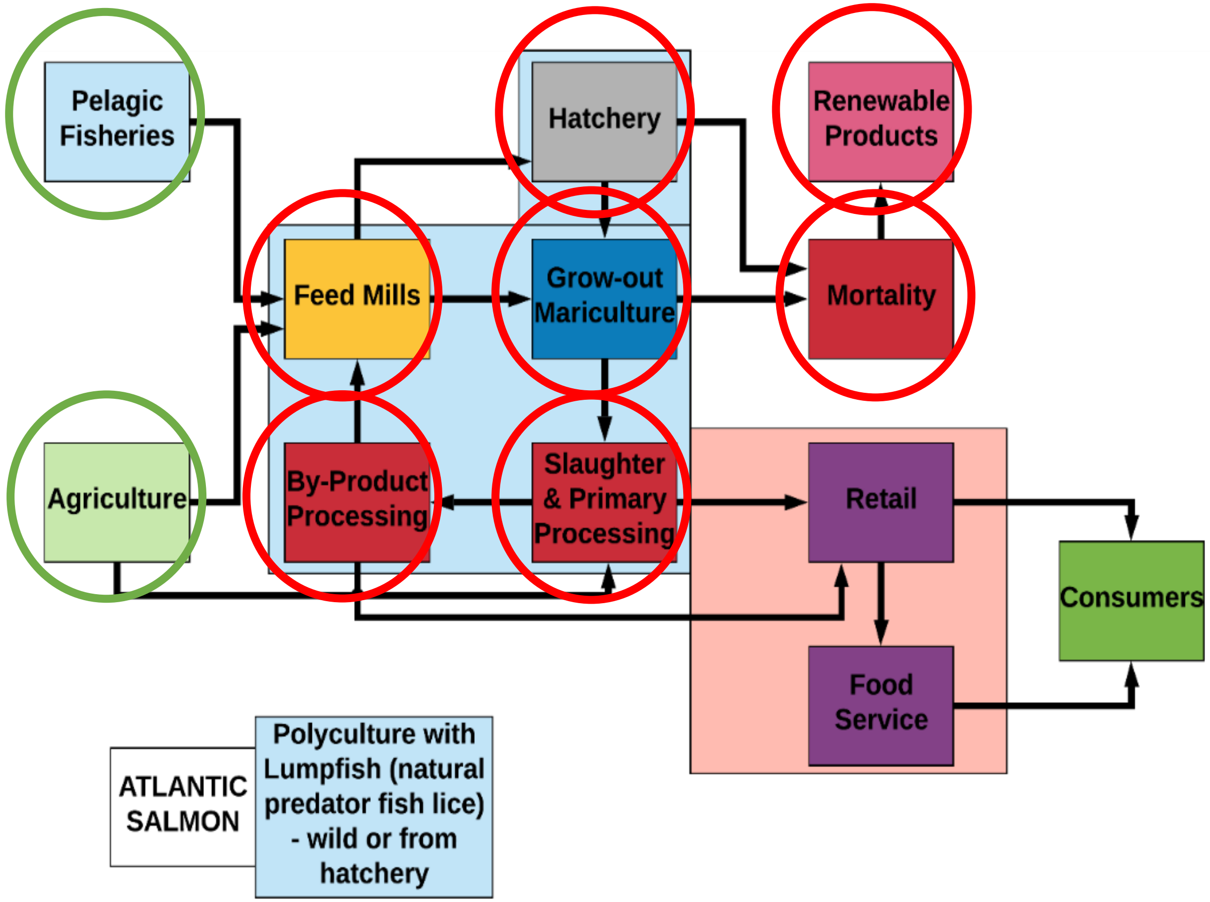
  - Provides comprehensive assessment of global impact and avoids trade-offs



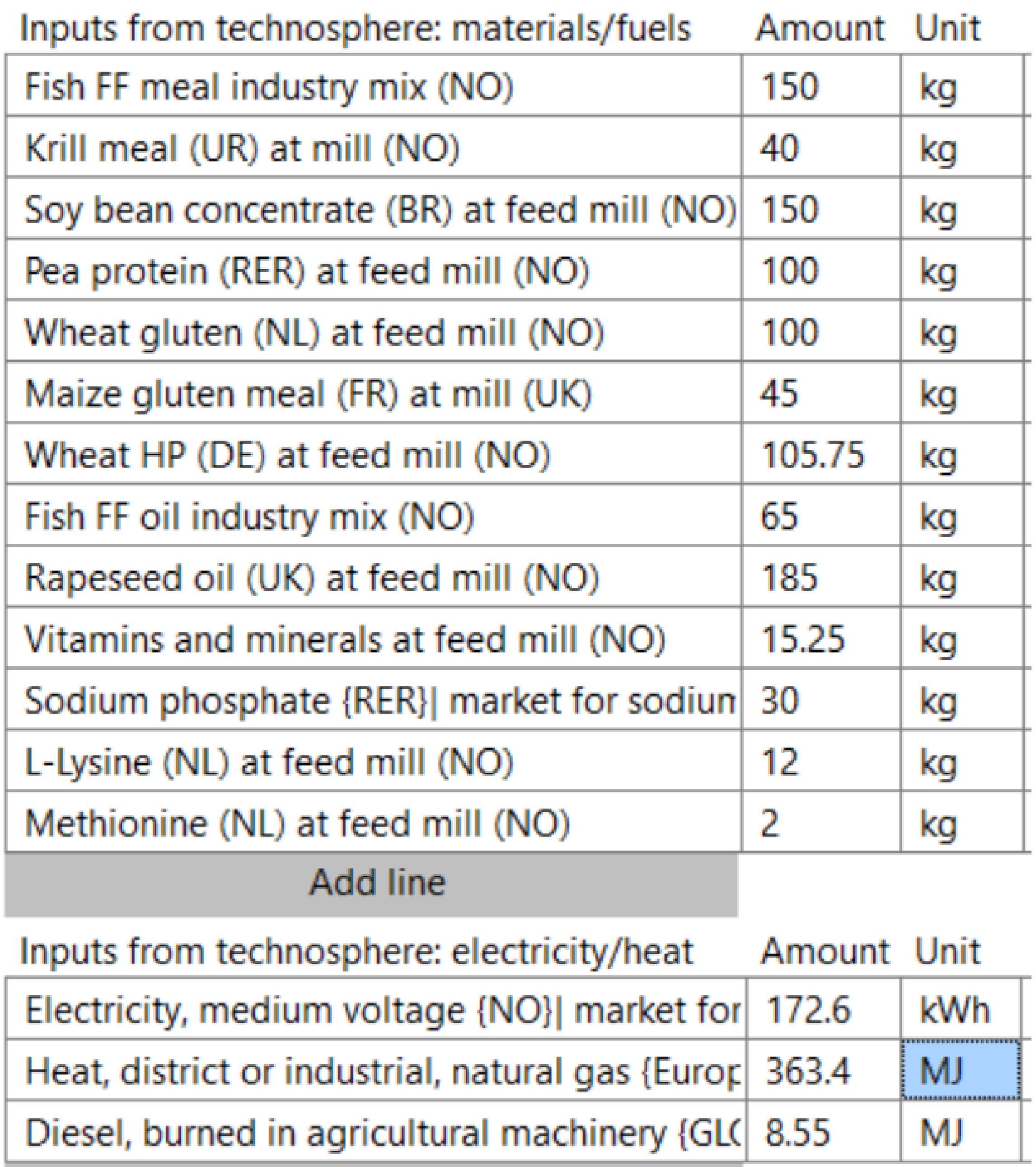
LCA – where does the data come from?? Considerations….

- What is the boundary of the study?
- What is the "functional unit"?
- Where is the data coming from at each point in the study?

  - Surveys (primary)
  - Literature / database (secondary)
  - Database (background)

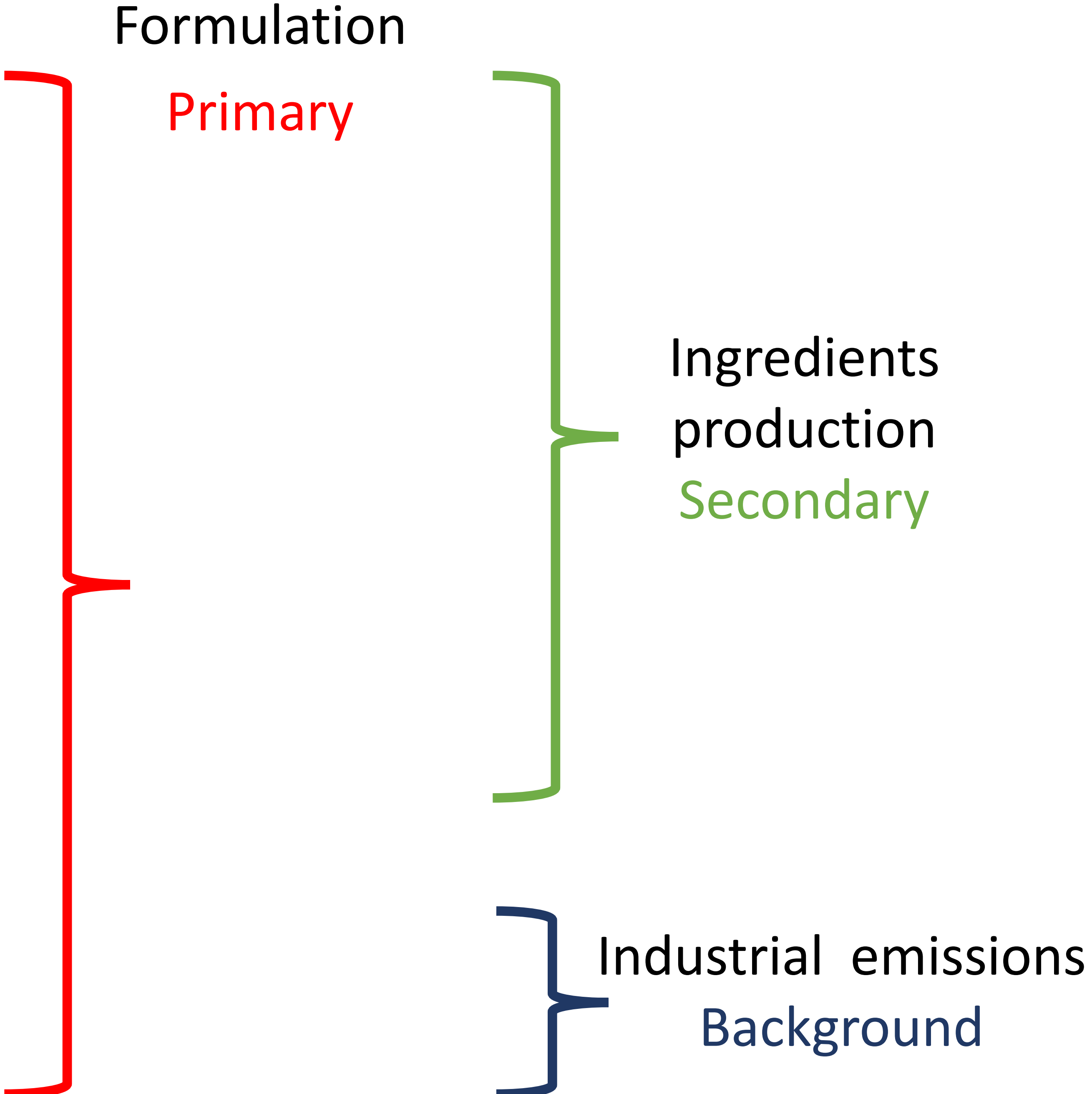


Data entry to Simapro software e.g. a test diet “process”



Inputs from technosphere: materials/fuels	Amount	Unit
Fish FF meal industry mix (NO)	150	kg
Krill meal (UR) at mill (NO)	40	kg
Soy bean concentrate (BR) at feed mill (NO)	150	kg
Pea protein (RER) at feed mill (NO)	100	kg
Wheat gluten (NL) at feed mill (NO)	100	kg
Maize gluten meal (FR) at mill (UK)	45	kg
Wheat HP (DE) at feed mill (NO)	105.75	kg
Fish FF oil industry mix (NO)	65	kg
Rapeseed oil (UK) at feed mill (NO)	185	kg
Vitamins and minerals at feed mill (NO)	15.25	kg
Sodium phosphate {RER}| market for sodiun	30	kg
L-Lysine (NL) at feed mill (NO)	12	kg
Methionine (NL) at feed mill (NO)	2	kg

Inputs from technosphere: electricity/heat	Amount	Unit
Electricity, medium voltage {NO}| market for	172.6	kWh
Heat, district or industrial, natural gas {Europ	363.4	MJ
Diesel, burned in agricultural machinery {GL	8.55	MJ



Formulation

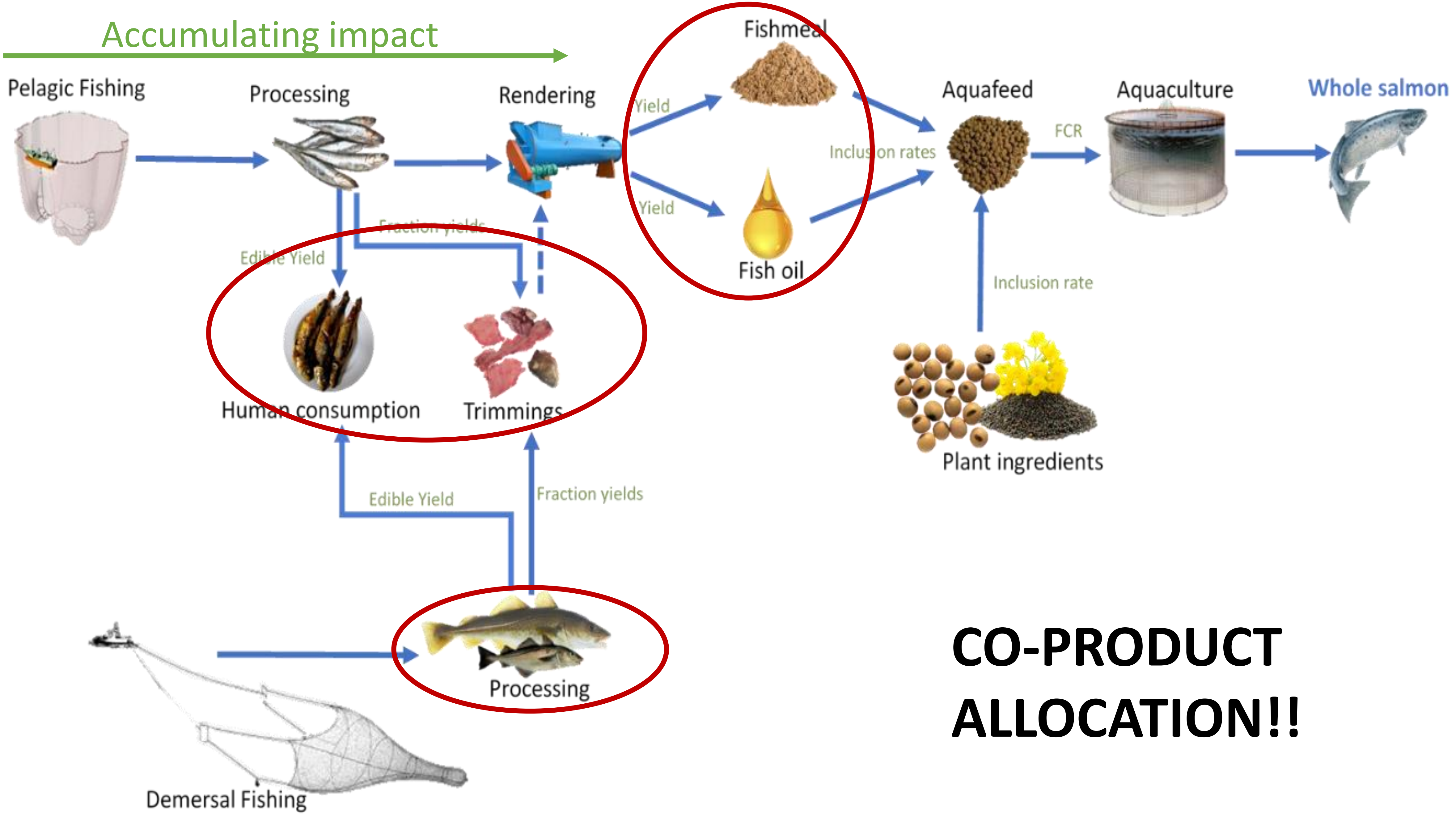
Primary

Ingredients production

Secondary

Industrial emissions

Background



Accumulating impact

Pelagic Fishing

Processing

Rendering

Fishmeal

Fish oil

Yield

Yield

Inclusion rates

Aquafeed

FCR

Aquaculture

Whole salmon

Inclusion rate

Plant ingredients

Fraction yields

Edible Yield

Human consumption

Trimmings

Edible Yield

Fraction yields

Processing

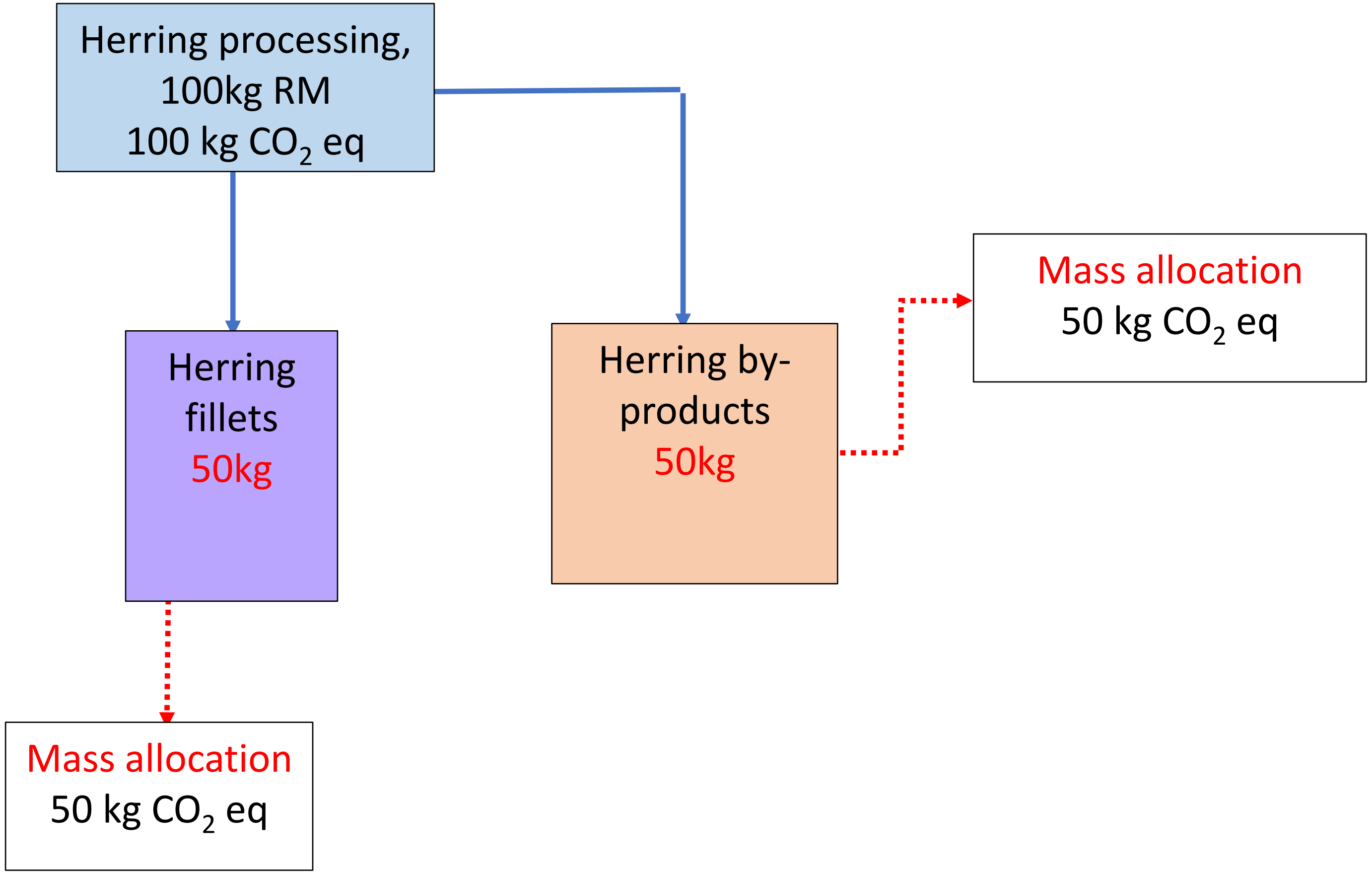
Demersal Fishing

CO-PRODUCT ALLOCATION!!

Methodological Issues – Co-product Allocation

Critical for data collection and interpretation

Fishing
Processing
Rendering


Herring processing, 100kg RM 100 kg CO_2 eq

Herring fillets 50kg

Herring by-products 50kg

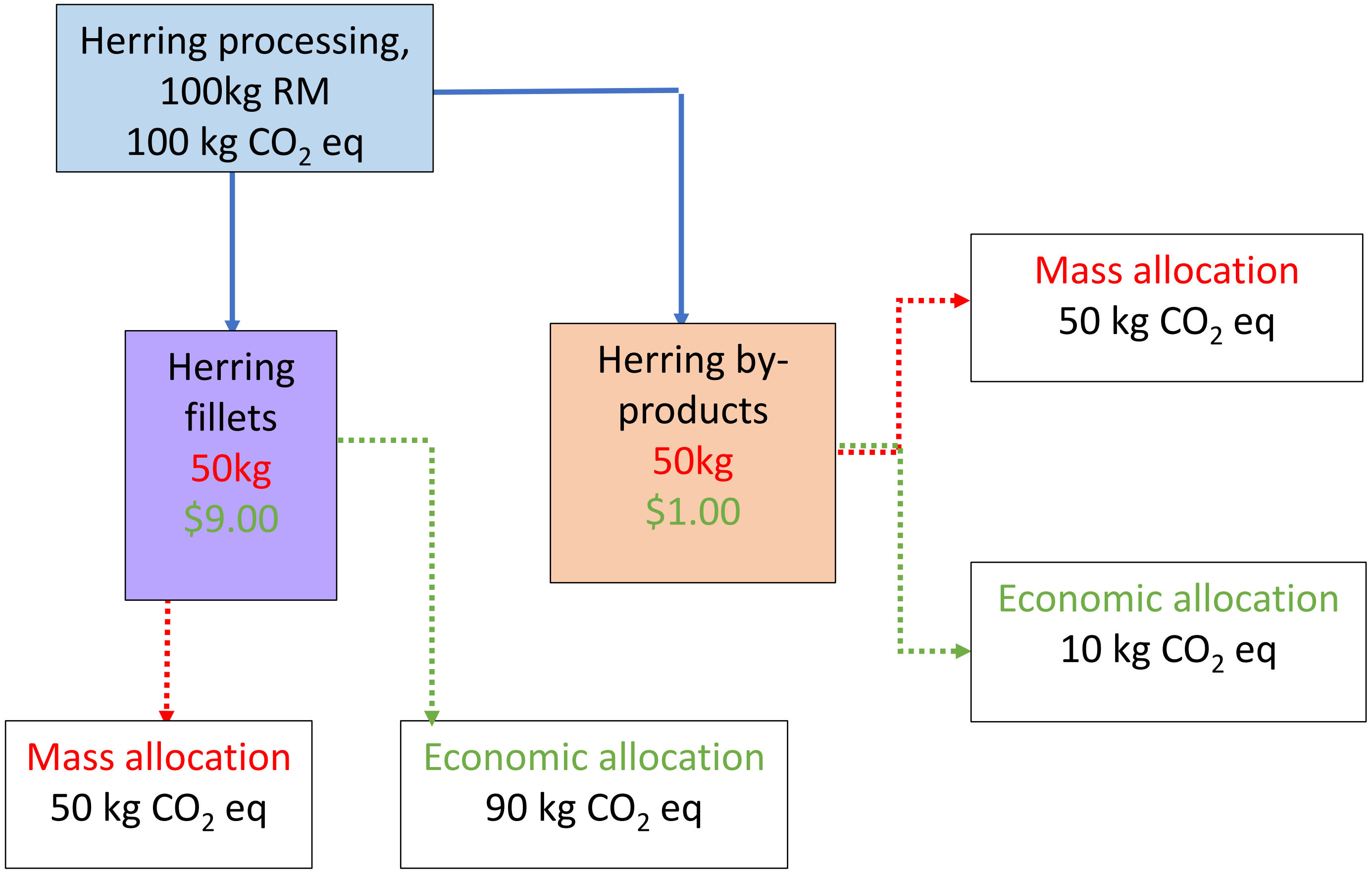
Mass allocation 50 kg CO_2 eq

Mass allocation 50 kg CO_2 eq

Methodological Issues – Co-product Allocation

Critical for data collection and interpretation

Fishing
Processing
Rendering



Herring processing,
100kg RM
100 kg CO_2 eq

Herring fillets
50kg
$9.00

Herring by-products
50kg
$1.00

Mass allocation
50 kg CO_2 eq

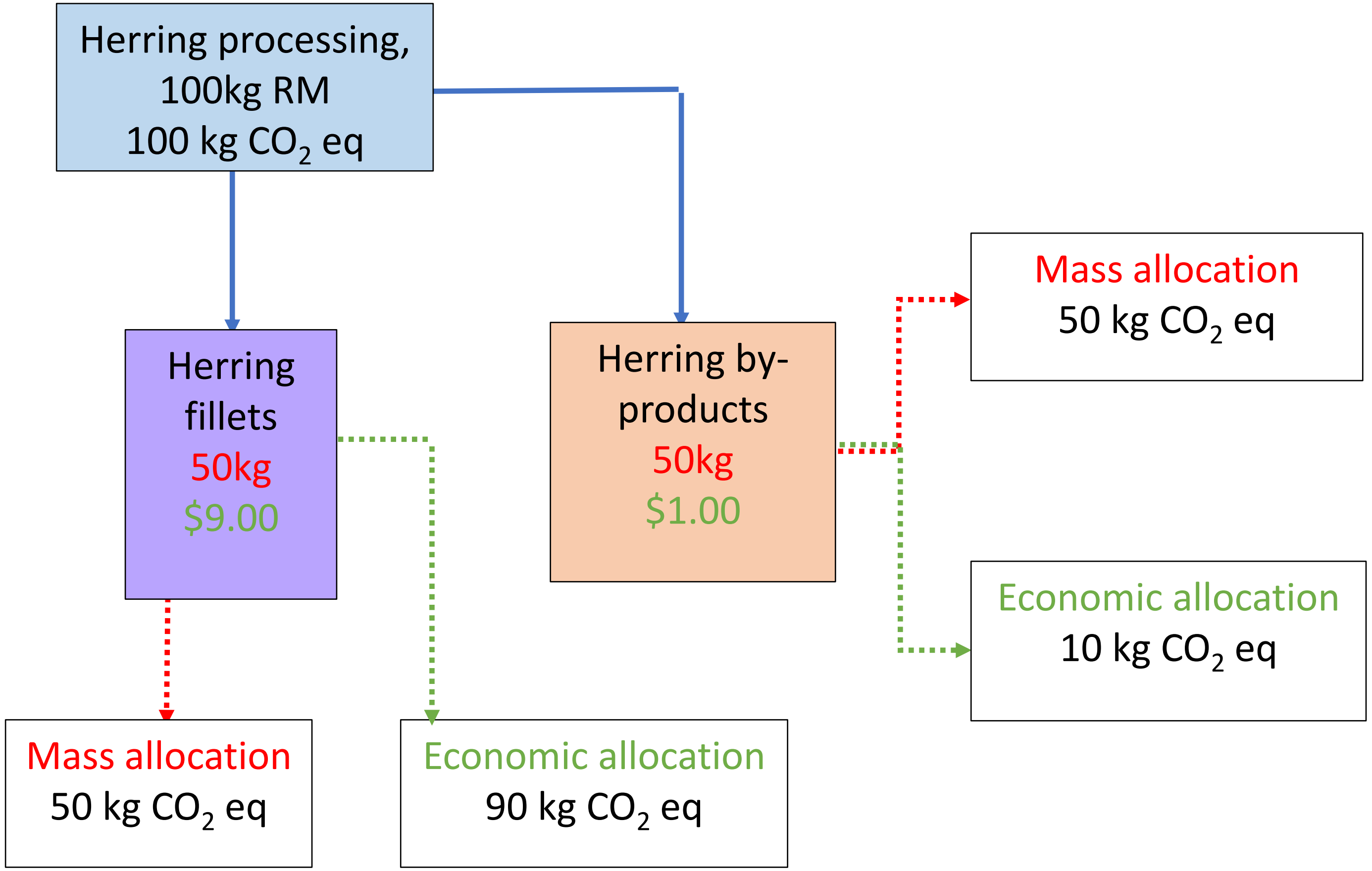
Economic allocation
90 kg CO_2 eq

Mass allocation
50 kg CO_2 eq

Economic allocation
10 kg CO_2 eq

Methodological Issues – Co-product Allocation

Critical for data collection and interpretation



Herring processing, 100kg RM 100 kg CO_2 eq

Herring fillets 50kg \$9.00

Herring by-products 50kg \$1.00

Mass allocation 50 kg CO_2 eq

Economic allocation 90 kg CO_2 eq

Mass allocation 50 kg CO_2 eq

Economic allocation 10 kg CO_2 eq

Example from fishing industry

Species	Catch, kg/tonne	Price, \$/kg	Price x catch	Mass allocation %	Economic allocation %
Atlantic Mackerel	210	0.65	135.48	21.0%	10.5%
Blue Whiting	430	1.03	443.53	43.0%	34.4%
European hake	180	2.89	520.07	18.0%	40.3%
Horse mackerel	180	1.06	191.12	18.0%	14.8%

eFIFO

- eFIFO method introduced by Kok et al to account for by-products and limiting ingredients
- Is calculated from the percentage value of “co-products” fishmeal or fish oil and by-products from processing

$$\left(\left(\frac{I_{fm}}{Y_{fm}} \times PF_{fm}\right) + \left(\frac{I_{fo}}{Y_{fo}} \times PF_{fo}\right)\right) \text{ x FCR}$$

- PF is the Price Factor (i.e. the % value)
- Fish oil contributes more to the eFIFO than fish meal
- By-products meals and oils contribute based on the value of by-products compared to e.g. fillets

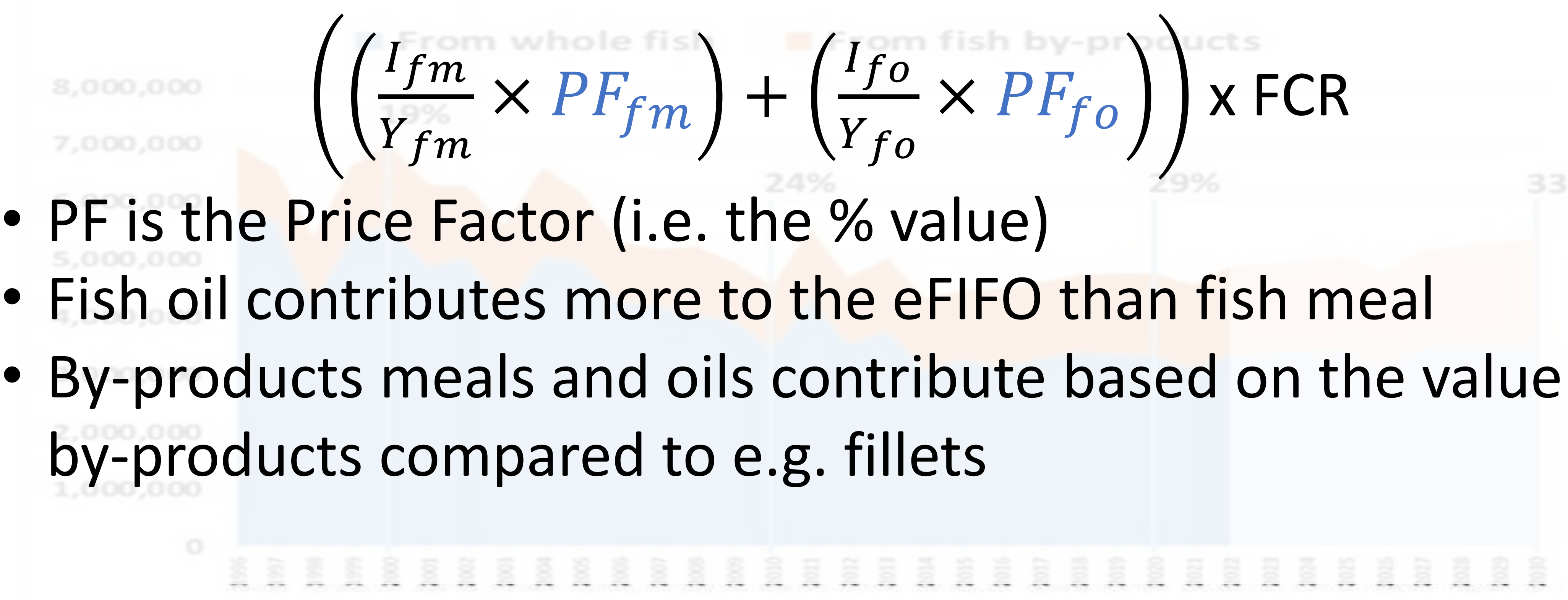


Figure 1. Global fishmeal production by raw material input origin 1996 - 2030 estimates.

Biotic Resource Use

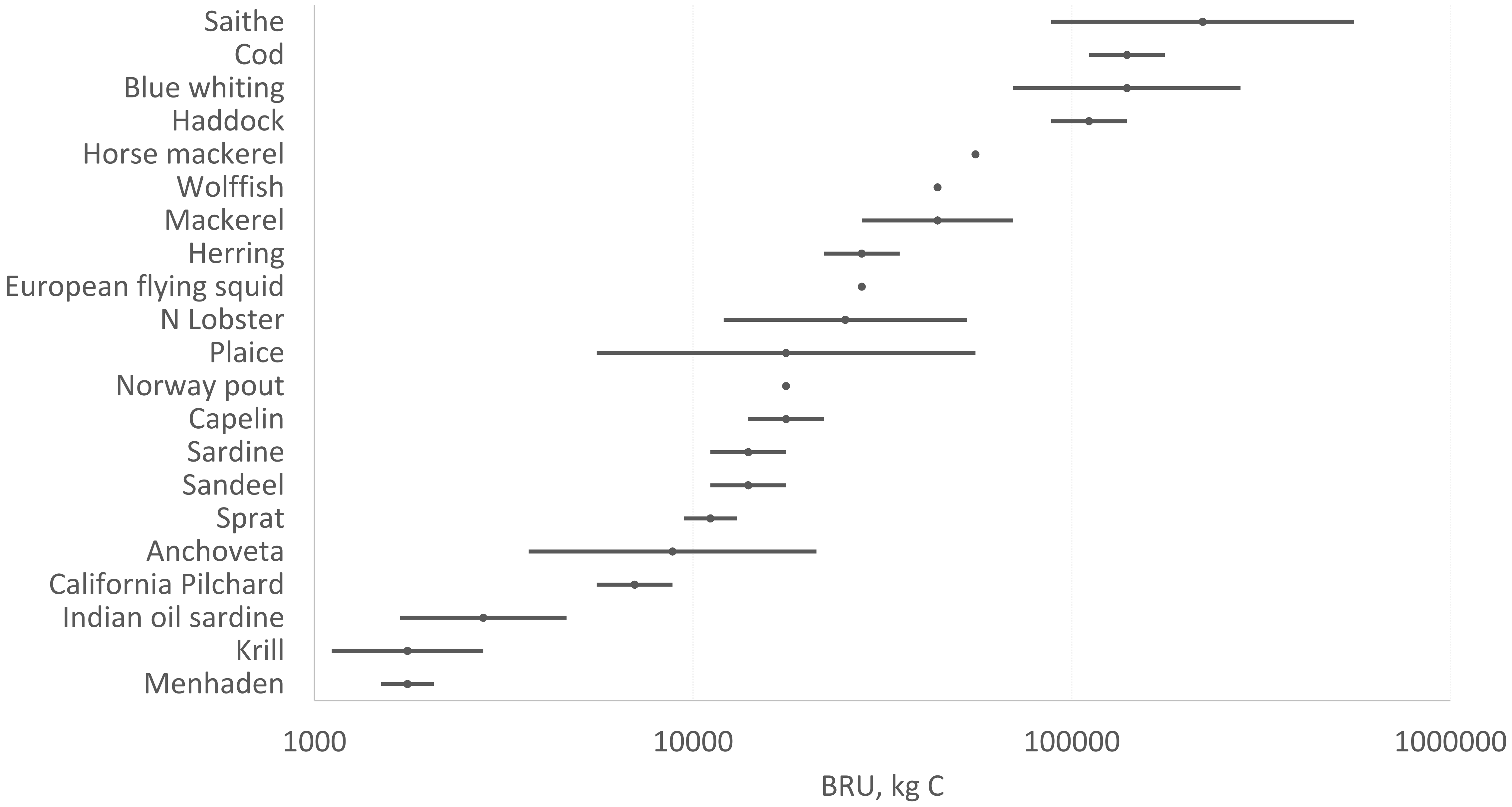
$$BRU = \frac{\mathrm{C}}{\mathrm{M}} * \left(\frac{1}{TE}\right)^{TL-1}$$

Where C is mass of the catch, M is the carbon content, TE is the transfer efficiency and TL is the trophic level of the species. Pauly and Christensen (1995)

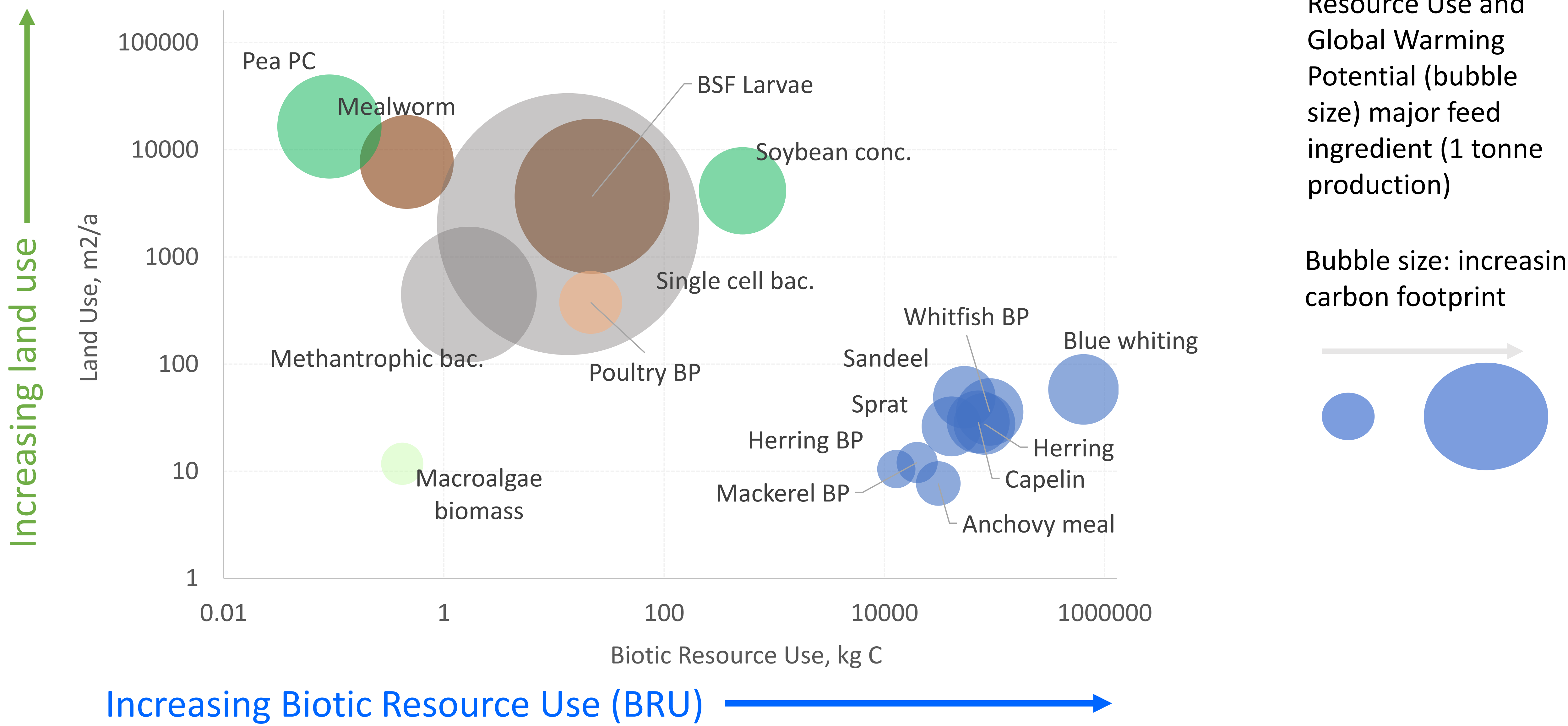
- Generally tracks FIFO
- Can also potentially be applied to terrestrial crops

Species	Trophic level	SD
Anchoveta (Engraulis ringens)	2.9	0.4
Blue whiting (Micromesistius poutassou)	4.1	0.3
Capelin (Mallotus villosus)	3.2	0.1
Atlantic herring (Clupea harengus)	3.4	0.1
Norway Pout (Trisopterus esmarkii)	3.2	0.0
Sandeel (Ammodytes marinus)	3.1	0.1
Indian Oil Sardine (Sardinella longiceps)	2.4	0.2
California pilchard (Sardinops sagax)	2.8	0.1
Gulf Menhaden (Brevoortia patronus)	2.2	0.1
Atlantic mackerel (Scomber scombrus)	3.6	0.2
Atlantic horse mackerel (Trachurus trachurus)	3.7	0.0
European sprat (Sprattus sprattus)	3.0	0.1
Sardine (Sardina pilchardus)	3.1	0.1
Cod (Gadus morhua)	4.1	0.1
Haddock (Melanogrammus aeglefinus)	4.0	0.1

Biotic Resource Use



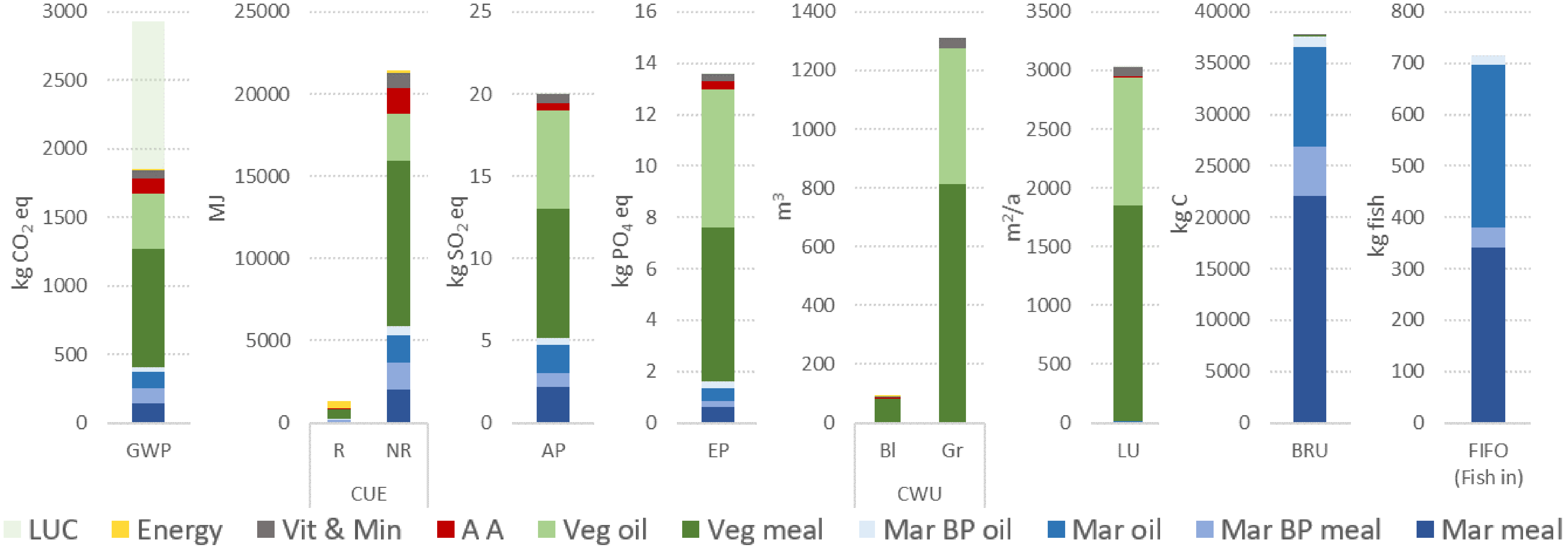
Marine ingredients sustainability trade-offs



Land Use, Biotic Resource Use and Global Warming Potential (bubble size) major feed ingredient (1 tonne production)

Bubble size: increasing carbon footprint

EISI sustainability Indicators examples – 1 tonne salmon feed



GWP – Global Warming Potential, CEU = Cumulative Energy Demand (Renewable and Non-Renewable), AP - Acidification Potential, EP – Eutrophication Potential, CWU – Cumulative Water Use (Green and Blue), LU – Land Use, BRU – Biotic Resource Use, FIFO – Fish In: Fish Out, LUC – Land Use Change, AA – Amino Acids, Mar – Marine

- Can measure trade-off between marine and other ingredients in feed

Summary and conclusions

- FIFO and FFDR have evolved to demonstrate efficiency and dependence on forage fish resources
- On it's own they are not good measures of "sustainability"
- LCA measures a wide range of impacts
- eFIFO and BRU is compatible with LCA and can be used to measure sustainability trade-offs
- LCA framework provides the potential to add more sustainability metrics
- Dependent on availability and quality of data

GAIN
Green Aquaculture Intensification

Richard Newton
rwn1@stir.ac.uk

Thank you for your attention

Any questions?

Methodological Issues 1 - Functional unit

- LCA measures and compares the **function** of different products and services
- The difference between a standard light bulb (SLB) and an energy saving light bulb (ESLB).

- Manufacturing impact of ESLB is higher
- Energy use is much lower
- Life time is much longer

- Disposal (end-of-life) concerns around ESLB - mercury

eFIFO full equations

Equation 3a economic Fish In: Fish Out (eFIFO) where PF is the price factor (Equation 3b) and BPF is the By-product factor (Equation 3c)

$$eFIFO = \sum_{n=1}^{x} \left\{ \left[\left(\left(\frac{I_{fm}}{Y_{fm}} \times PF_{fm} \right) + \left(\frac{I_{fo}}{Y_{fo}} \times PF_{fo} \right) \right) \times BPF \right]_{1} + \cdots \left[\left(\left(\frac{I_{fm}}{Y_{fm}} \times PF_{fm} \right) + \left(\frac{I_{fo}}{Y_{fo}} \times PF_{fo} \right) \right) \times BPF \right]_{x} \right\} \times FCR$$

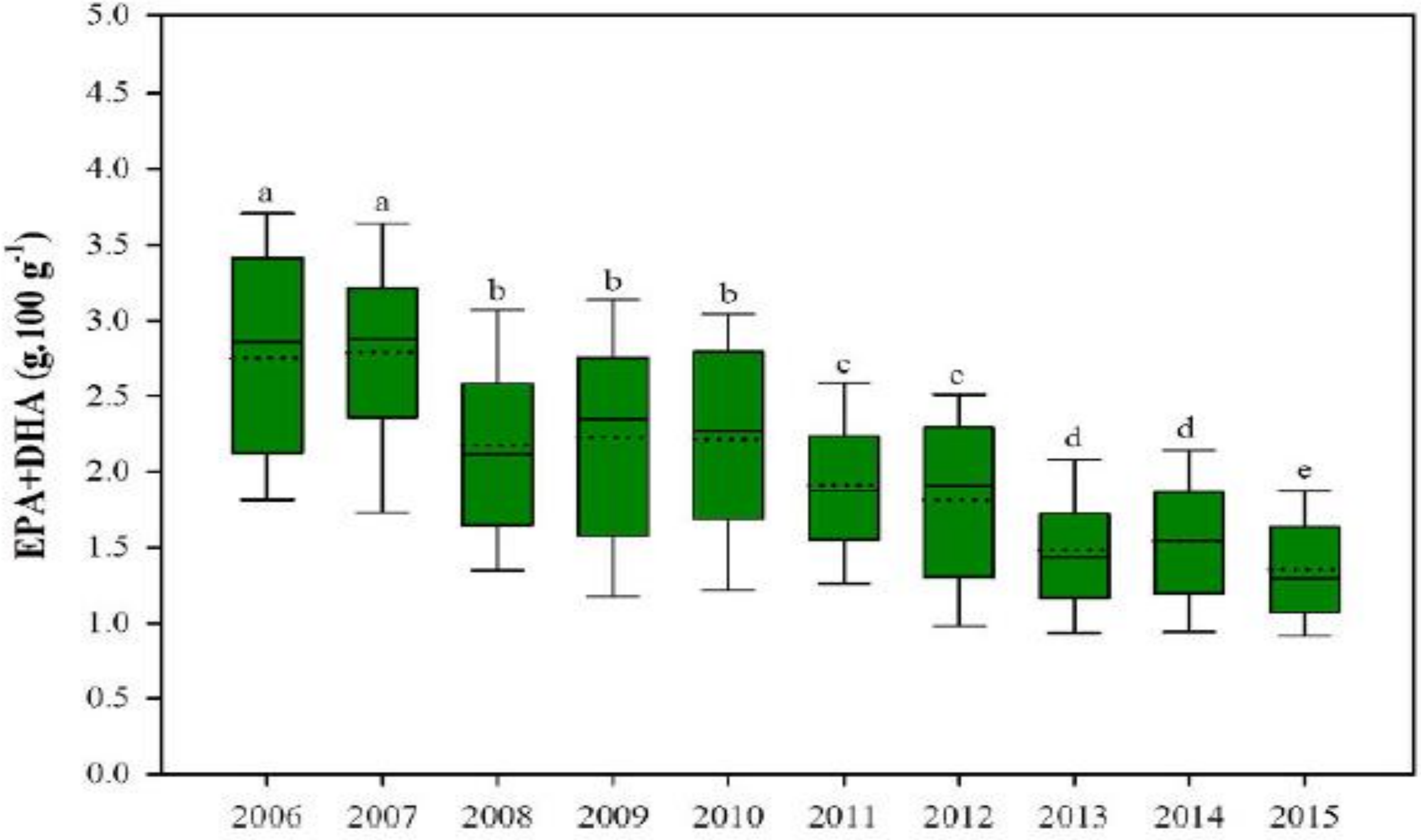
Equation 3b

$$PF_{fm} = \frac{(Y_{fm} \times P_{fm})}{(Y_{fm} \times P_{fm}) + (Y_{fo} \times P_{fo})}$$

Equation 3c

$$BPF = \frac{(Y_{BP} \times P_{BP})}{\sum_{x}\{(Y_{BP} \times P_{BP}) + (Y_{CP1} \times P_{CP1}) + \cdots (Y_{CPx} \times P_{CPx})\}}$$

- In Equations 3b and 3c *P* is the price of the marine ingredient, by-product or other co-products (BP, CP). Therefore, the PF is the proportion of value of any particular marine ingredient of the total value and the BPF is the proportion of the value of that by-product of the total co-product value from fish processing. FIFO and eFIFO are the sum of all the marine ingredients from different species or by-products 1 to x multiplied by the FCR.



Sprague et al 2016