BLUEBIO ON LIFE CYCLE ASSESSMENT

AquaHealth

MASSIMO PIZZOL, 21 May 2024

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Today

- LCA in Aquahealth
- LCA model of production of microalgal compounds
- Upscaling to EU-level system
- LCA model of fish farm
- Multi-model results (risk vs uncertainty)
- Overall reflections

Credits

Pierre Jouannais, pijo@plan.aau.dk ,pierre.jouannais@minesparis.psl.eu

- Jouannais, P., Blanco, C. F., & Pizzol, M. (2024). ENvironmental Success under Uncertainty and Risk (ENSURe): A procedure for probability evaluation in ex-ante LCA. *Technological Forecasting and Social Change*, *201*, 123265. https://doi.org/10.1016/j.techfore.2024.123265
- Jouannais, P., Gibertoni, P. P., Bartoli, M., & Pizzol, M. (2023). LCA to evaluate the environmental opportunity cost of biological performances in finfish farming. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-023-02211-8
- Jouannais, P., Hindersin, S., Löhn, S., & Pizzol, M. (2022). Stochastic LCA Model of Upscaling the Production of Microalgal Compounds. *Environmental Science & Technology*, *56*(14), 10454–10464. https://doi.org/10.1021/acs.est.2c00372
- Jouannais, P., & Pizzol, M. (2022). Stochastic Ex-Ante LCA under Multidimensional Uncertainty: Anticipating the Production of Undiscovered Microalgal Compounds in Europe. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.2c04849

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SINTEF

Sea & Sun Technology

https://aquahealth-project.com/

LCA in AquaHealth

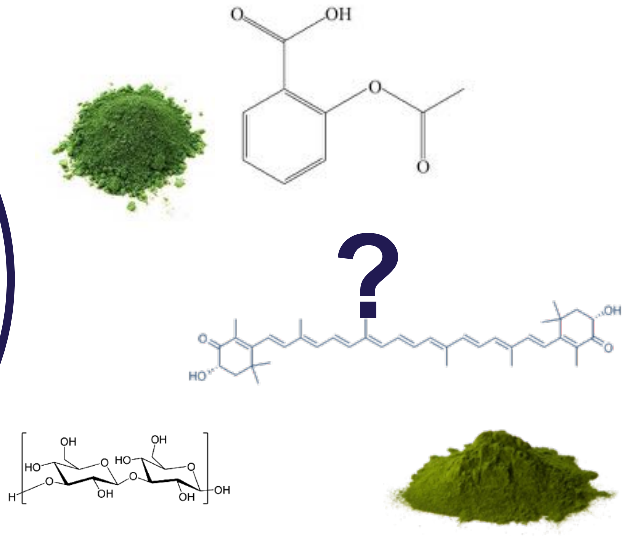
Challenges in doing LCA in AquaHealth

- Future uncertain system in which microalgae produce bioactive molecule for fish health issues

The object that we model and assess is :

“A future system/technology in which **a or some** microalgae strains are producing bioactive compounds for fish health management”

High uncertainty, Large scope of possibilities



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Future environmental performance of the system depends on:

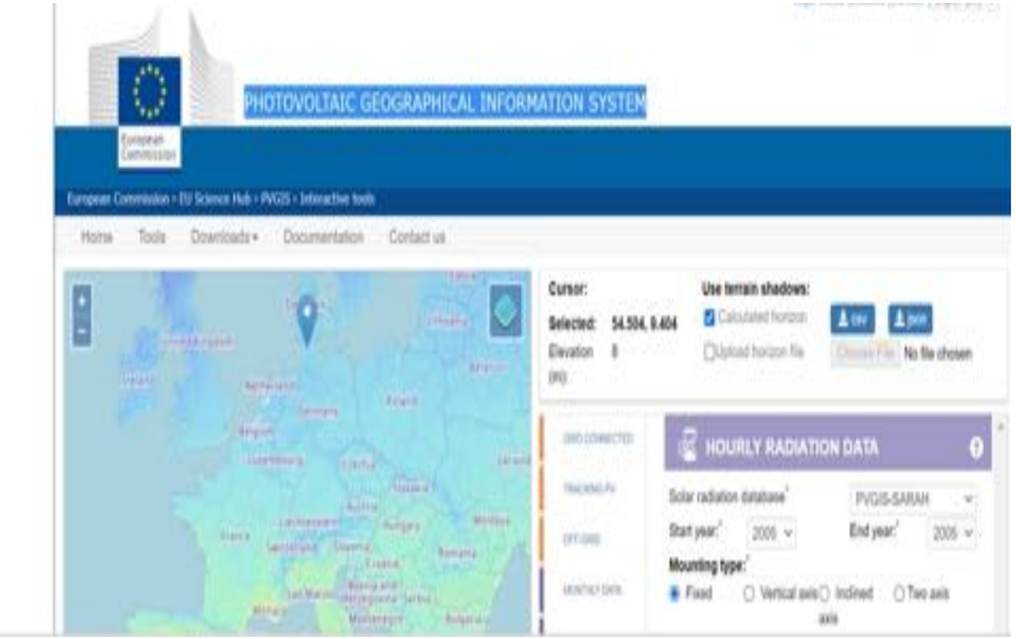
- How will this molecule be produced?
- What disease/health issue will the molecule tackle?
- How much of the new molecule will be needed for a given effect?
- What will be the effect of the molecule?

How will this microalgal molecule be produced?

It will depend on :

- The duo strain/molecule
- The way the strain is cultivated (PBR design and operation)
- The location

Parameterization



https://re.jrc.ec.europa.eu/pvg_tools/en/#HR

A parameterized LCA model:

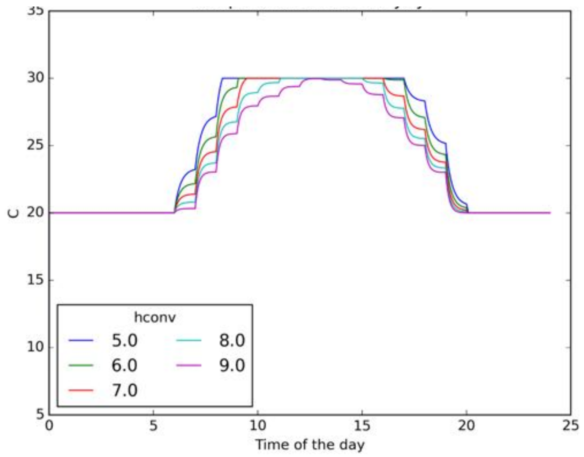
- 1 kg of molecule has FU
- Simulates cultivation of a parameterized strain/molecule in any given location via the European Photovoltaic Geographical Information System.
- Calculates associated LCI and LCIA
- Considers high uncertainty regarding the productivity obtained in each PBR design

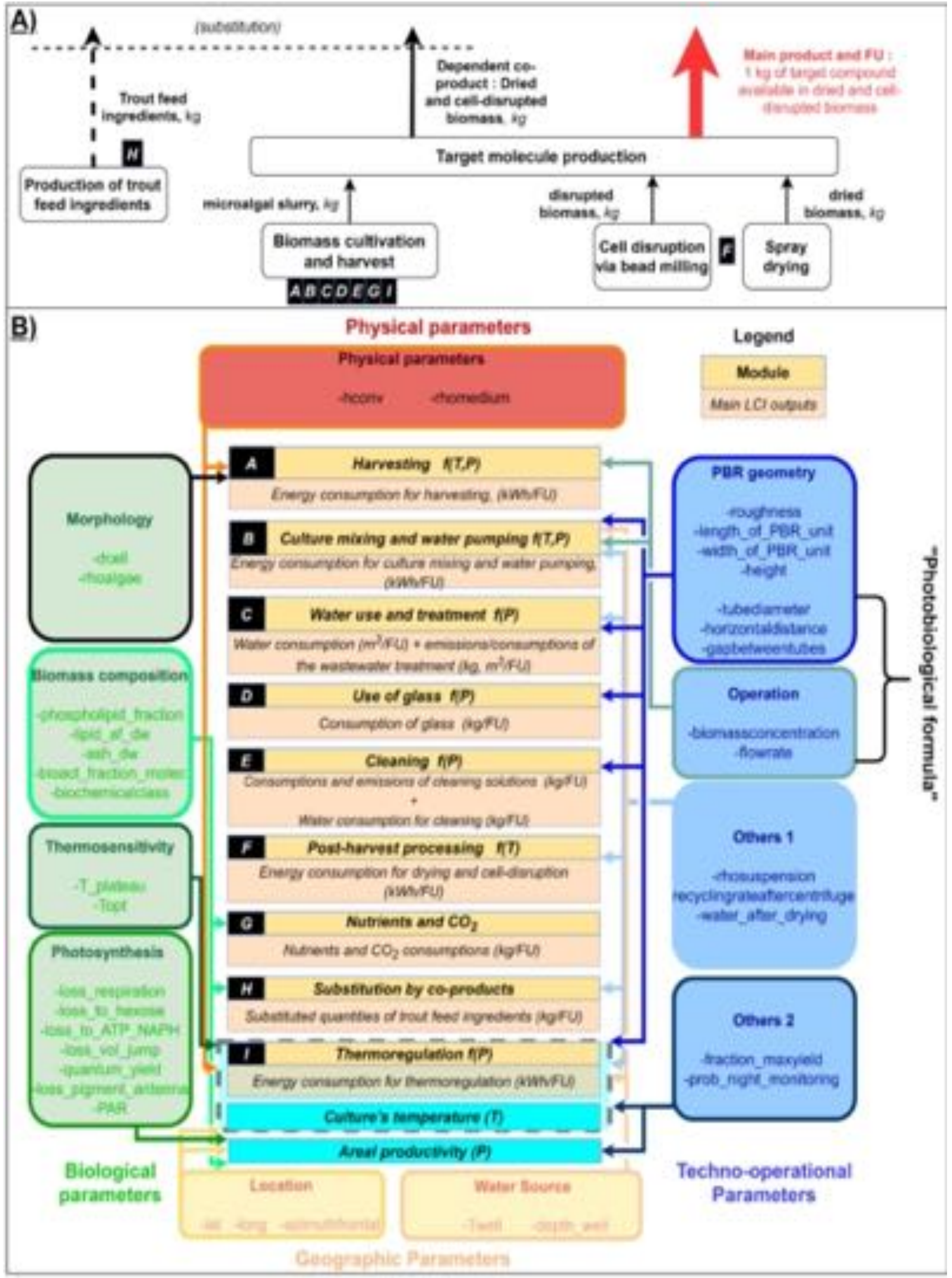
Parametrized microalgae cultivation model

What can we expect from a strain/molecule without knowing about its upscaled behavior in a specific reactor and location?

Assumptions and key ideas

- Separating Biological, Techno-operational, Geographic parameters
- Any strain can be cultivated in a PBR under the right conditions.
- Conditions depend on the **photobiological formula** which directly affects the LCI.
- A percentage of the strain specific maximum energetic yield will be reached.
- All conditions uncertain/unknown a priori : Ranges found in the literature in different contexts.





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Addressing techno-operational uncertainty

For one strain defined by :

-its composition
-its nitrogen source
-its maximum energetic yield
-its thermal range : 20-30C
-its diameter
-its density
*-the type of bioactive molecule **: Carbohydrate***
*-the content in bioactive molecule **: 2%***

+

Location: *latitude, magnitude, azimuth*

Cultivation period : *April to September*

Yield achieved: *30 % of maximum*

Fourier Amplitude Sensitivity Analysis Sample

= 9000 different combinations of the uncertain photobiological formula (tube diameter, gap between tubes, horizontal distance, biomass concentration, flow rate) + uncertain convective coefficient. Uniform distributions

	tubediameter	gapbetweentubes	horizontaldistance	biomassconcentration	flowrate	hconv	**LCI**	FETPinf	HTPinf	METPinf	TETPinf	MDP	ALOP	GWP100	FDP	FEP	MEP	NLTP	ODPinf	WDP
0	0.055182	0.042377	0.41585	3.158495	0.487799	6.798746	...	308.7466	2141.301	271.6669	-1.01787	190.1525	2202.913	3369.494	1372.041	2.762283	2.801111	-16.6043	0.00046	29.42336
1	0.037819	0.042202	0.411162	3.064745	0.470612	6.652262	...	259.9281	1804.515	228.6894	-1.04828	160.8803	1836.94	2825.269	1147.792	2.330324	2.51402	-16.5899	0.000385	23.30705
2	0.039544	0.042026	0.406475	2.970995	0.453424	6.505777	...	262.5499	1822.484	231.0015	-1.04653	162.5722	1855.389	2855.826	1160.509	2.356074	2.607596	-16.5908	0.000389	23.81251
3	0.056907	0.04185	0.401787	2.877245	0.436237	6.359293	...	300.724	2085.332	264.626	-1.02229	185.9355	2136.349	3286.923	1338.878	2.698036	2.994776	-16.6025	0.000448	29.3042
4	0.074271	0.041674	0.3971	2.783495	0.419049	6.212809	...	319.8947	2216.377	281.5457	-1.00927	198.5162	2267.528	3513.688	1434.301	2.869913	3.298579	-16.6087	0.000479	33.34548
5	0.091634	0.041499	0.392412	2.689745	0.401862	6.066324	...	327.9255	2270.196	288.6717	-1.00287	204.7443	2311.302	3620.272	1480.859	2.942514	3.560274	-16.6119	0.000493	36.48852
6	0.091003	0.041323	0.387725	2.595995	0.384674	5.91984	...	322.6769	2233.772	284.0585	-1.00594	201.8052	2269.749	3564.139	1458.005	2.899102	3.630432	-16.6105	0.000485	36.14107
7	0.073639	0.041147	0.383037	2.502245	0.367487	5.773356	...	305.5675	2116.862	268.9562	-1.01757	190.5749	2153.194	3361.419	1372.44	2.75208	3.516872	-16.6051	0.000458	32.51963
8	0.056276	0.040971	0.37835	2.408495	0.350299	5.626871	...	279.2647	1936.292	245.7687	-1.03473	174.0347	1965.267	3058.719	1246.102	2.522844	3.353175	-16.5971	0.000416	28.05622
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	..	...	...
6143	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

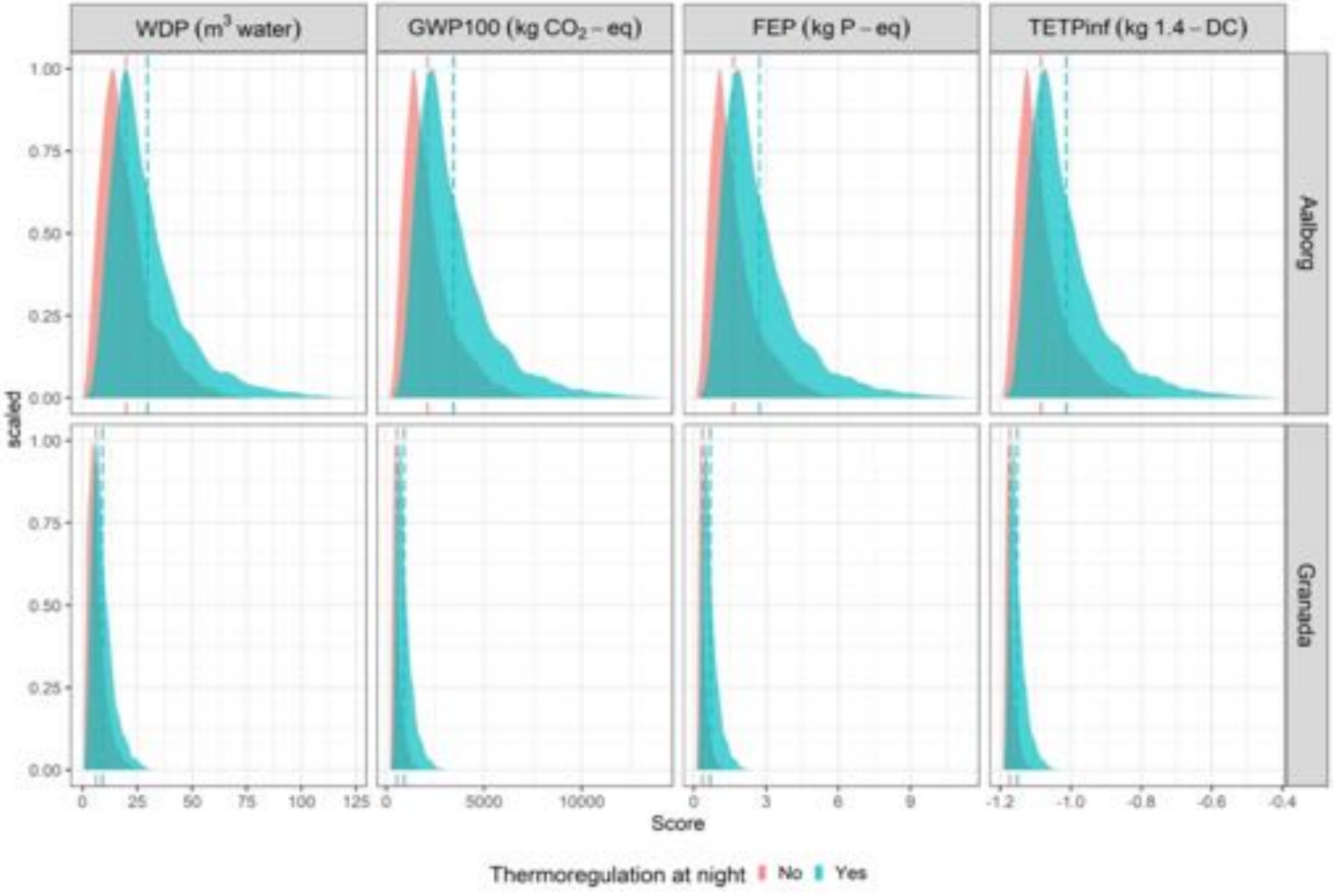
Results on microalgae cultivation

Conclusions about the environmental impacts

- Very dependent on the location
- Thermoregulation is the key contributor (even in optimized continuous systems)
- Volumetric Yield is key and should be privileged

Conclusions about the model

- High sensitivity of the model to the geometrical parameters : Volumetric yield + Solar heating + Exchange area
- The uncertainty on these parameters (which geometry could entail a given productivity for a strain in a location) should be ideally reduced



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LCA of upscaled system

So far…

1 strain-molecule + 1 location + ? Photobioreactor

Techno-operational uncertainty

In larger scale…

What can we expect in term of environmental impacts for the development of this production in Europe ?

? Strain-molecule + ? locations + ? Photobioreactor

Bioprospecting uncertainty

5735 random strain-molecules

Geographic/ Production mix Uncertainty

400 random combinations of locations in Europe

Techno-operational uncertainty

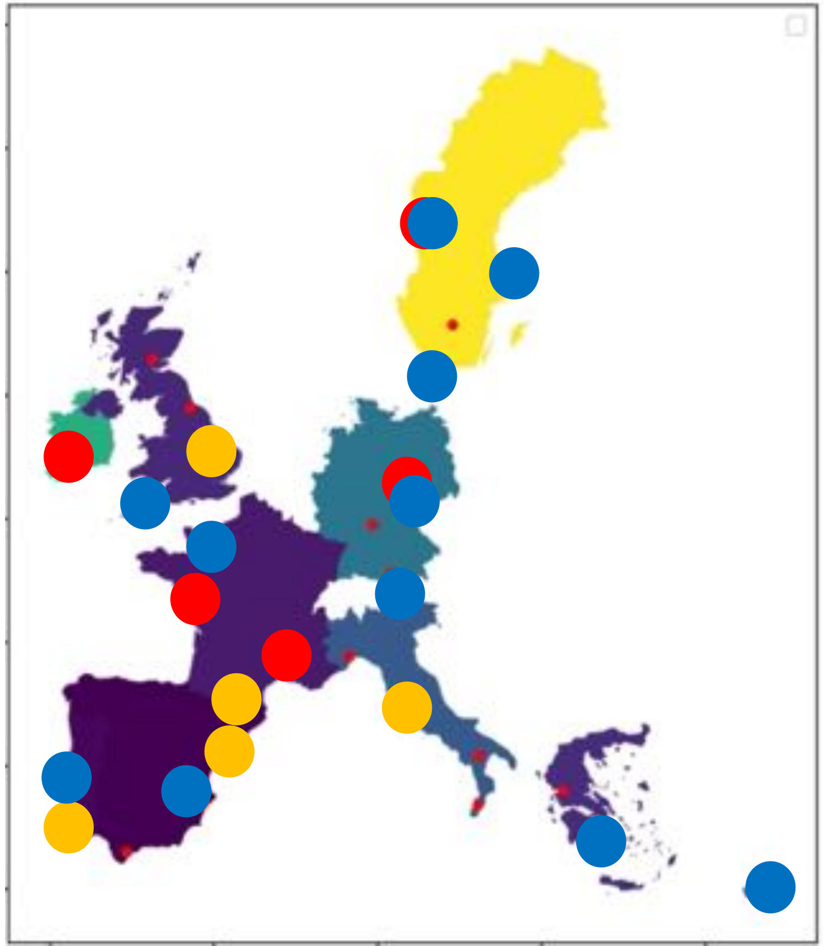
200 Photobioreactors for each strain

Production mix uncertainty

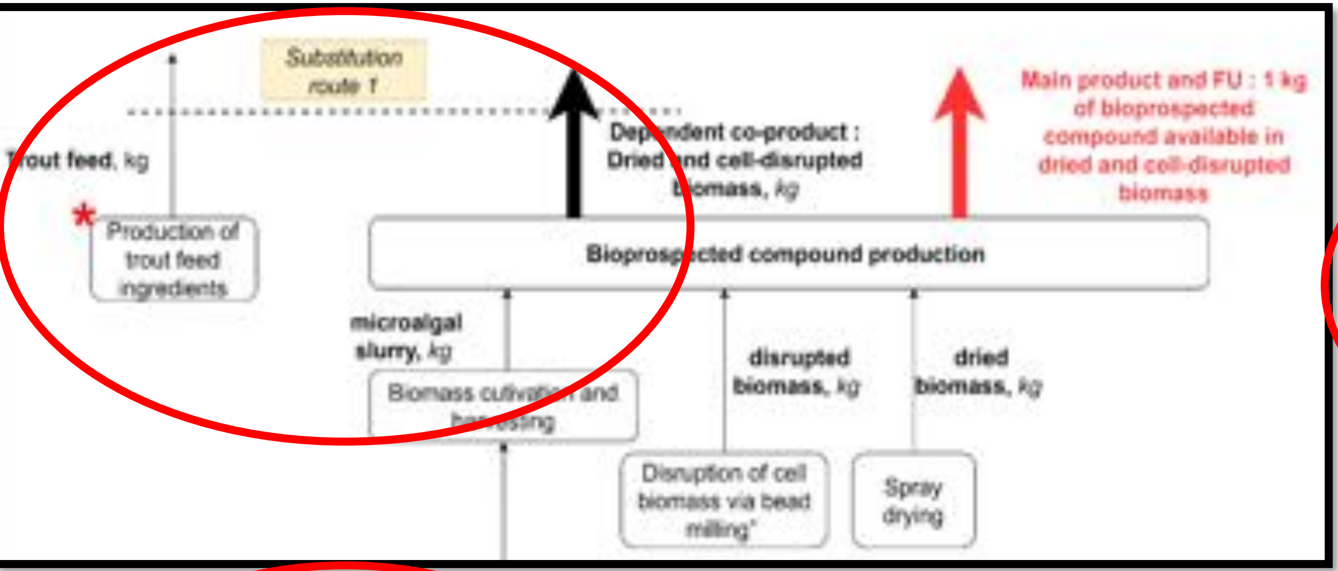
- When a useful, effective molecule is found, developed and upscaled, the production is made available for industrial actors in Europe.
- An increase in demand for this molecule is answered by different plants in distinct locations in Europe.

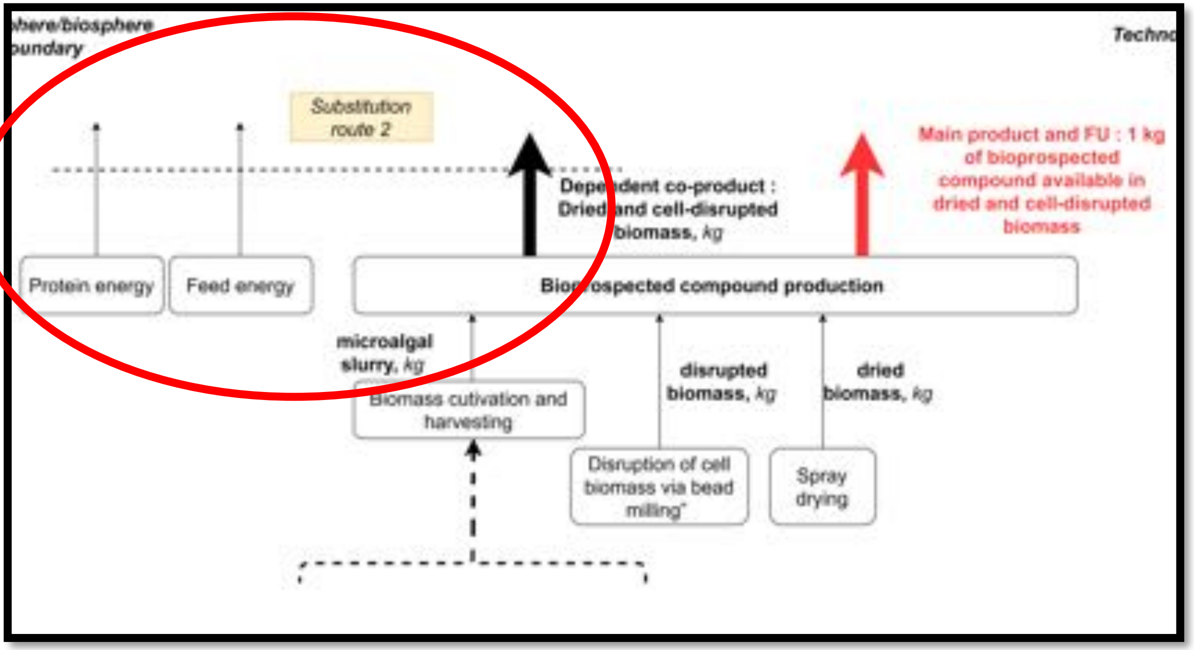
1) Generate a random grid of locations over the 10 countries with the highest potential.

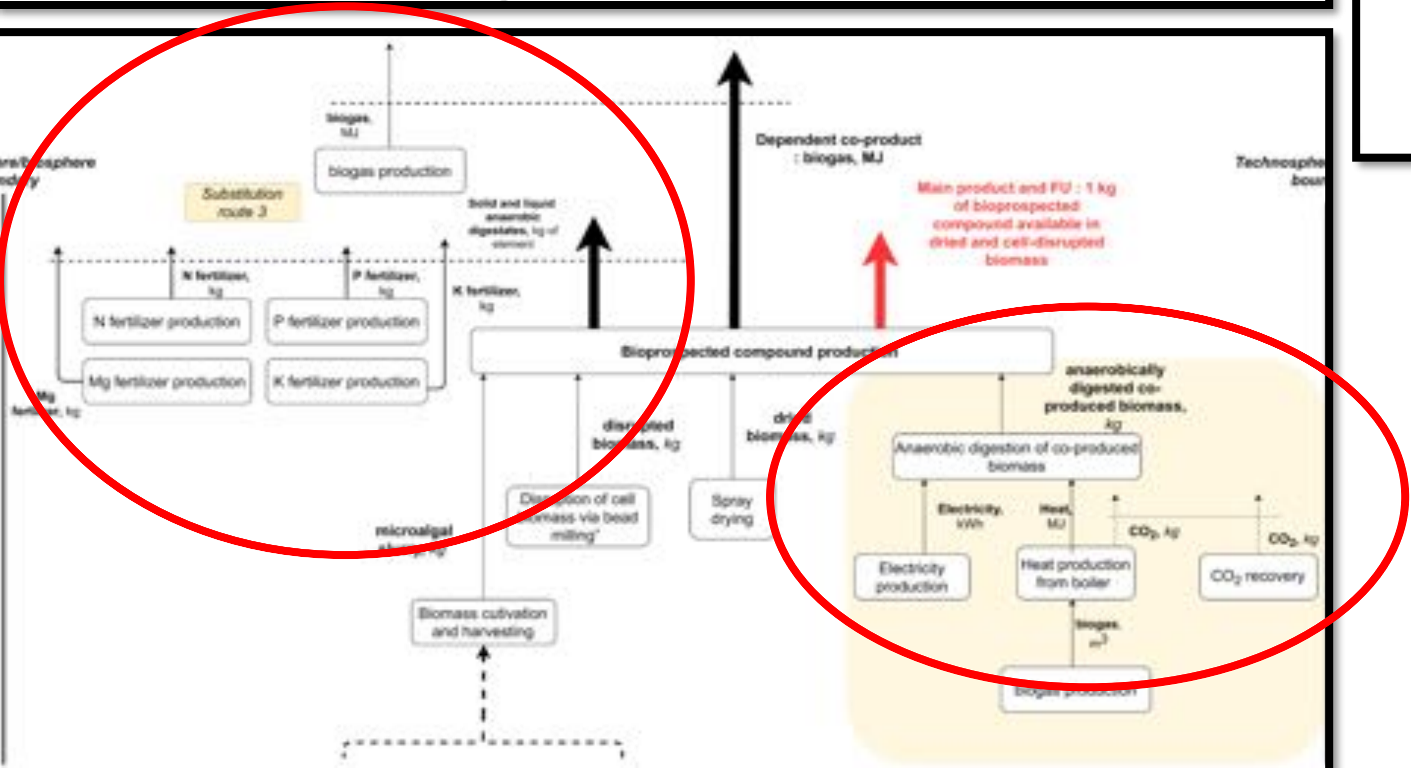
2) Generate random combinations of locations, with weighted probabilities of being part of the mix.



Substitution routes



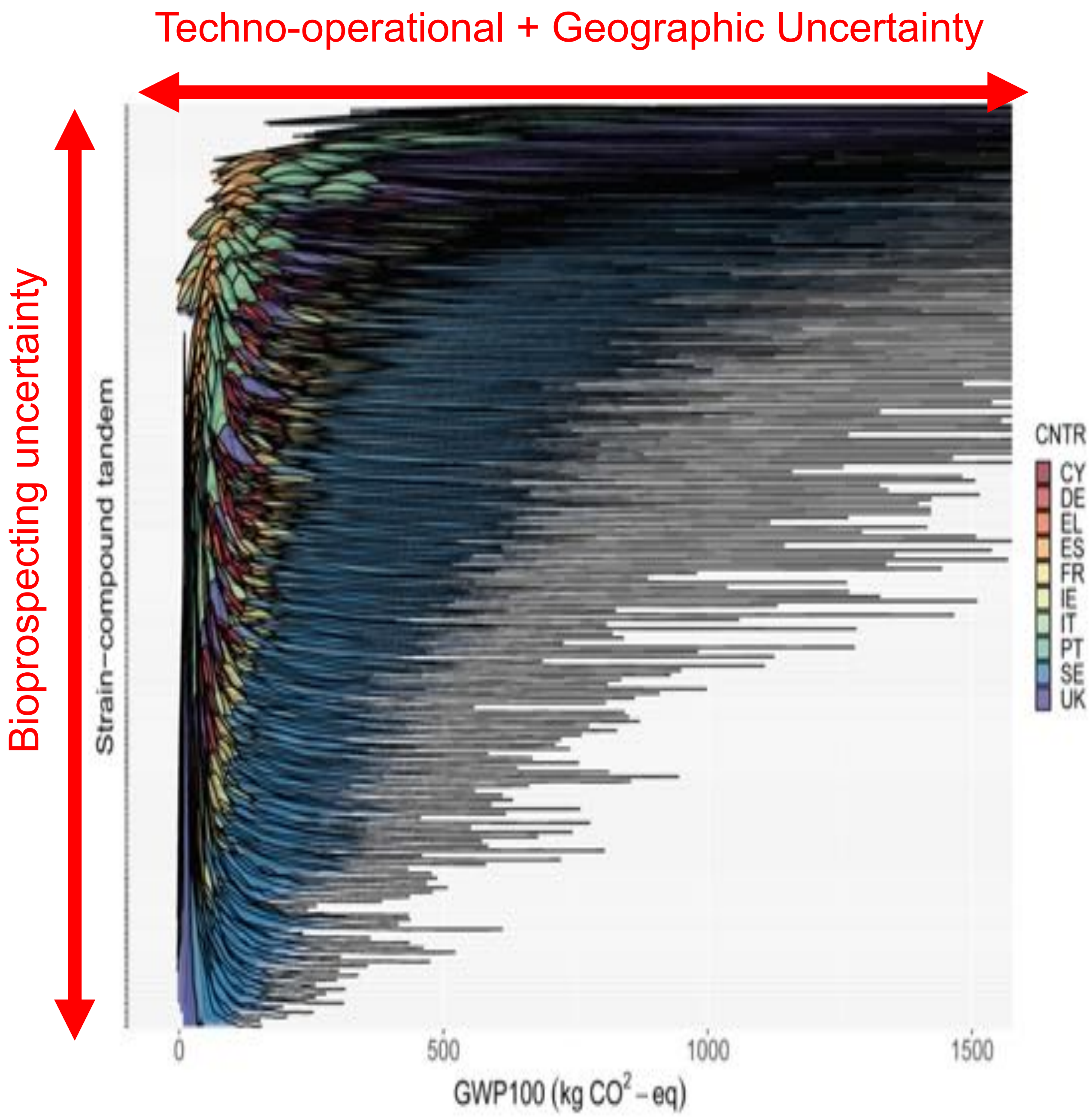




Strain-specific parameter

Probability of each route = 1/3

Simulation results



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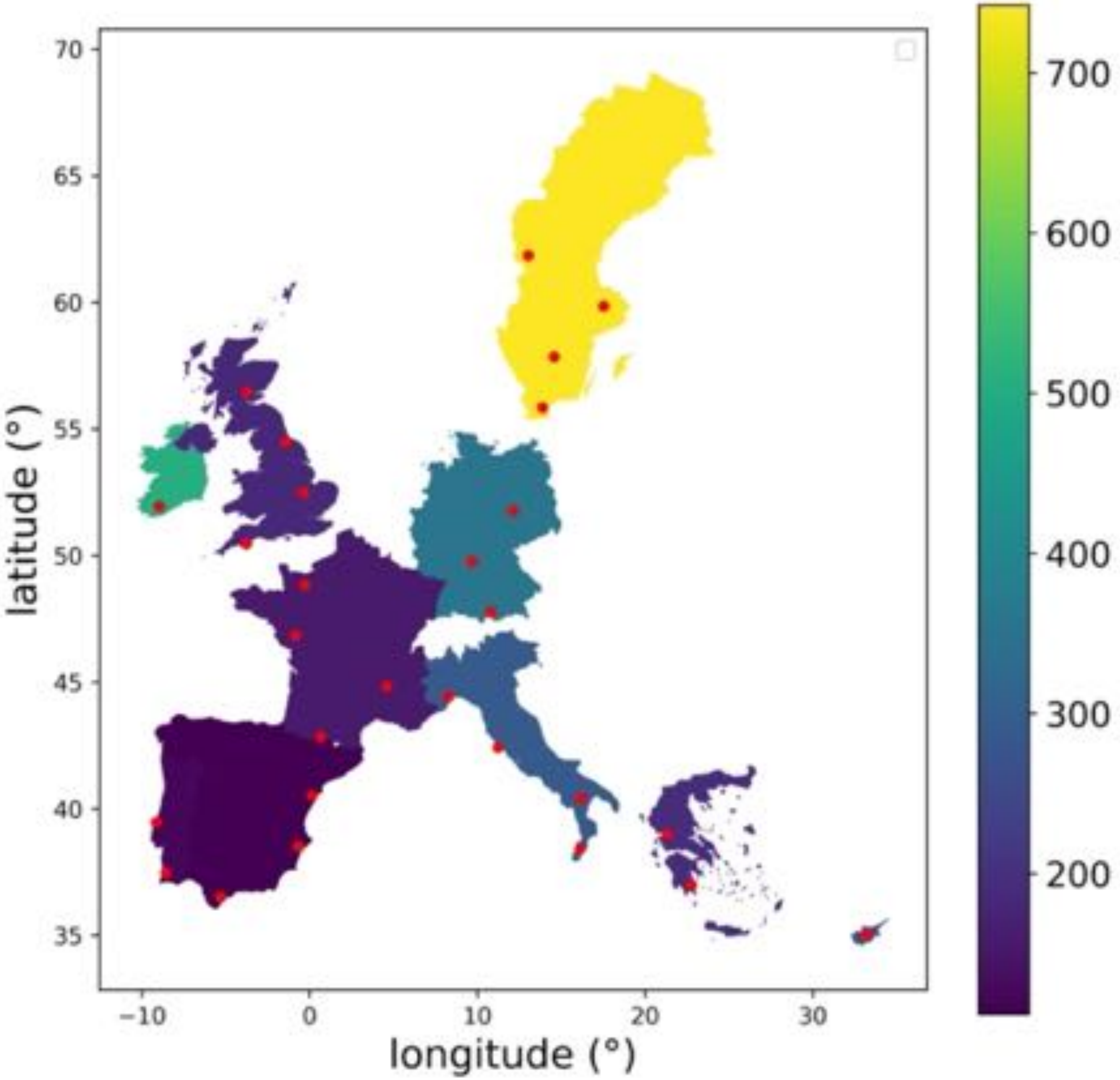
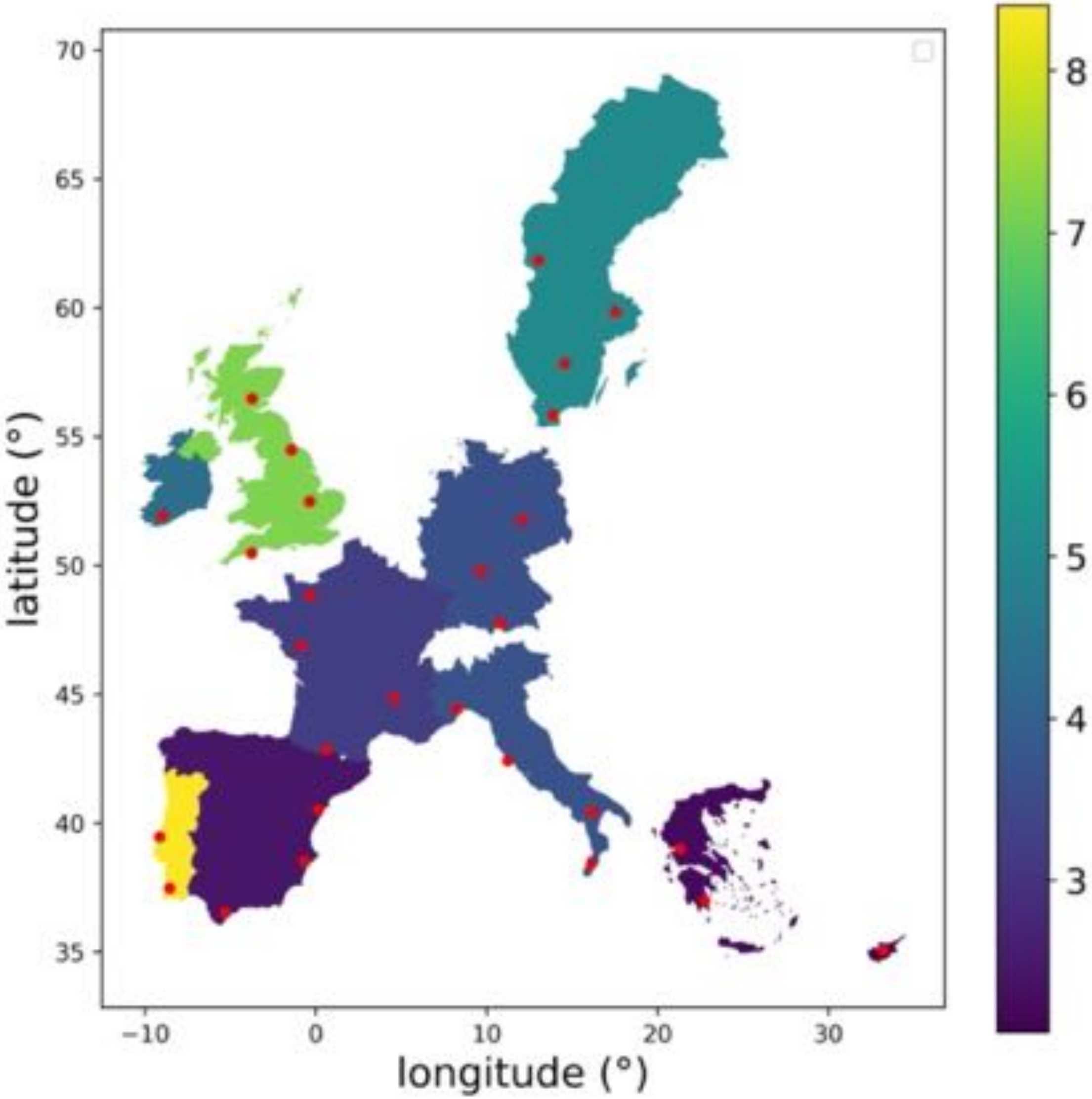
Global warming



Water depletion



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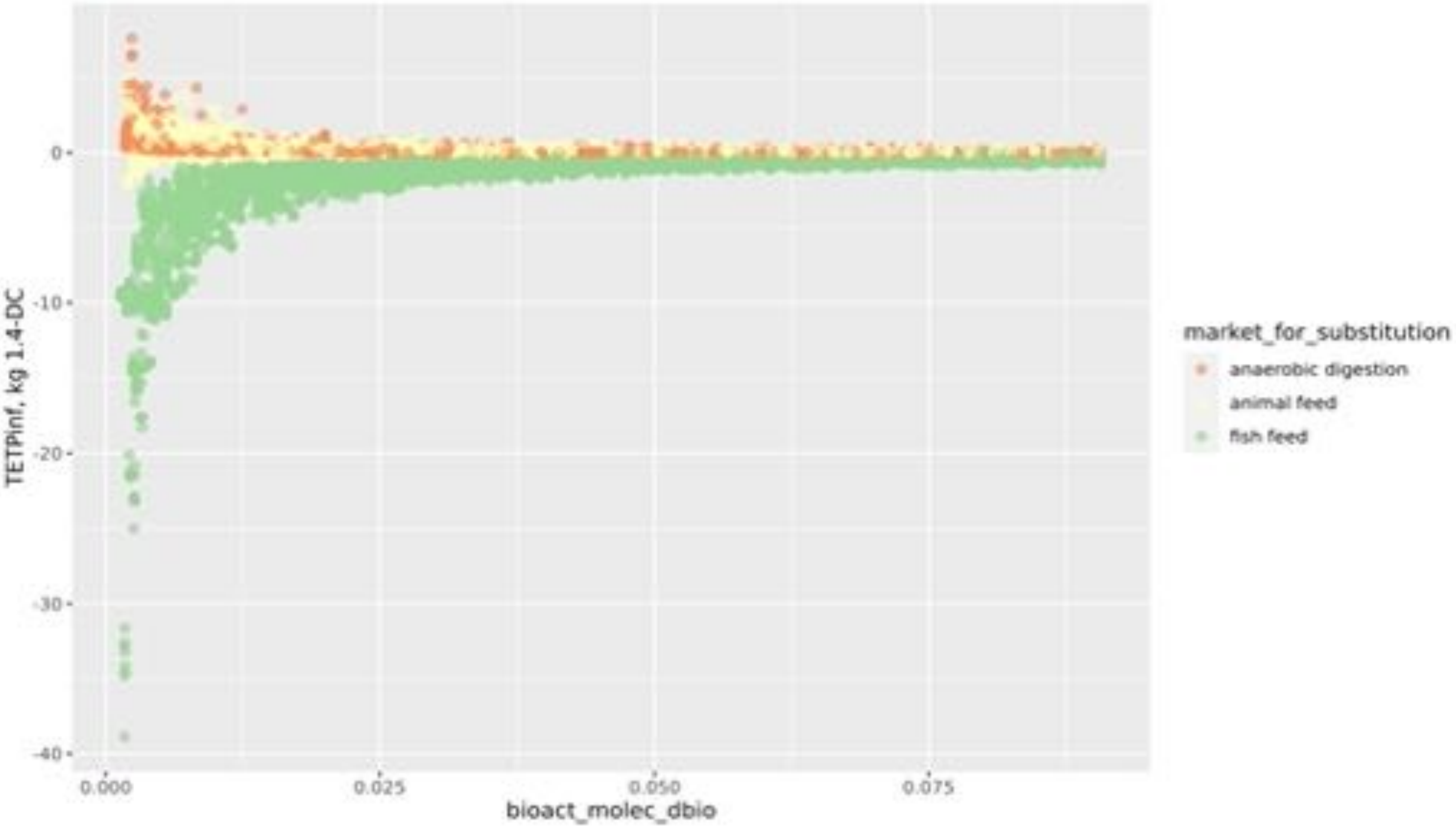
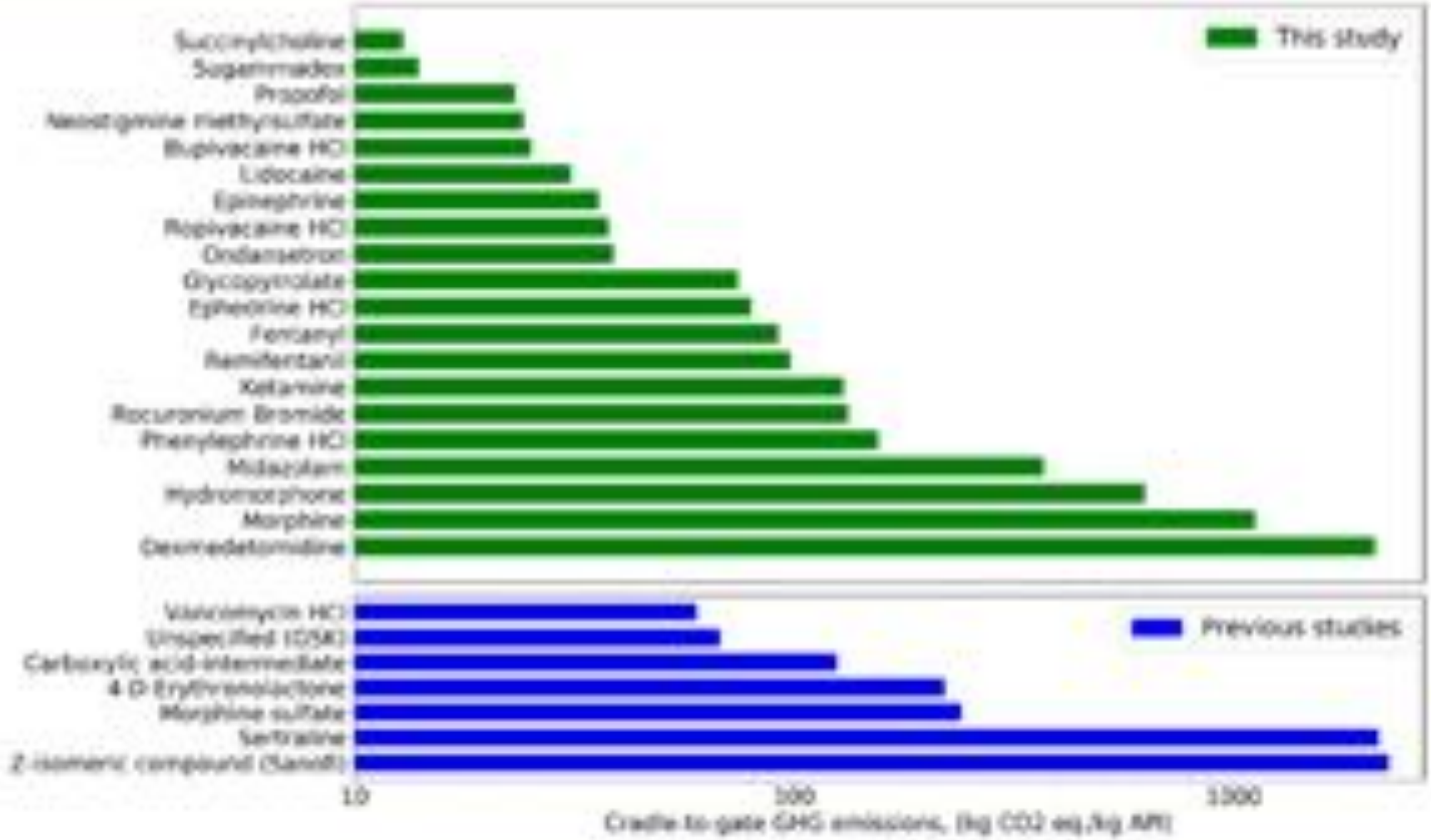
Influence of the substitution route for the co-produced the biomass

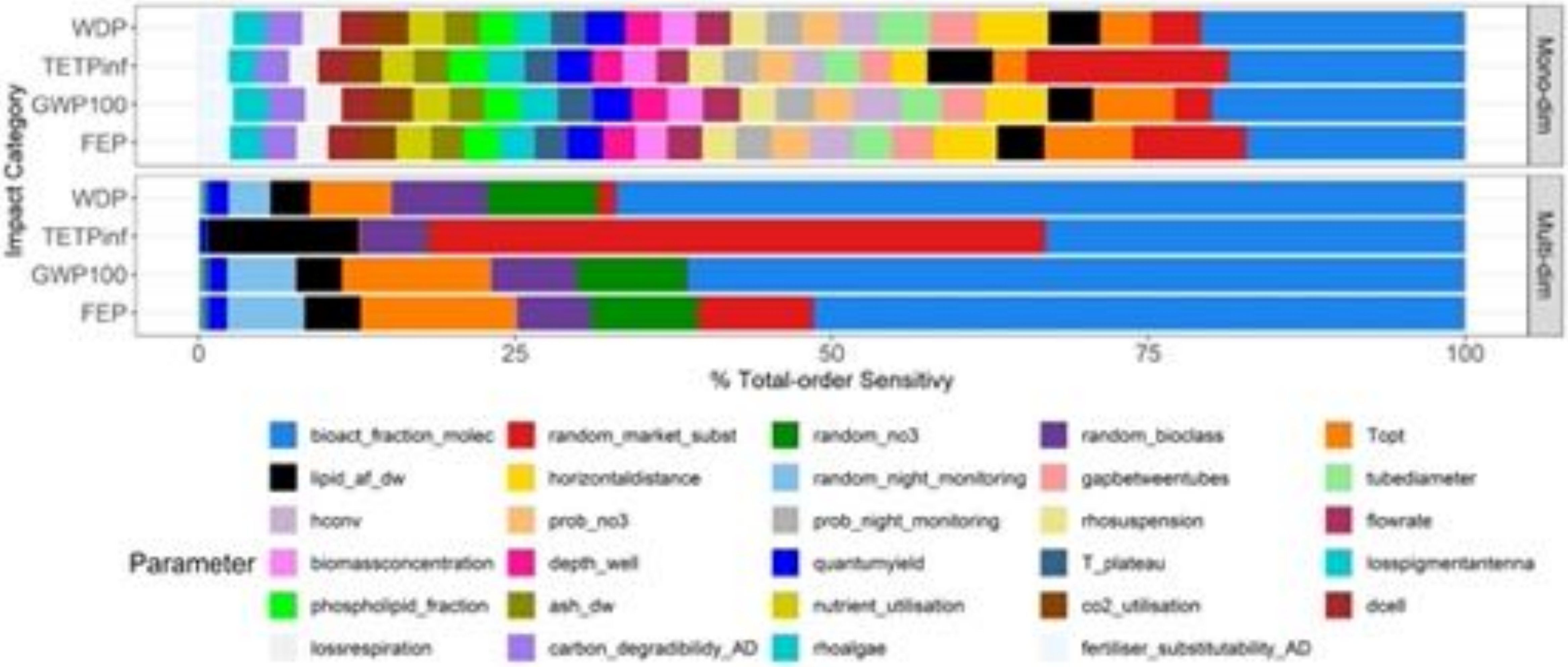


A **rough** comparison with “alternatives”



Parvatker, A. G. *et al.* (2019) ‘Cradle-to-Gate Greenhouse Gas Emissions for Twenty Anesthetic Active Pharmaceutical Ingredients Based on Process Scale-Up and Process Design Calculations’, *ACS Sustainable Chemistry and Engineering*, 7(7), pp. 6580–6591. doi: 10.1021/acssuschemeng.8b05473.

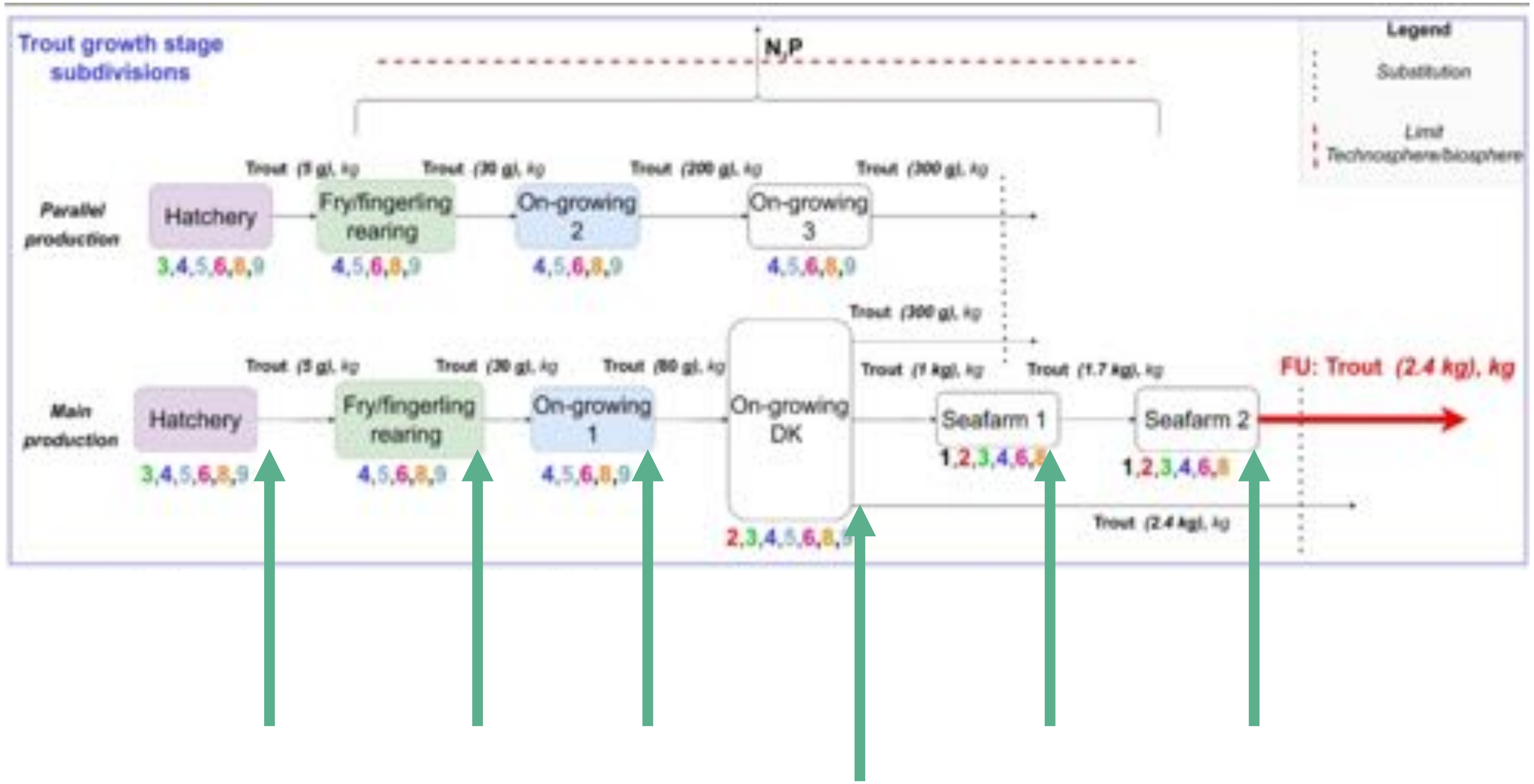
Sensitivity analysis



LCA of fish farm

How does the compound affect the fish farm?

No parameterized LCA model for fish farms
→ Developed our own



- Sea-reared trout production
- Primary data from Denmark and Italy
- Differentiates distinct growth stage divisions
- Allows modulating the mortality and the biological FCR in each division
- Anaerobic digestion of fish sludge and dead fish

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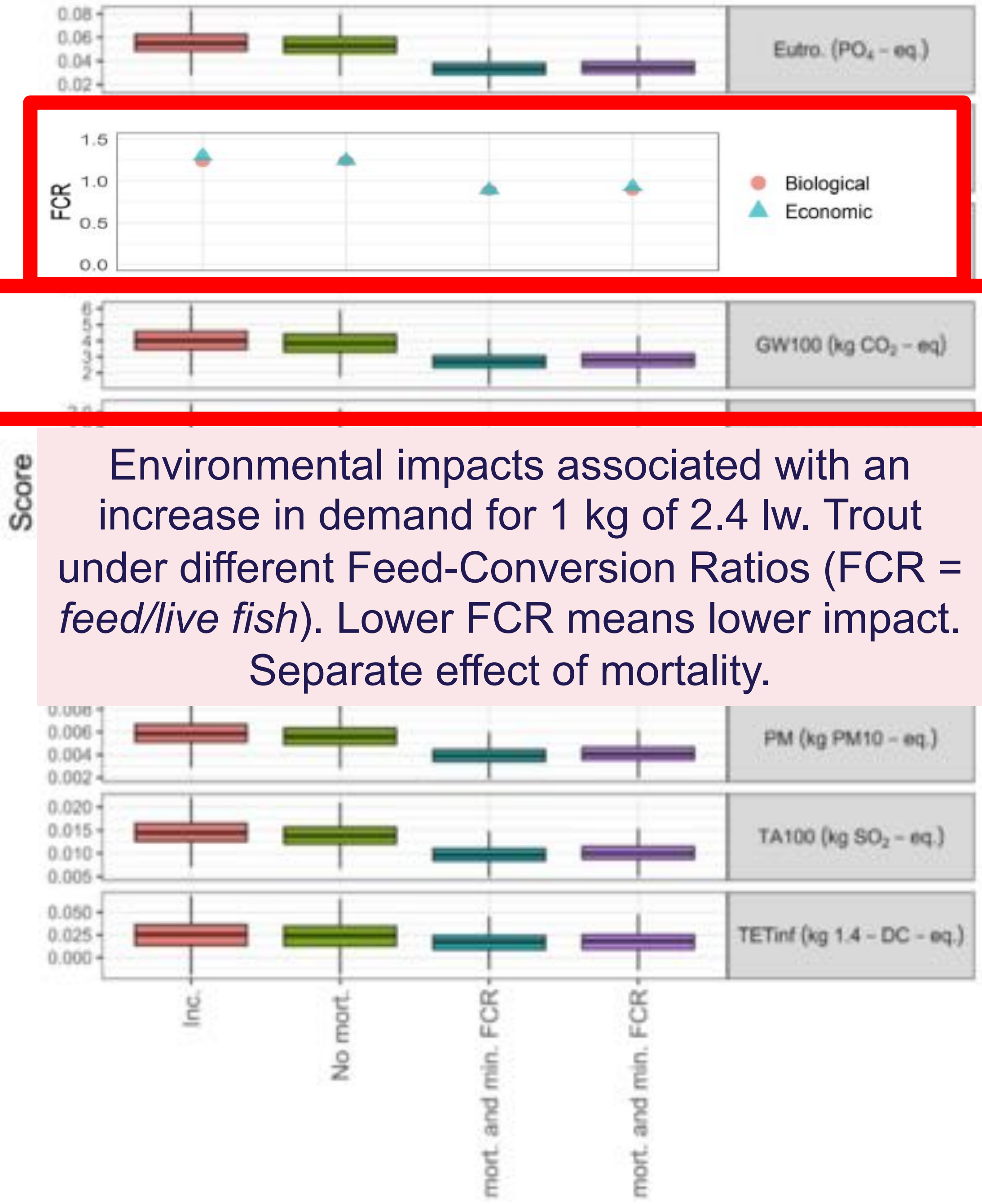
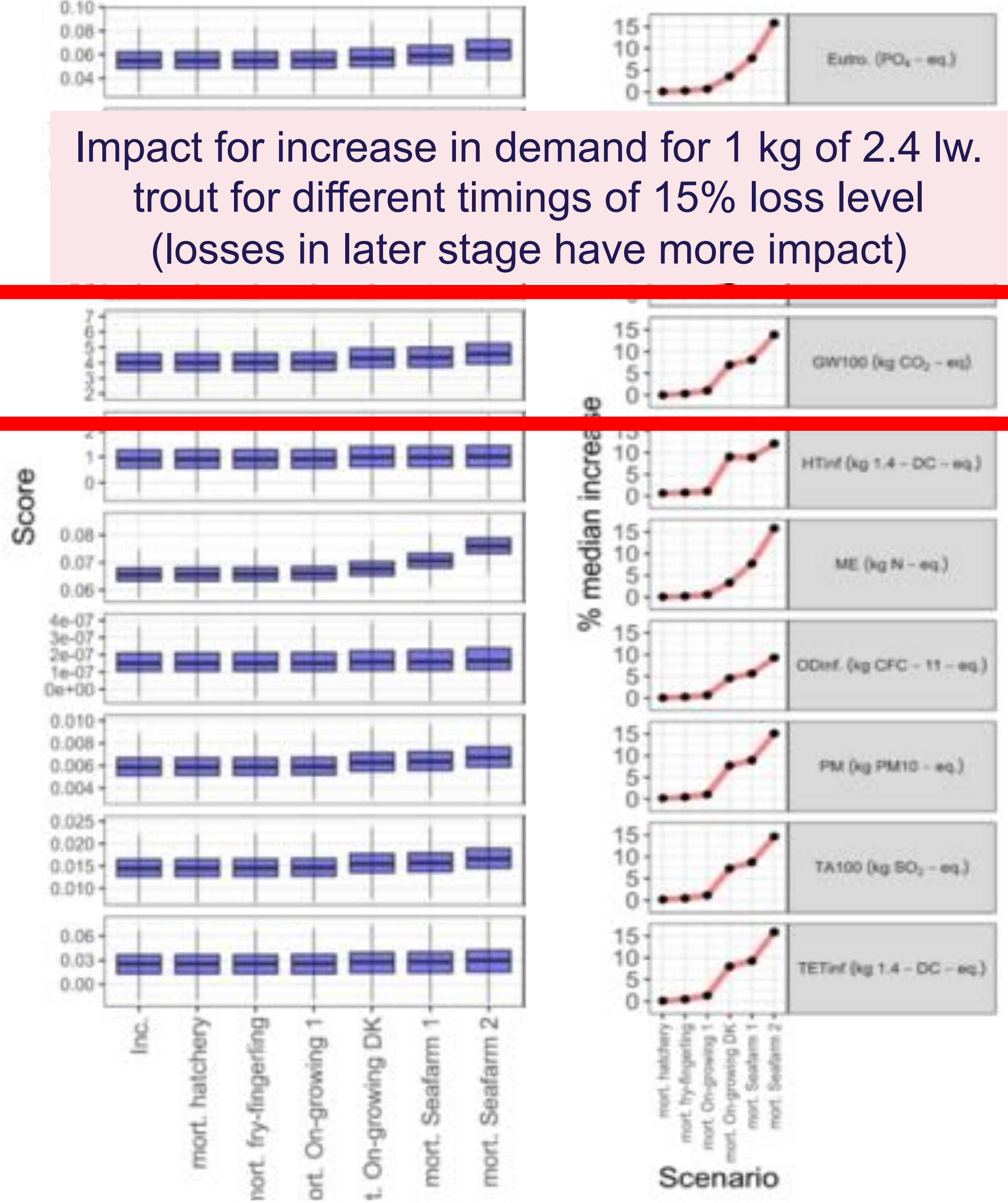
Jouannais, P., Gibertoni, P. P., Bartoli, M., & Pizzol, M. (2023). LCA to evaluate the environmental opportunity cost of biological performances in finfish farming. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-023-02211-8



Environmental impacts associated with an increase in demand for 1 kg of 2.4 lw. Trout under different Feed-Conversion Ratios (FCR = *feed/live fish*). Lower FCR means lower impact. Separate effect of mortality.

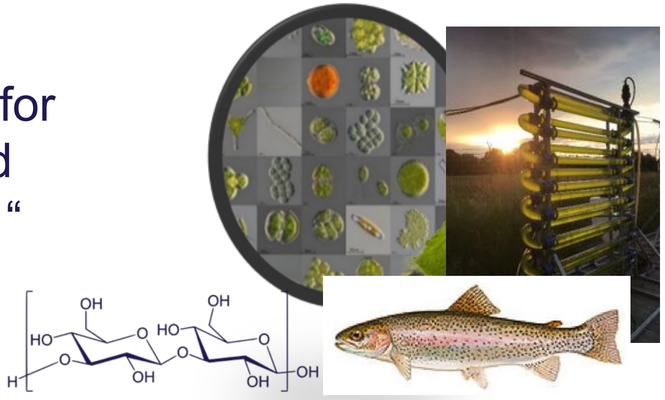


Impact for increase in demand for 1 kg of 2.4 lw. trout for different timings of 15% loss level (losses in later stage have more impact)

Jouannais, P., Gibertoni, P. P., Bartoli, M., & Pizzol, M. (2023). LCA to evaluate the environmental opportunity cost of biological performances in finfish farming. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-023-02211-8

Multi-model results

“Should we initiate bioprospecting for microalgal compounds that could enhance fish farming in Europe? “

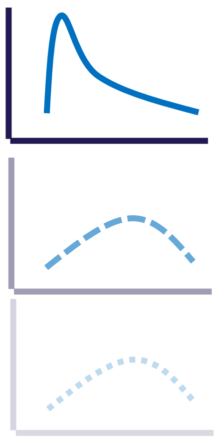


We will invest time and resources only if the total probability of success is over 85%.

A success = Lower impact for fish production with the compound than without

Our “reasonable” expectations for the parameters’ values :

- Microalga ?
- Photobioreactor setup ?
- Locations ?
- Effect on the farm ?
- Losses in the farm at time of application?



?

?

Risk

Uncertainty

Types of incertitude

Stirling, A. (2010) ‘Keep it Complex - 4681029a’, *Nature*, 468(1031).

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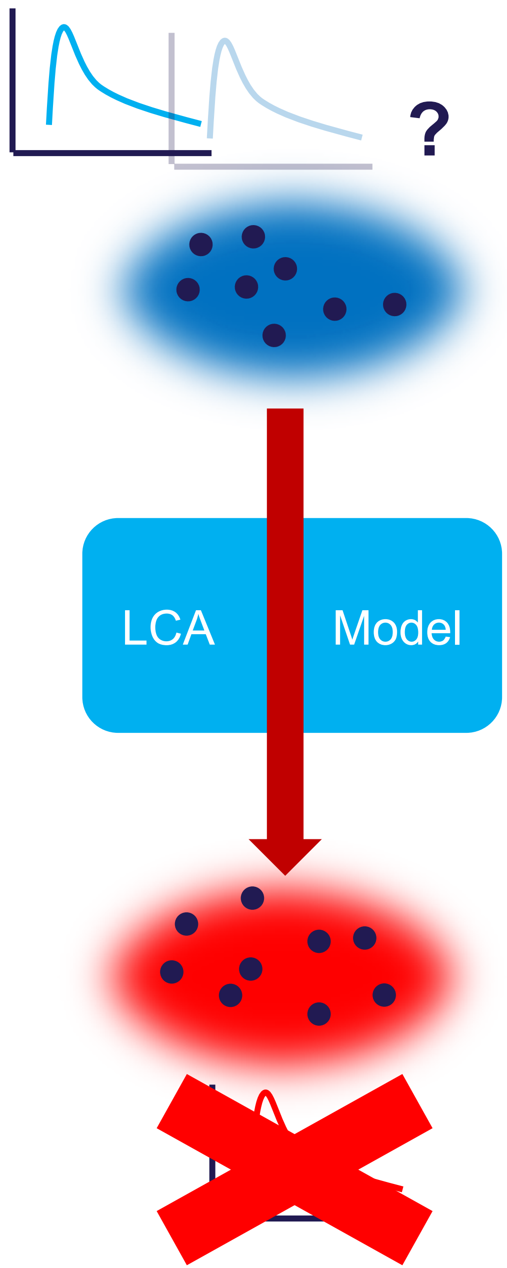
No probability in the input



No probability in the output

Risk and uncertainty should not be treated similarly and propagated together as “probabilities”

So how do we make decisions ?

ENSURe

R1	R2	U1	U2	U3	Y
4.5	3.2	a	b	c	110
5.2	10	a	b	c	-9
…	…	…	…	…	…

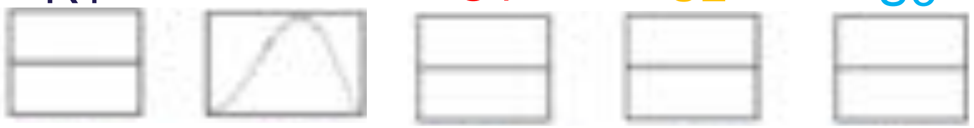
P(S| U1 = a, U2=b, U3=c) = **0.3**

"Risk-only" conditional probability

1) Define a success
2) Define a decision-threshold : 85%
3) Build LCA model
4) Define probability distributions for the parameters

Risk *Uncertainty*

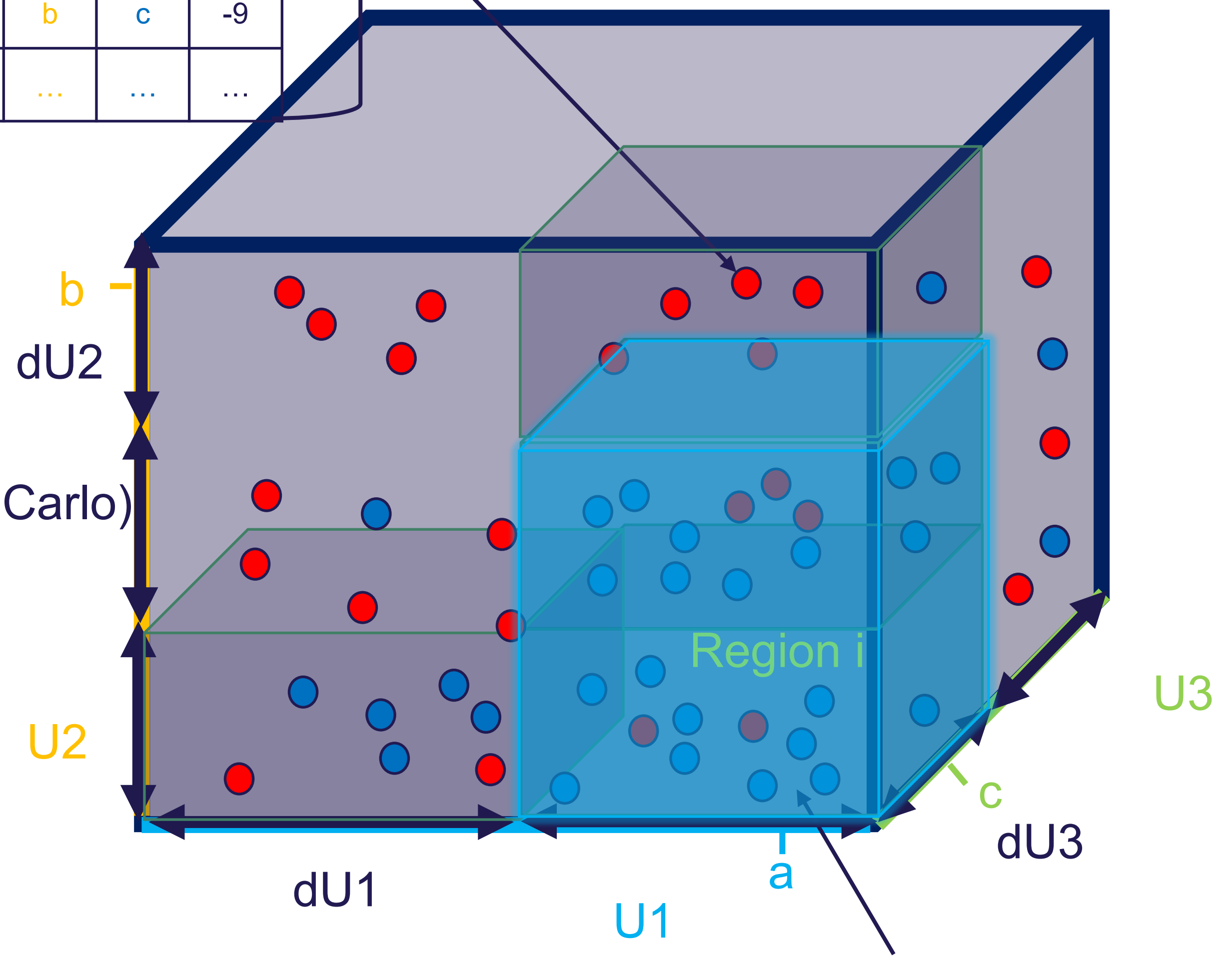
R1 R2 U1 U2 U3



(Arbitrary large ranges)

5) Propagate distributions to environmental impacts (Monte Carlo)

R1	R2	U1	U2	U3	Output	Success
4.5	3.2	5	2	100.3	110	Yes
5.2	10	0.65	23.2	50	-9	No
9	3	10.4	12	270.4	12.5	Yes
…	…	…	…	…	…	…



6) Regionalize the uncertain space

P(S| Region i) = **0.86**

7) Assess conditional probabilities of success in the regions

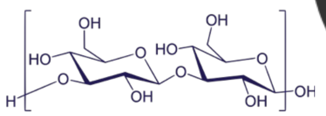
If P(Box) =1, then P(S) ≥ P(S|Box) * P(Box) ≥ 0.85

8) Apply PRIM to find boxes

Kwakkel, J. H. and Jaxa-Rozen, M. (2016)

“We will invest time and resources only if the total probability of success is over 85%.”

40 Risk parameters
35 Uncertain parameters

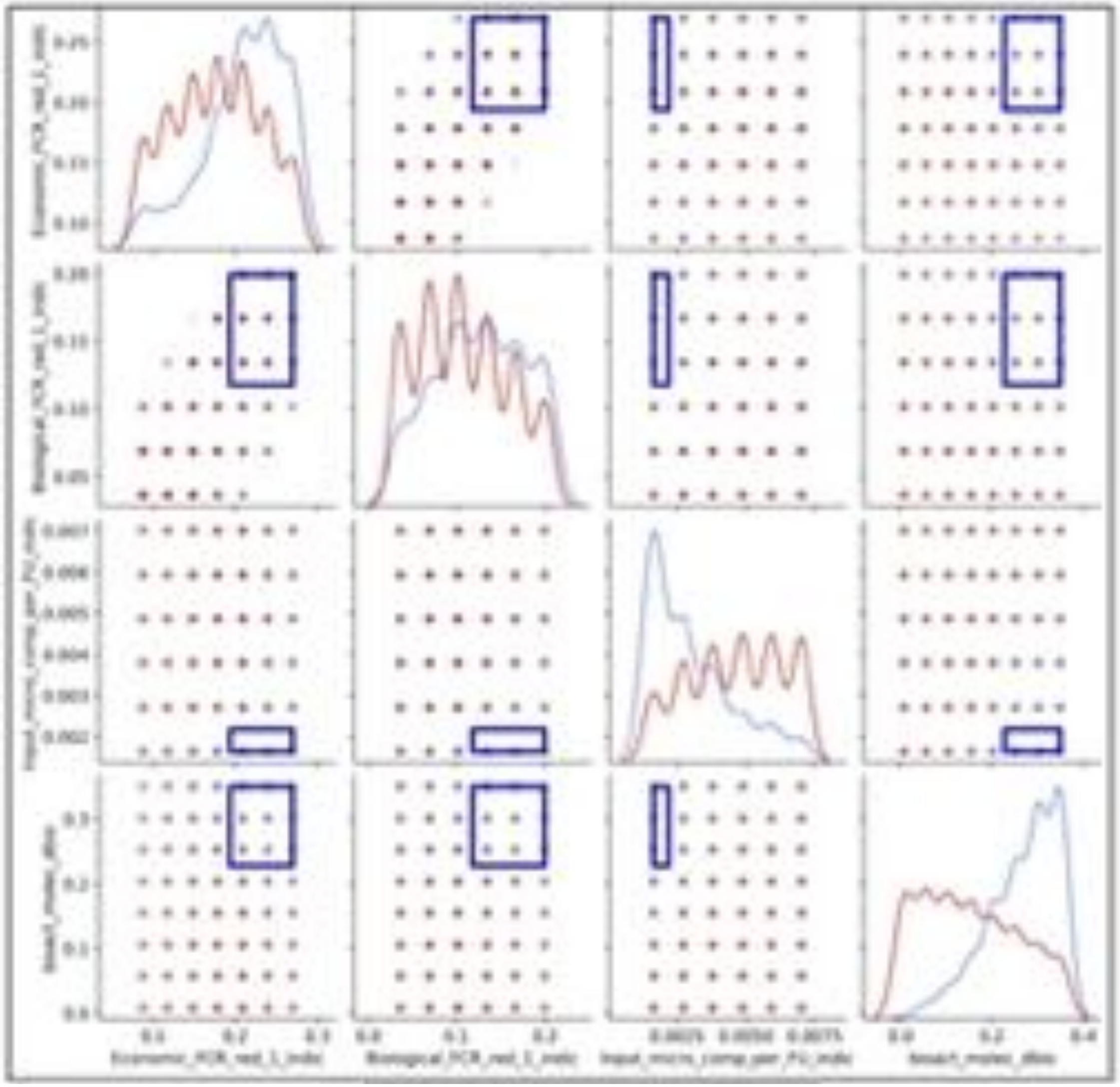


Decision Threshold : 0.85

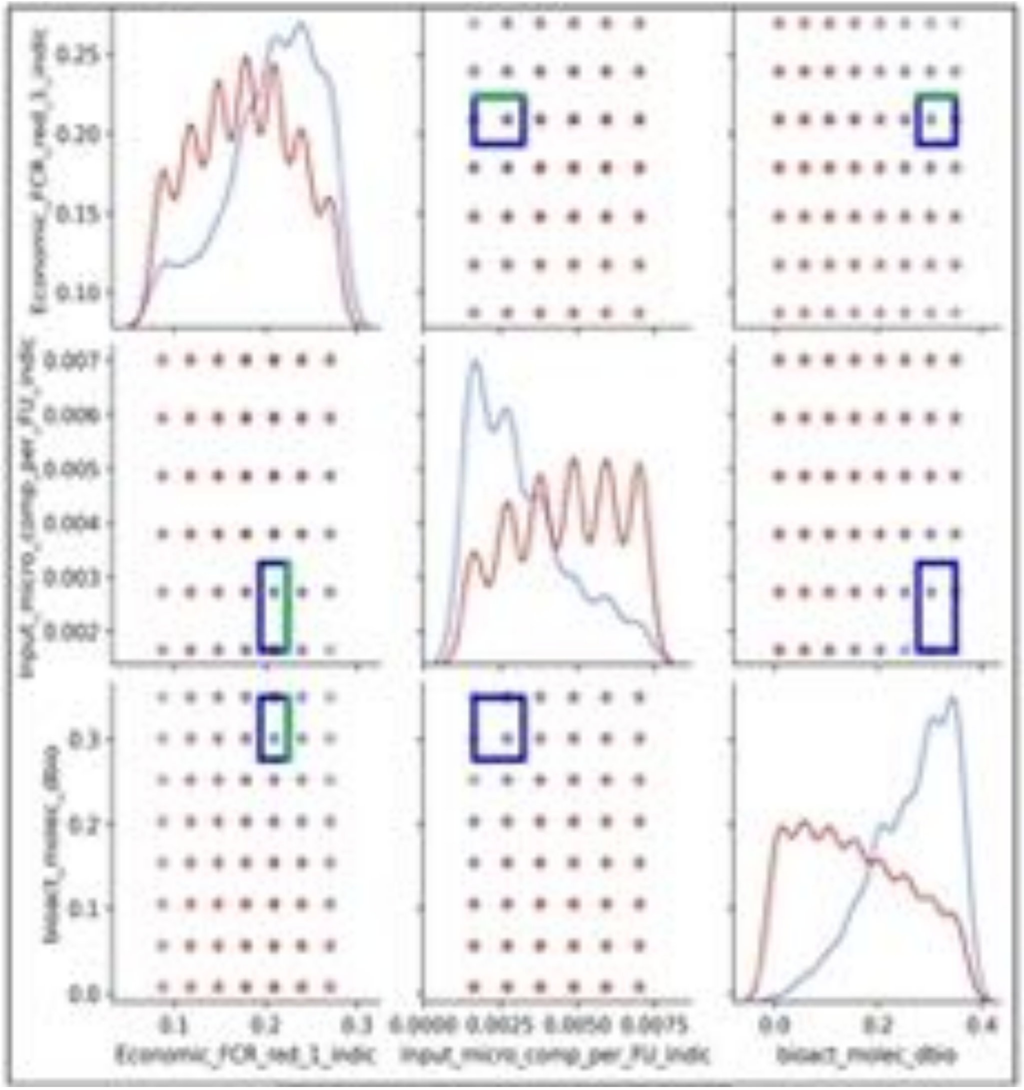
350 000 000 process simulations and LCAs

Global Warming

Box 1



Box 2



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Results ENSURe

Considering the risk on all parameters, to ensure a probability of success >85 %, we would need to be sure that..

Global warming boxes

Aggregated parameter	Box 1	Box 2	Box 3	Box 4
Compound content in the biomass ($g.g^{-1}$)	>0.2	>0.3	>0.2	>0.3
Overall Economic FCR reduction compared to projected alternative (%)	>22	>22	>17	>22
Overall Biological FCR reduction compared to projected alternative (%)	>15	Any [0,25]	Any [0,25]	>7
Dose of microalgal compound supplied to fish during their whole life cycle ($g.kg^{-1}$)	<2.5	<3.5	<2.5	<5
Impact per kg of currently used pharmaceutical (kg CO_2-eq. kg^{-1})	Any [10-1000]	Any [10-1000]	Any [10-1000]	Any [10-1000]
Level of losses experienced by the farm before application of the compound = % projected mortality / % current mortality	Any [1-6]	Any [1-6]	>3	>4.2

- No need to propose probabilities within the boxes.
- No need to propose probabilities for the parameters which are not delimiting a box.
- Ensuring 85% success probability requires predicting a very performant compound in a challenging context for the fish farm.

Jouannais, P., Blanco, C. F., & Pizzol, M. (2024). ENvironmental Success under Uncertainty and Risk (ENSURe): A procedure for probability evaluation in ex-ante LCA. *Technological Forecasting and Social Change*, *201*, 123265. https://doi.org/10.1016/j.techfore.2024.123265

Overall reflections

Challenges

- System Boundaries: full system still not known so impossible to get the scope right → assumptions and uncertainty analysis

- Functional Unit: focused on microalgal or fish biomass as functionality of compound unknown. Makes comparison difficult with other studies (e.g. pharmaceuticals)

- Product Complexity: Several assumptions of substitution of side-streams. Affect results but no more than other parameters or even less.

- Scope Differences: Multiple IC assessed

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Forecasting green technology

- Pilot scale ≠ full scale
- Not even the developers know how & when (time to market usually underestimated)
- Future context unclear (resource availability? Energy mix?)

Photo by ThisisEngineering RAEng on Unsplash

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Prospective assessment

Start **Research on emerging technology** End

LCA work starts here

Decisions made already here

Good data only here

LCA of emerging tech
= predict the future (which is uncertain)
= dealing with uncertainty

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What we learned

Current paradigm:

Focus on the single LCA numerical result.

Looking for the “right” number.

Narrowing scope.

Uncertainty last (“nice to have”).

Think how to model then think about uncertainty.

“Uncertainty first” paradigm:

Focus on assumptions and data ranges.

There is a “cloud” of numbers.

Expanding scope.

Separate signal from noise.

Think uncertainty then think how to model.

Thank you

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