CAMBIOSCOP
Carbon management towards low fossil carbon use

Sustainable transitions towards low fossil carbon economies: challenges and prospects

Lorie Hamelin

@hamelinlab hamelin@insa-toulouse.fr

Professor, INRAE Chairholder (CPJ) on Sustainable Transitions towards low fossil carbon economies. Based at TBI lab of INSA Toulouse (part of Federal University of Toulouse)

Principal Investigator, Make Our Planet Great Again project Cambioscop (2018 – 2023)

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Transdisciplinary research for a healthy planet * Reims * 30.03.2023

1

The transition

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Doing all we do now … without fossil C?

Routes towards low fossil C

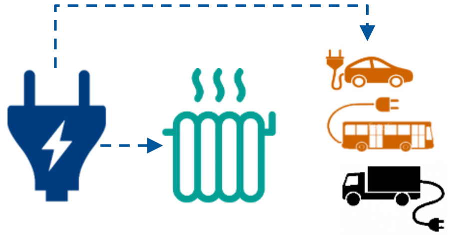
No C (decarbonize)

Biomass C
- Land dependant
- Residues

Atmospheric C

Recycle C

Essentially electricity!



In the low fossil economy:
Carbon becomes a limited resource
to use as efficiently as possible!

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Doing all we do now … without fossil C?

Message 1: Don't waste biomass C on services that can be supplied without carbon

Message 2: Help us creating solutions using C as efficiently as possible (more for the service, less as unrecoverable C)

Message 3: Help us with solutions to recycle C as much as possible

It's not about C. It's about fossil C.

Stop this decarbonization non-sense.

We need C! It's the basis of all life on Earth!

Paris agreement: a delicate balance

Recognizing that **"climate change represents an urgent and potentially irreversible threat"** to humanity, the Paris Agreement calls for limiting global average temperature to well below 2°C above pre-industrial levels. It also calls for a **"balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century".**

GHG mitigation

(biophysical) CO_2 removals

Keep fossil C in the ground (substitution)

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Paris agreement: a delicate balance

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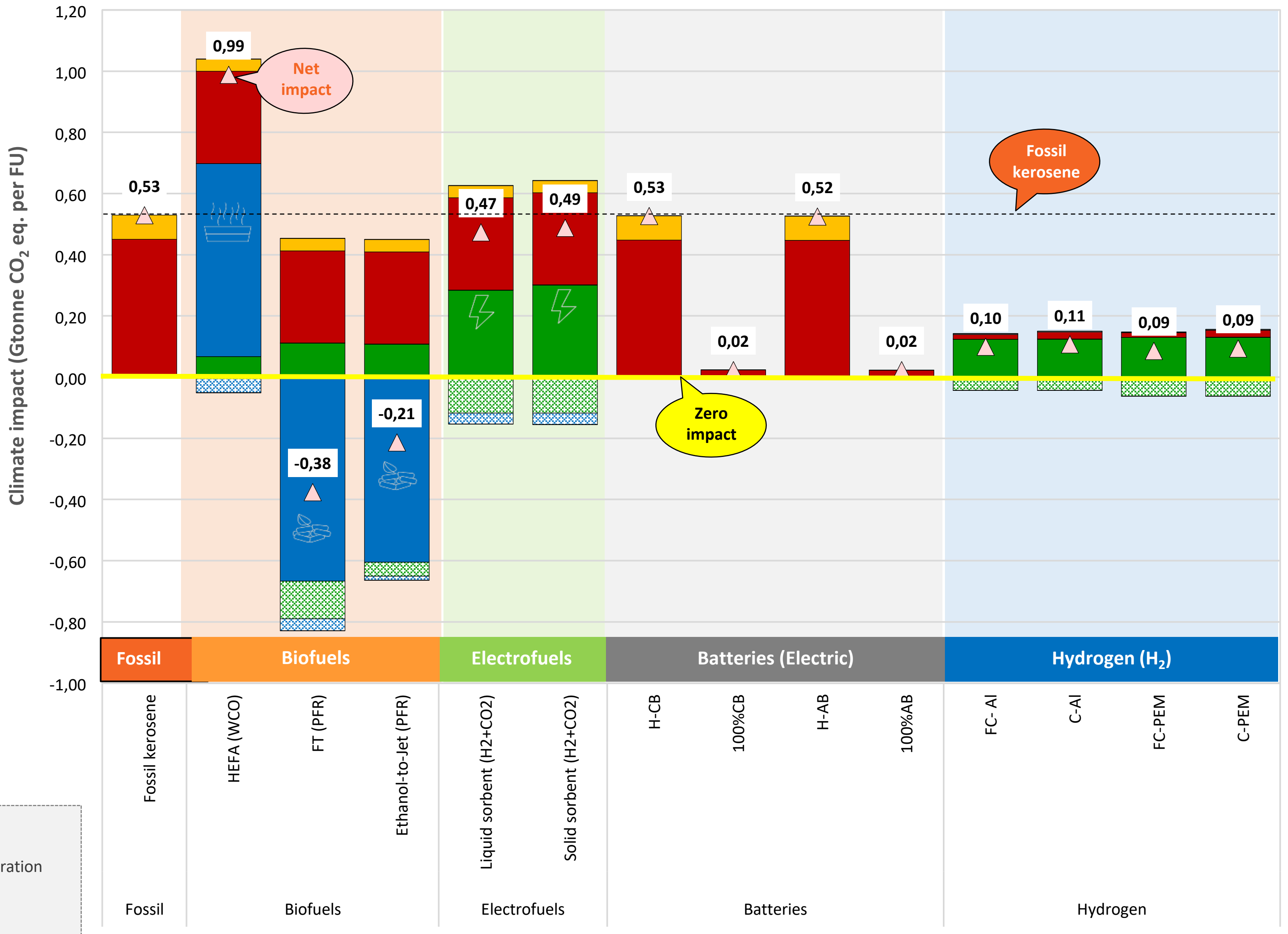
Keep fossil C in the ground (substitution)



Legend

- Conversion processes (any processes prior to operation)
- Fossil kerosene system
- End-of-Life management (whether battery and/or aircraft)
- Counterfactual & Displacement
- Aircraft manufacture
- Other (additional) infrastructure
- Aircraft operation

2

The constrained resources challenge: land and « waste »

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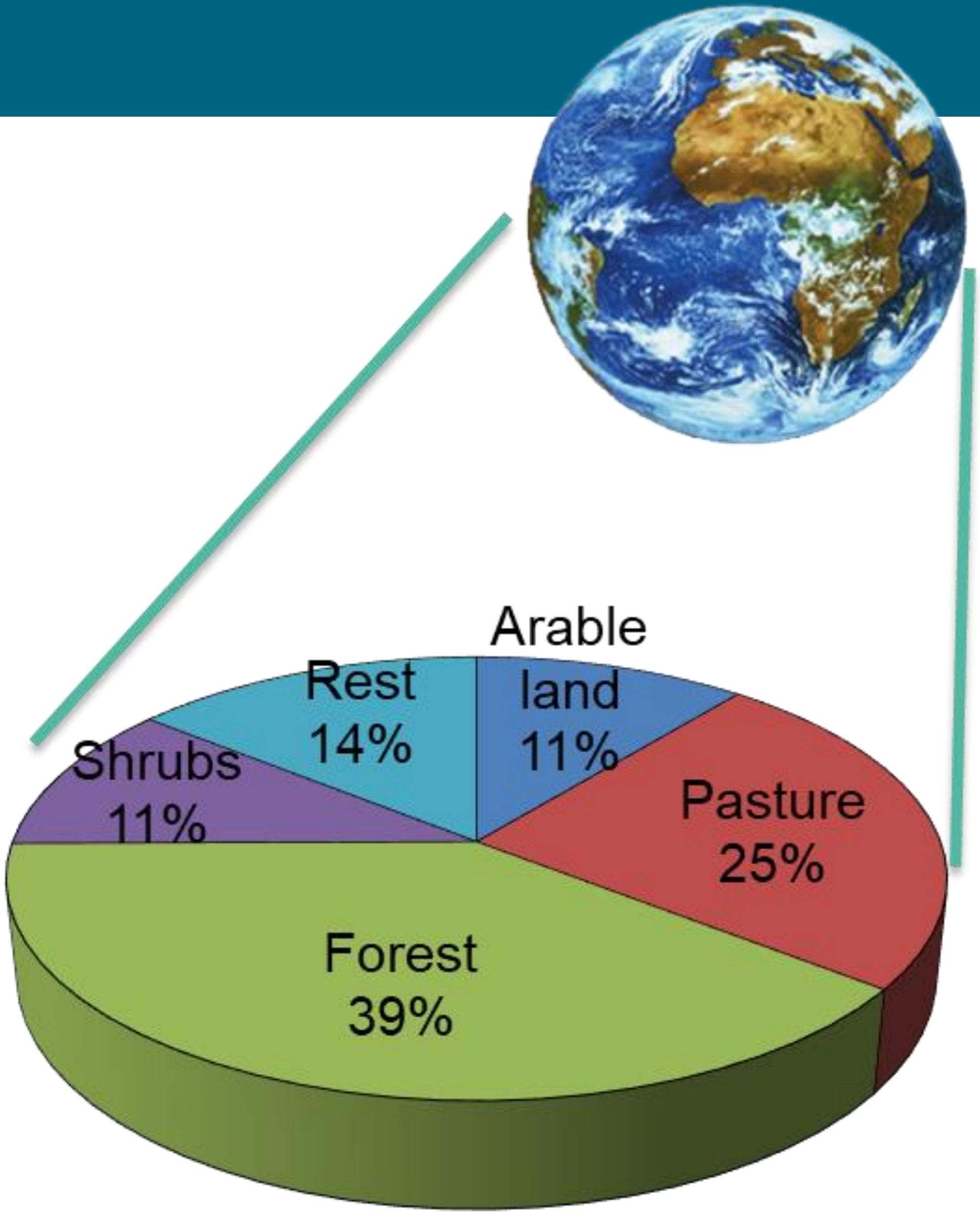
Global outlook on land use

12.5 Gha of land area on Earth*:

- **4.5 Gha agricultural land**
  - 1.4 Gha arable land;
  - 3.1 Gha pastures

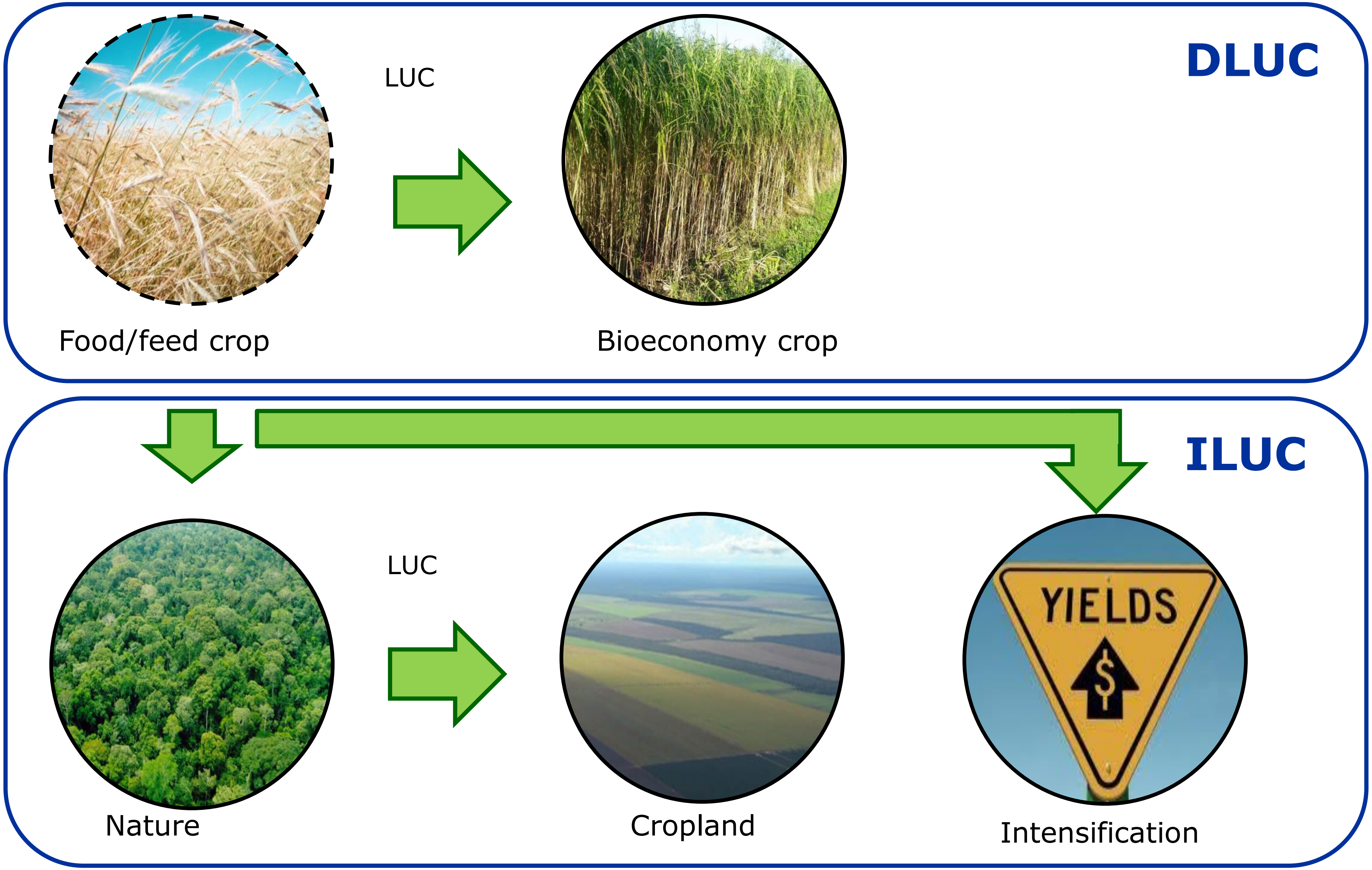
- **4.9 Gha forest**
  - ~1.6 Gha primary forest;
  - ~ 0.3 Gha plantations;
  - ~ 2.9 Gha naturally regenerated;

- **3.1 Gha other land**
  - 1.7 Gha uncultivable (permanent snow, water);
  - 0.08 Gha rest (urban)
  - 1.4 Gha shrub



*(*Excludes Antarctica; FAOSTAT, retrieved in 2020 (data for 2017; MODIS data); FAO 2010; Kampman et al. 2008; Kok et al. 2008); Inconsistencies due to rounding*

Land Use Changes: case of crops



COMMENT · 27 MARCH 2019

Why the US–China trade war spells disaster for the Amazon

An analysis of global soya-bean production forecasts massive deforestation in Brazil – stakeholders must act fast to prevent it, warn Richard Fuchs and colleagues.

Peter Alexander, Calum Brown, Frances Cossar, Roslyn C. Henry & Mark Rounsevell

Richard Fuchs ,

Fields of soya beans (left) sit alongside untouched natural forest in the Cerrado ecoregion of Brazil. Credit: Marizilda Cruppe/Greenpeace

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doi: 10.1038/d41586-019-00896-2

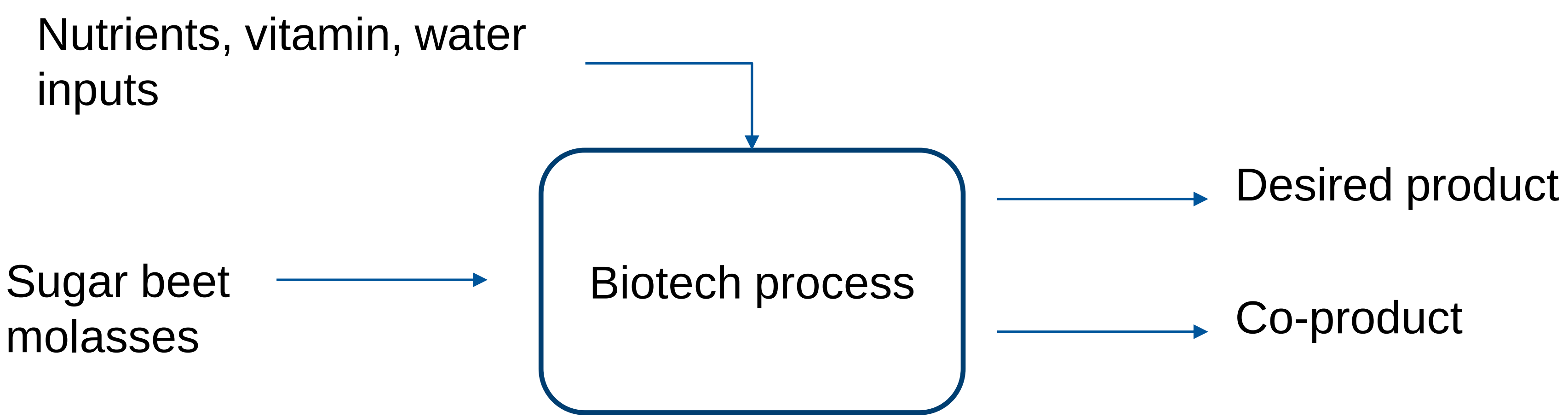
Source: Hamelin (2013). https://www.ceesa.plan.aau.dk/publications/phd-dissertations/

Land

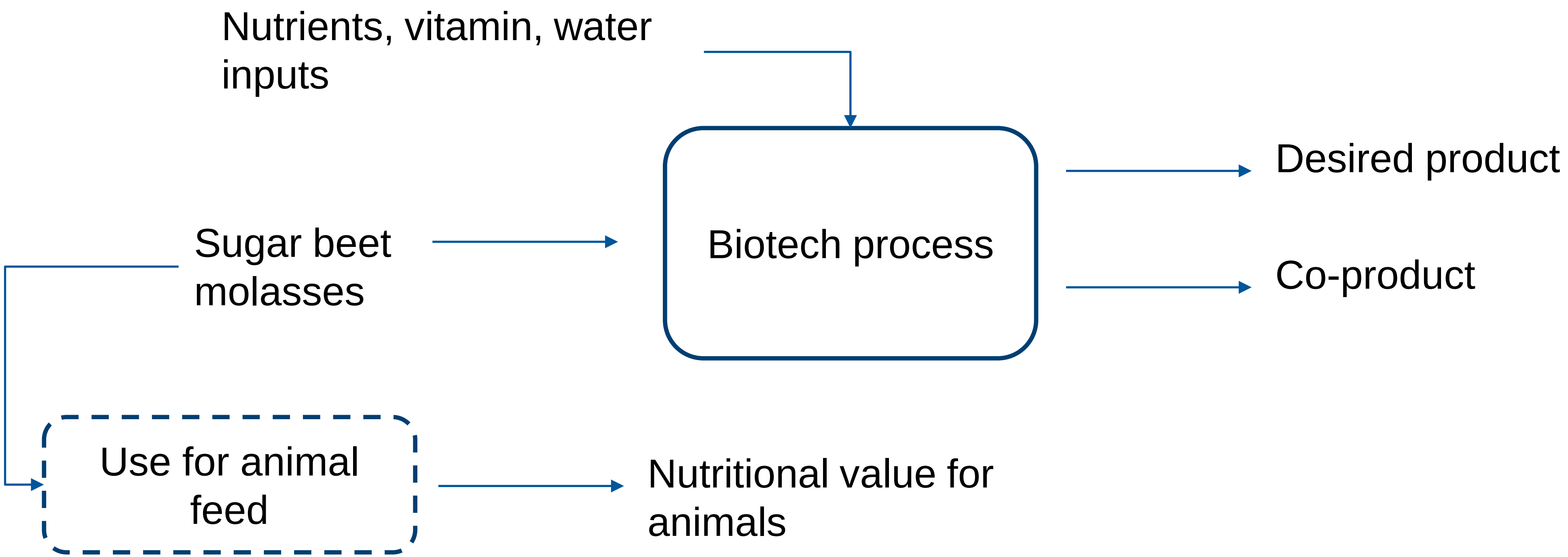
Message 4: Does your solution demands extra land? The moment this is the case, it implies a share of deforestation (and intensification), and emission that goes with it

Message 5: On the other hand, if you have a solution that can prevent the additional demand for land (e.g. new food production), then this can lead to important GHG savings

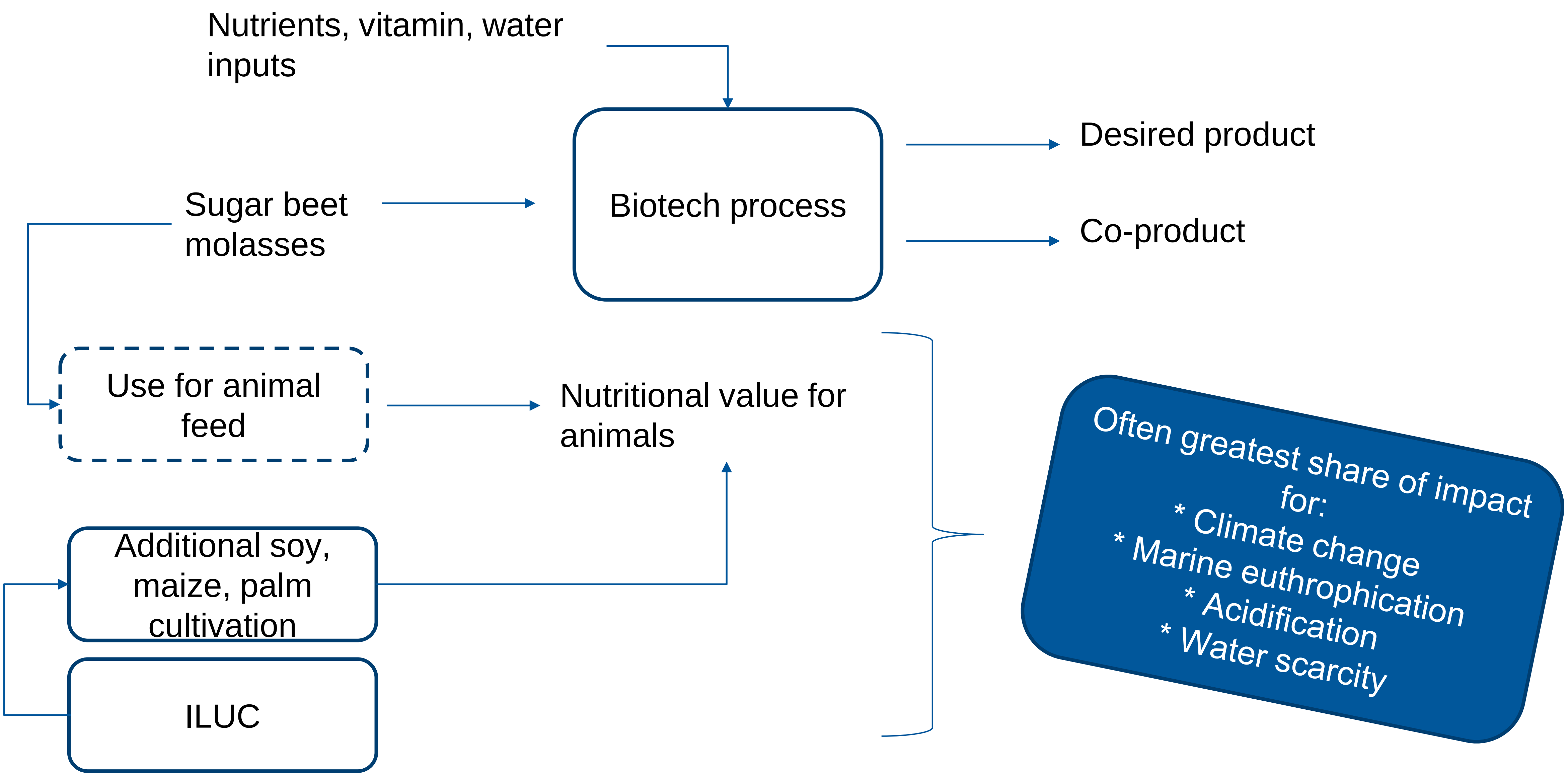
Beyond land-dependant feedstock: residual feedstock



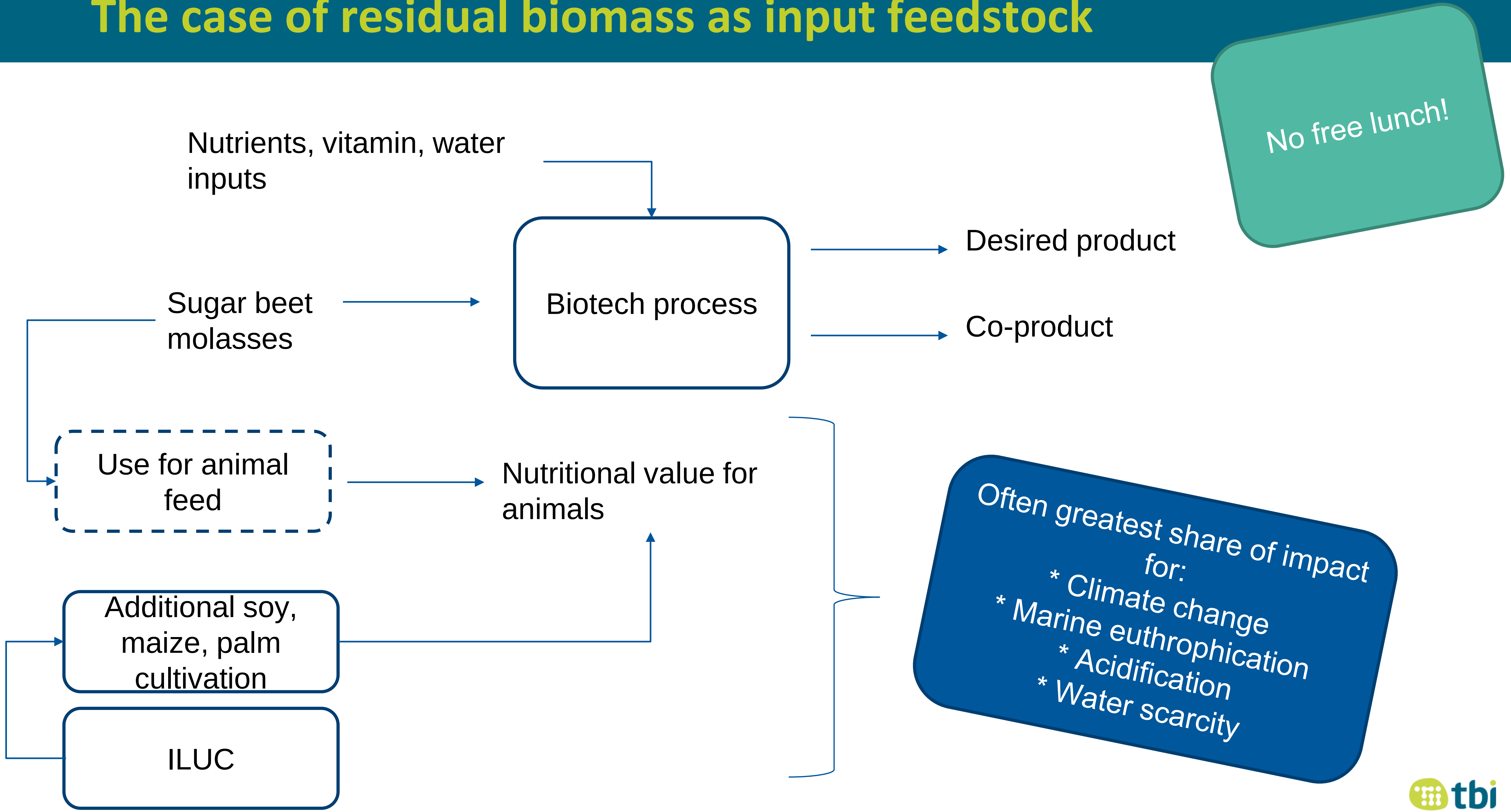
The case of residual biomass as input feedstock



The case of residual biomass as input feedstock



The case of residual biomass as input feedstock



Residual biomass

Message 6: Always consider what was done with the resource BEFORE you mobilize it.

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3

Fluctuating power challenge

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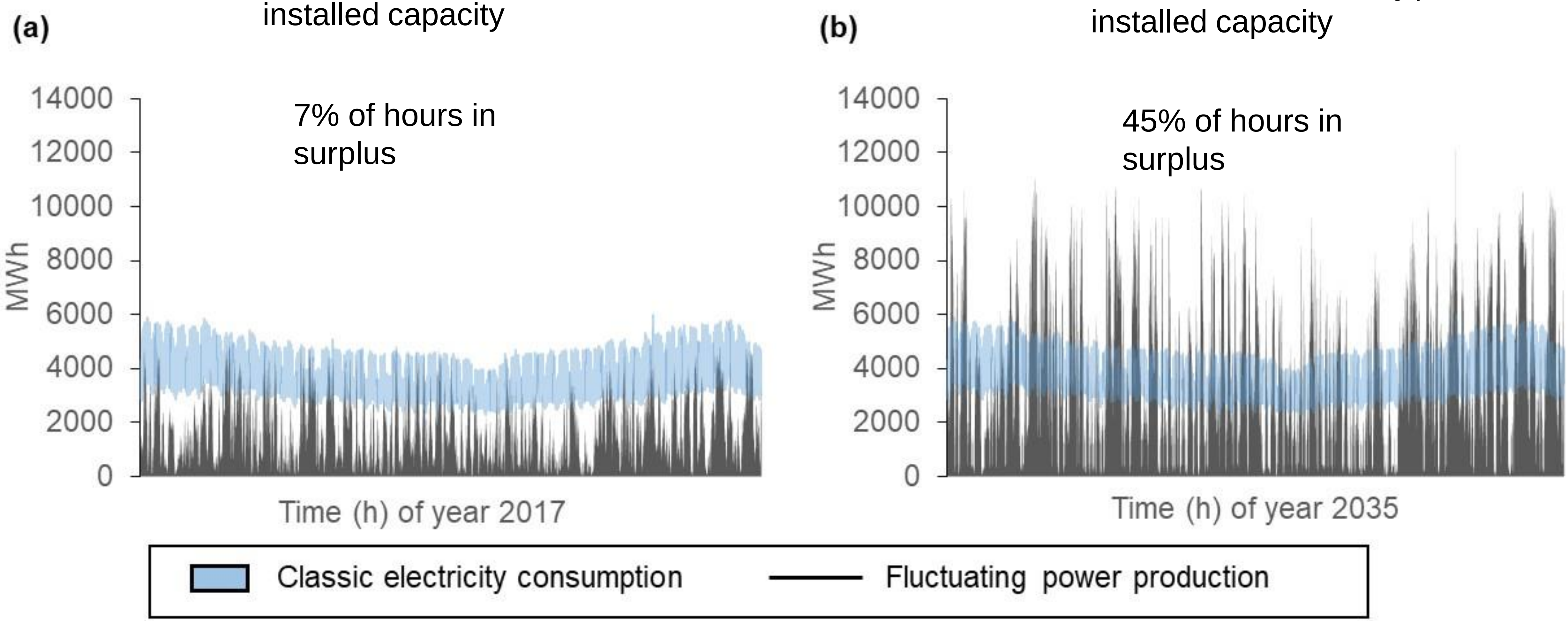
The opportunities of more fluctuating power

2017
6092 MW fluctuating power installed capacity

2035
13,409 MW fluctuating power installed capacity



Source: Hamelin et al. 2021. https://doi.org/10.1016/j.rser.2020.110506

Fluctuating power

Message 7: Don't kill an idea because it needs a certain quantity of power. This may not be an issue in the future. We cannot exclude electrifying heat.

Message 8: Renewable gas is not just a source of power, but of hydrocarbon

4

Nutrients

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Where we get our N and our P

N: Haber Bosch process and interaction with natural gas

P: Limited reserves

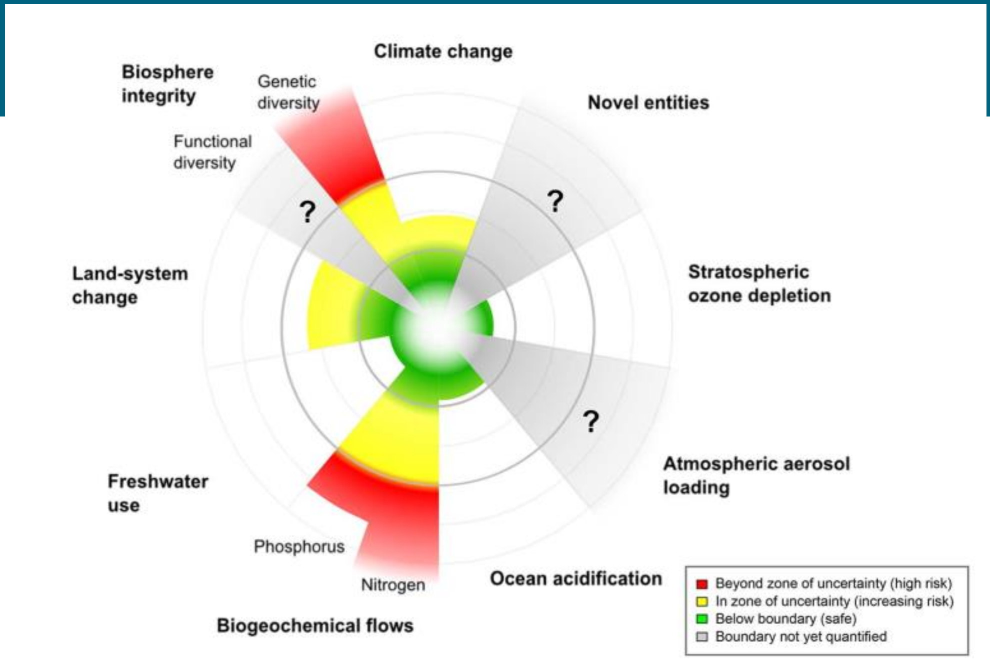
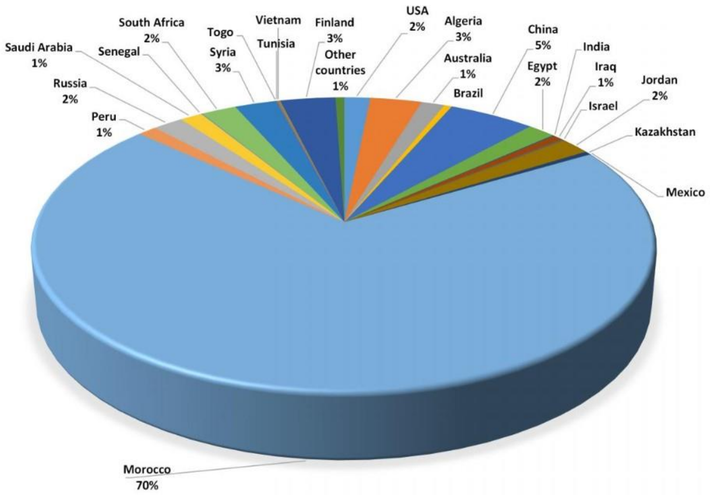
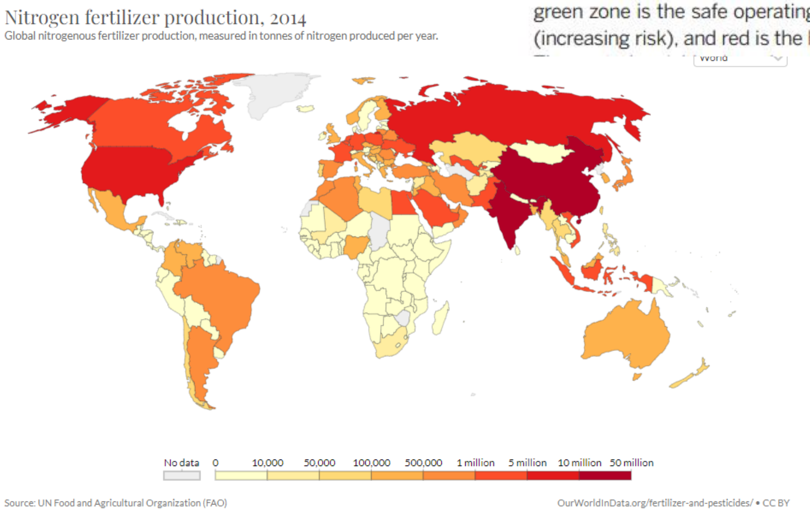


Fig. 3. The current status of the control variables for seven of the nine planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle.

Steffen et al. (2015). DOI: 10.1126/science.1259855





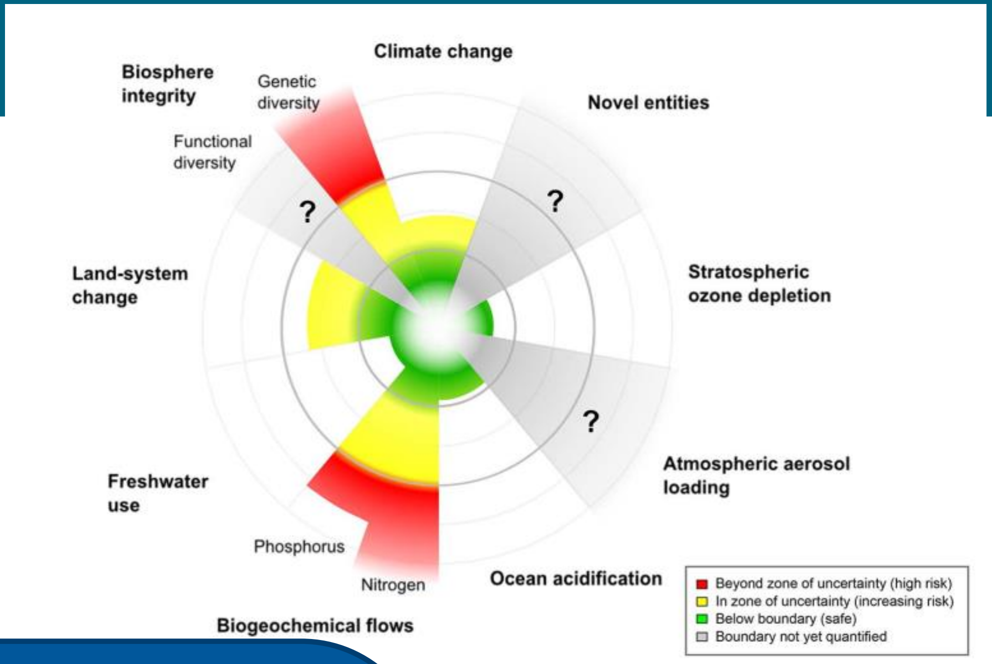
https://ourworldindata.org/grapher/nitrogen-fertilizer-production?tab=map

Rosemarin (2016). https://dakofa.com/fileadmin/user_upload/1600_Arno_Rosemarin_Stockholm_Environment_Institute.pdf

Where we get our N and our P

N: Haber Bosch process and interaction with natural gas

P: Limited reserves



…trol variables for seven of the nine planetary boundaries. The …below the boundary), yellow represents the zone of uncertainty …one. The planetary boundary itself lies at the inner heavy circle.

Steffen et al. (2015). DOI: 10.1126/science.1259855

Message 9: Recovering nutrients makes a lot of sense! Also to decouple N from natural gas (and ensure security of supply). For N, can you do it at a lower (environmental) cost than Haber-Bosch?

…ap

Ros… …df

5

For France?

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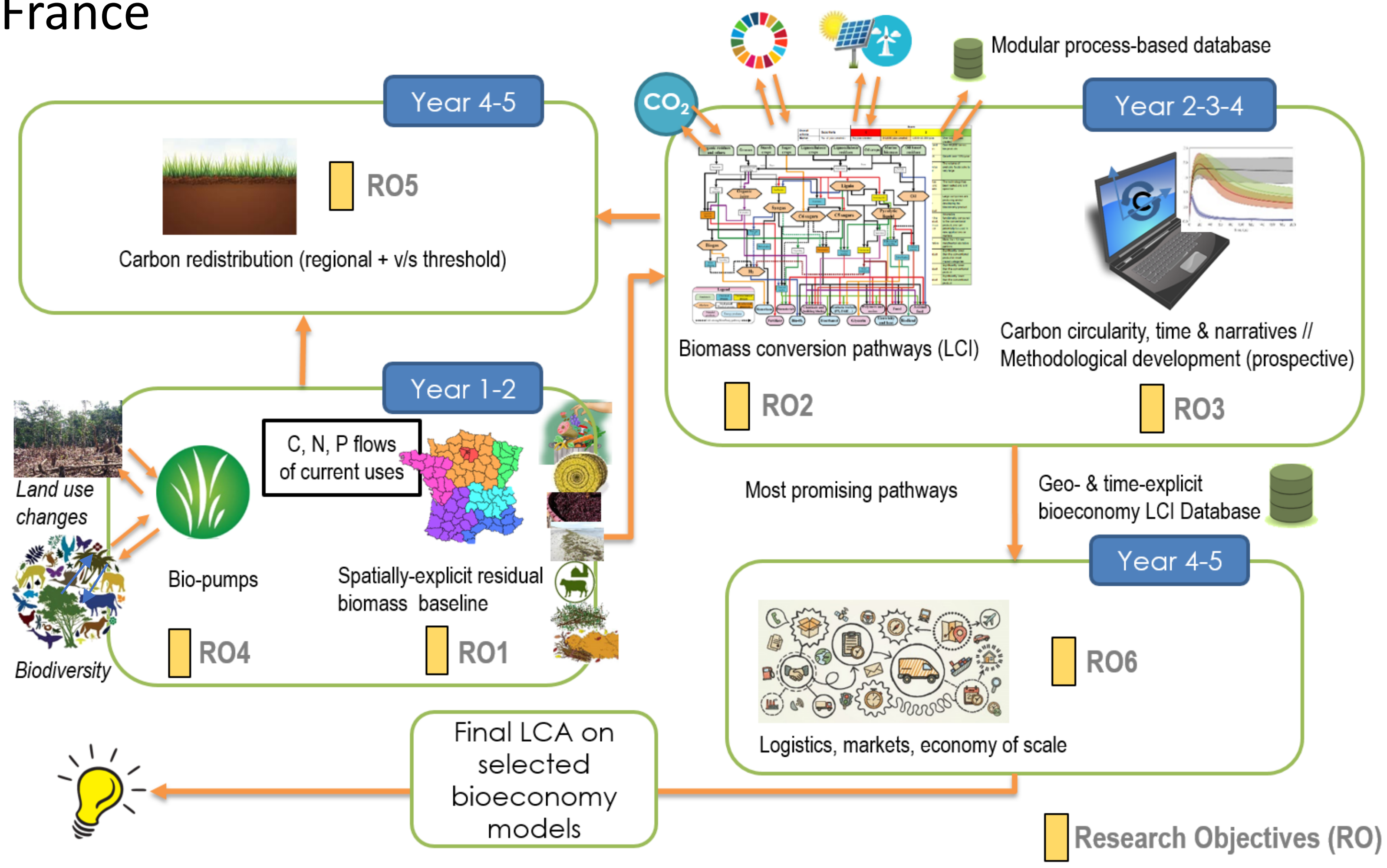
Cambioscop and some key results

Aim: Building a sustainable roadmap towards a low fossil C economy in France



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MAKE OUR PLANET GREAT AGAIN

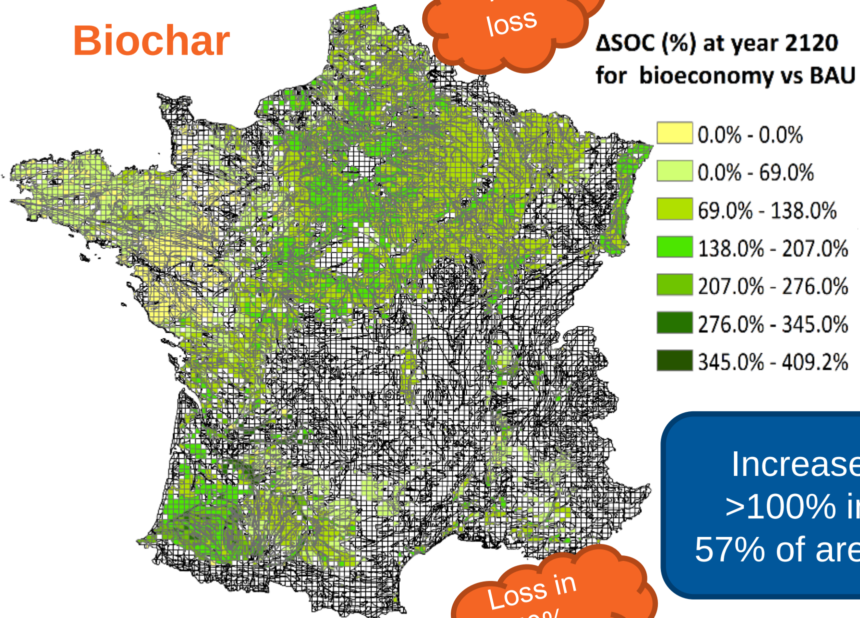
http://cambioscop.cnrs.fr

- Baseline: Not exporting for bioeconomy
- Bioeconomy scenario: Exporting 100% of available harvestable crop residues

RESULTS BASELINE VS BIOECONOMY *Year 2120*

Biochar

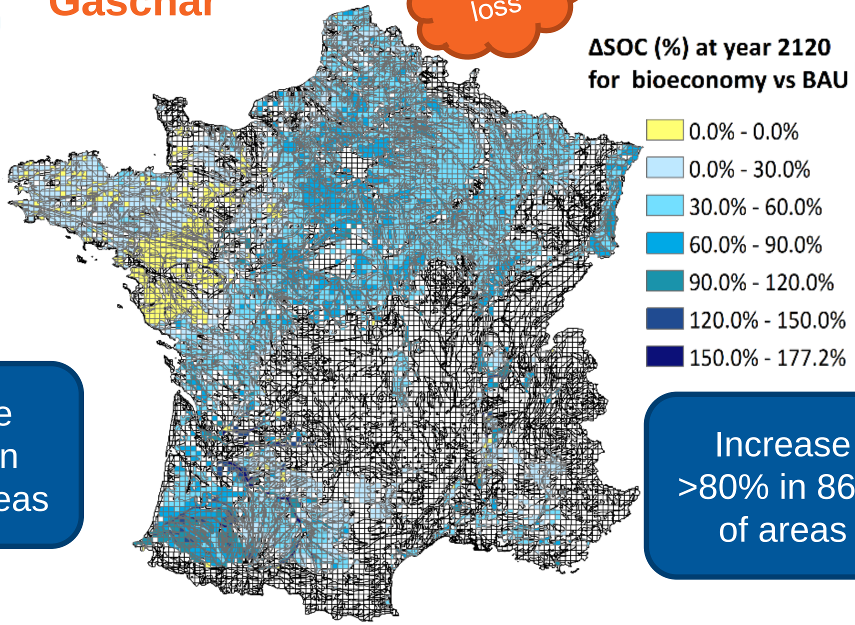
No loss



Increase >100% in 57% of areas

Gaschar

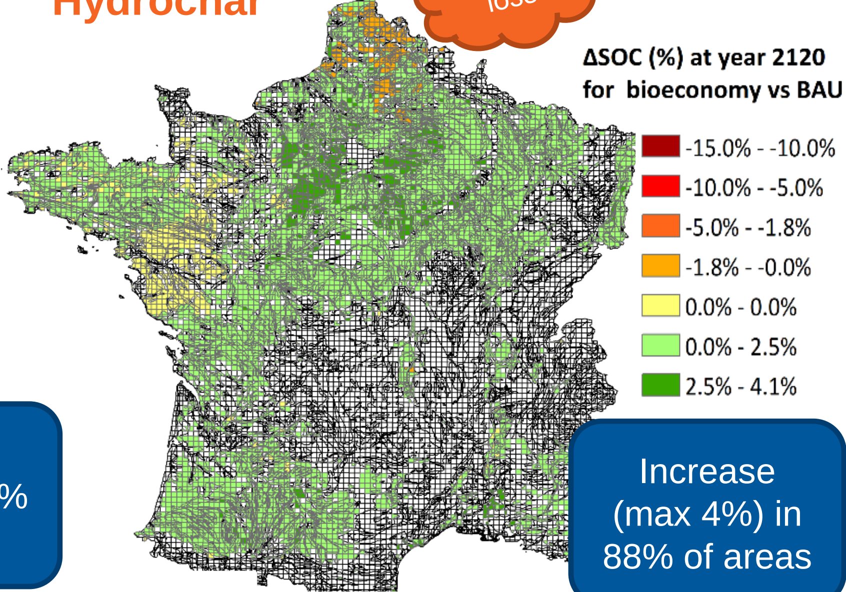
No loss



Increase >80% in 86% of areas

Hydrochar

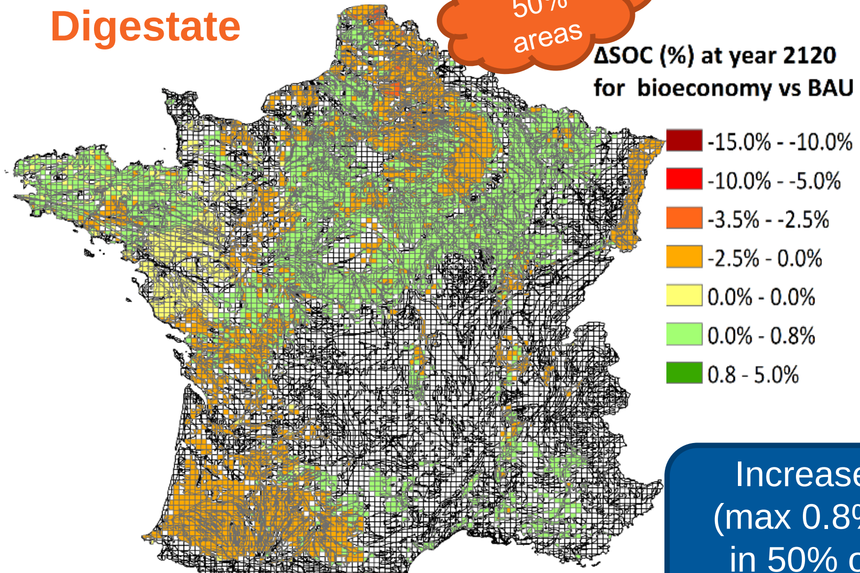
Minor loss



Increase (max 4%) in 88% of areas

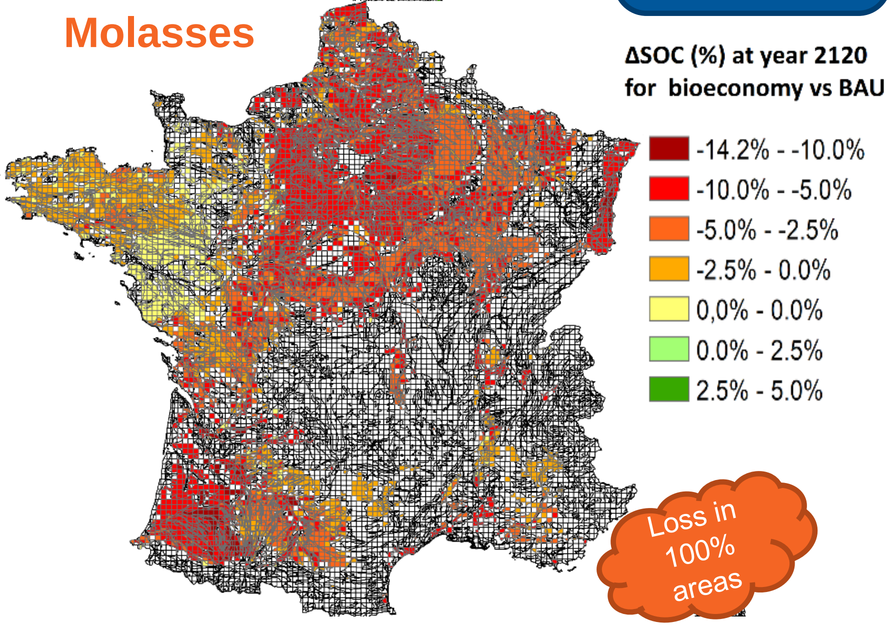
Digestate

Loss in 50% areas



Increase (max 0.8%) in 50% of areas

Molasses



Loss in 100% areas

Increases and losses refer to SOC stock after 100y, compared to no harvest

If maintaining soil organic carbon stocks is our only concern, we have much more biomass potential than we think! **No need to lose 170 - 225 PJ/y to atmosphere**!

Andrade et al. 2023:
https://doi.org/10.1016/j.apenergy.2022.120192

PhD defense on June 23rd AM

Message 10: Leaving a biomass on land is no magic for soil C enhancement, most C is lost as CO_2 to atmosphere

(but organic matter input does brings a lot of magic, beyond carbon. This trade-off, in the long-term, is still not fully understood, in quantitative terms at least. Idem for long-term effect of biochars)

No silver bullet. Digestate return would not bring negative emissions, but safer as structure not changed. Losses could be avoided by combining with other strategies of carbon return (cover crops)

Waste-to-nutrition: a good idea (environmentally)?

PhD defense on April 12th, AM

Final LCA model

11 selected streams

- Hardwood residues
- Sawmill waste
- Wheat straw
- Bovine manure
- Sewage sludge
- Countryside management grass
- Sugarbeet tops
- Household food waste
- Transformed animal proteins
- Distiller' spent grains
- Potato screenings

dry matter
ashes
Cellulose
Hemicellulose
Lignin
Proteins
Lipids
Starch
Sugars
Others
C, H, O, N, P, K, S

293 process parameters & variation ranges

French deployment context

27 biomass management pathways

Waste-to-nutrition

- Green biorefinery (3 variants)
- Insects farming (2 variants)
- Solid fermentation (2 variants)
- Mycoproteins production (2 variants)
- Microbial proteins production (6 variants)

Counterfactuals

- Direct livestock feeding
- Decay on land
- Spreading on land
- Composting
- Open-air burning
- Domestic heating
- Industrial heating
- Combined heat & power (incineration)

Alternatives

- Anaerobic digestion (2 variants)
- Gasification (2 variants)

LCA

GSA

Statistical analysis

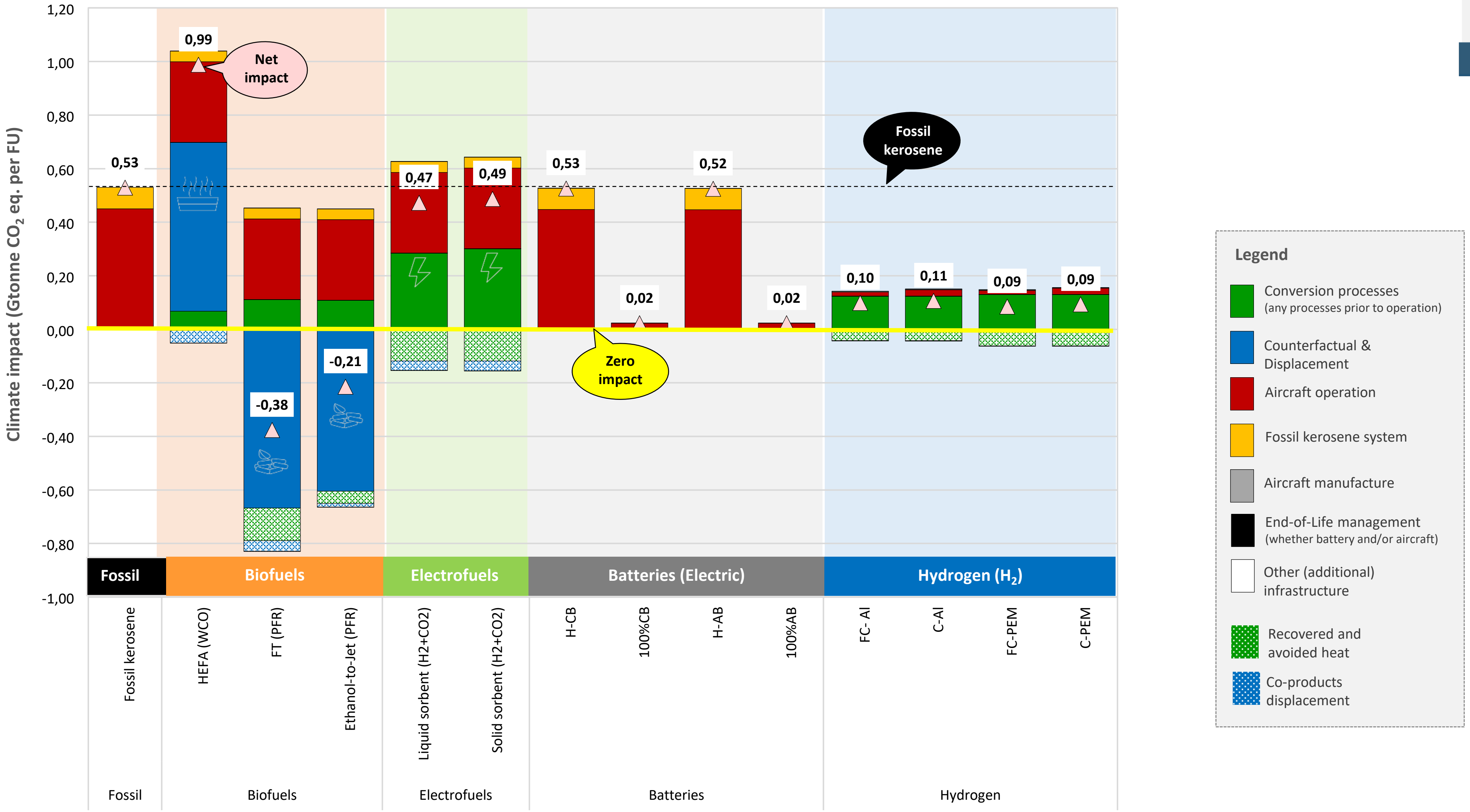
Waste-to-nutrition: a good idea (environmentally)?

Finding : The ONLY way that feed-grade residual streams provide more environmental benefits than direct feeding to livestock, is to produce ingredients **substituting meat** production, here insects and mycoproteins. Yet, it must under best conditions (decarbonized power, highest conversion yields, highest substitution rate)

Message 11: **How good/bad the alternative (here marginal protein) is likely to become (governance, yield gap)?** Here, if protein is < 4 kgCO2-eq.$kgDM^{-1}$ (today 4.5), then no much value to do waste-to-nutrition (rather HT heat, in short-term). If >5, then microbial protein makes sense.

Message 13: Adaptation or mitigation? Here, adaptation, as waste-to-nutritions is only interesting under prevailing failing global governance

Key result 3: how to fly?



Next steps

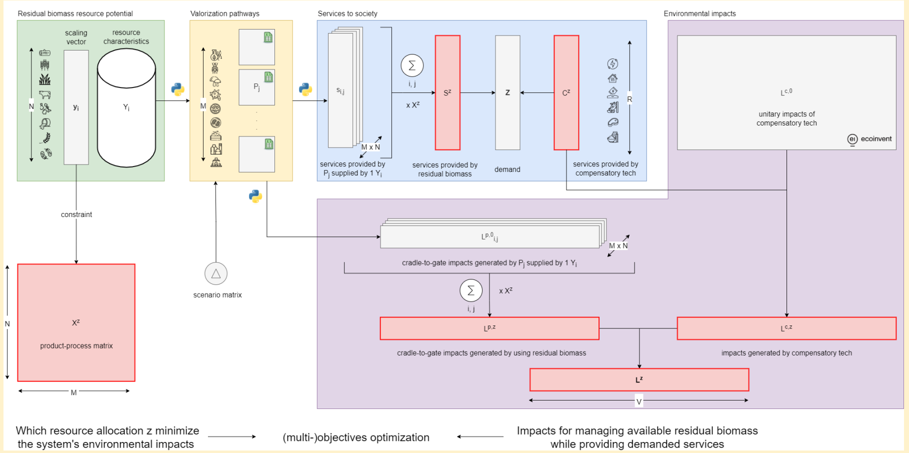
i) Final optimization for France 2050

§ Given the quantity of residual biomass we have, and what we already do with it;

§ Given fixed ENERGY, FOOD, FEED, MATERIALS, CHEMICALS, FERTILIZERS demands;

§ Given that marginal suppliers will compensate the production where residual biomass / C capture is not enough

=> Proposition of allocation strategies for the various biomasses to each technologies, to optimize on <u>climate AND 15 other environmental impacts</u>



ii) Role, potential, strategies for cover crops (bare agricultural soils especially)

iii) Make this a societal project : Aligning / developing Key Performance Indicators (KPI) considering stakeholders viewpoint

Take home messages

- **Towards Solutions: we are allowed to think beyond current constraints (e.g. legislative)**
- **But: it must make sense! We can do many things, but does it make (environmental) sense to prioritize this biomass ressource, time, efforts and money on this solution?**
- **Some success elements:**

  => Minimize demand for additional land

  => Beware what you replace! It must be very « bad », so the impacts associated to all processes you put in are compensated

  => Processes using less energy

  => No free lunch

  => Avoid Haber-Bosch

- **Transport is often meaningless!**

Cambioscop publications

1. Brassard P, Godbout S, Hamelin L (2021). Framework for the consequential Life Cycle Assessment of pyrolysis biorefineries: A case study for the conversion of primary forestry residues. *Renewable & Sustainable Energy Reviews*, 110549. DOI: 10.1016/j.rser.2020.110549

2. Gomez-Campos A, Vialle C, Rouilly A, Hamelin L, Rogeon A, Hardy D, Sablayrolles C. Natural Fiber Polymer Composites – A game changer for the aviation sector? (2021) *Journal of Cleaner Production*, 124986. DOI: 10.1016/j.jclepro.2020.124986

3. Gomez-Campos A, Vialle C, Rouilly A, Sablayrolles C, Hamelin L (2021). Flax fiber for technical textile: a consequential life cycle inventory. *Journal of Cleaner Production*, 125177. DOI: 10.1016/j.jclepro.2020.125177

4. Hamelin L, Møller HB, Jørgensen U (2021). Harnessing the full potential of biomethane towards tomorrow's bioeconomy: A national case study coupling sustainable intensification, emerging biogas technologies and energy system analysis. *Renewable & Sustainable Energy Reviews,* 110506. DOI: 10.1016/j.rser.2020.110506

5. Hamelin L, Borzecka M, Kozak M, Pudelko R (2019). A spatial approach to bioeconomy: quantifying the residual biomass potential in Europe. *Renewable & Sustainable Energy Reviews,* 100, 127-142. DOI: 10.1016/j.rser.2018.10.017

6. Hansen JH, Hamelin L, Taghizadeh-Toosi A, Olesen JE, Wenzel H (2020). Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways. *Global Change Biology Bioenergy 12*, 1002-1013. DOI: 10.1111/gcbb.12733

7. Javourez U, O'Donohue M, Hamelin L (2021). Waste-to-nutrition: a review of current and emerging conversion pathways. Biotechnology Advances 53, 107857. DOI: https://doi.org/10.1016/j.biotechadv.2021.107857

8. Karan SK, Hamelin L (2021). Crop residues may be a key feedstock to bioeconomy but how reliable are current estimation methods? *Journal of Resources, Conservation and Recycling 164,* 105211. DOI: 10.1016/j.resconrec.2020.105211

9. Karan SK, Hamelin L (2020). Towards local bioeconomy: A stepwise framework for high-resolution spatial quantification of forestry residues. *Renewable & Sustainable Energy Reviews 134,* 110350. DOI: 10.1016/j.rser.2020.110350

10. Lakshman V, Brassard P, Hamelin L, Raghavan V, Godbout S (2021). Pyrolysis of Miscanthus: Developing the mass balance of a biorefinery through experimental tests in an auger reactor. *Bioresource Technology Reports*, 100687. DOI: 10.1016/j.biteb.2021.100687

11. Shapiro-Bengsten S, Hamelin L, Bregnbaek LM, Zhou L, Munster M (2022). Should Residual Biomass be used for Fuels, Power and Heat, or Materials? Assessing Costs and Environmental Impacts for China in 2035. *Energy & Environmental Science.* DOI: 10.1039/D1EE03816H

12. Teigiserova DA, Hamelin L, Titura-Barna L, Ahmadi A, Thomsen M (2022). Circular bioeconomy: Life Cycle assessment of scaled-up cascading production from orange peel waste under current and future electricity mixes. *Science of the Total Environment,* 812, 152574. DOI: 10.1016/j.scitotenv.2021.152574

13. Teigiserova D, Barna L, Ahmadi A, Hamelin L, Thomsen M (2021). *A step closer to circular bioeconomy for citrus peel waste: a review of yields and technologies for sustainable management of essential oils. Journal of Environmental Management, 812, 152574. DOI:* 10.1016/j.scitotenv.2021.152574

14. Teigiserova D, Hamelin L, Thomsen M (2020). Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. *Science of the Total Environment,* 706, 136033. DOI: 10.1016/j.scitotenv.2019.136033

15. Teigiserova D, Hamelin L, Thomsen M (2019). Review of high value food waste and food residues biorefineries with focus on unavoidable waste from processing. *Journal of Resources, Conservation and Recycling,* 149, 413-426. DOI: 10.1016/j.resconrec.2019.05.003

16. Shen Z, Tiruta-Barna L, Hamelin L (2022). Simultaneous carbon storage in arable land and anthropogenic products (CSAAP): Demonstrating an integrated concept towards well below 2°C. *Journal of Resources, Conservation and Recycling,* 182, 106293. DOI: 10.1016/j.resconrec.2022.106293

What do you think are the greatest challenges ahead?

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https://cambioscop.cnrs.fr/

hamelin@insa-toulouse.fr

@hamelinlab
@Cambioscop

https://www.youtube.com/channel/UCvWM2__5hSWN1zujJ4vEZNA

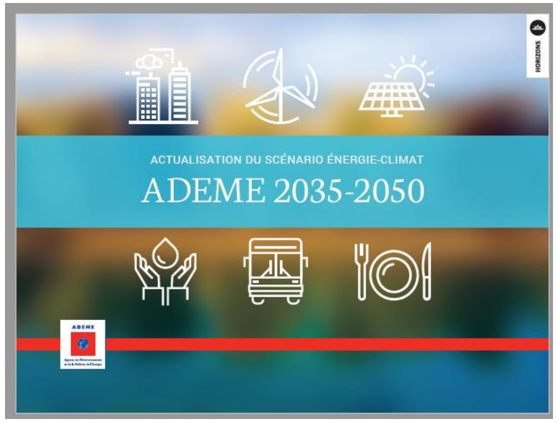
Video on the project on the MOPGA channel:
https://www.youtube.com/watch?v=0I7VkgHM9lw&list=UUegK_BEcsgqJt1YOeFsenNg&index=12&ab_channel=MakeOurPlanetGreatAgain

Note: all of our data are publicly available when ready, on the Cambioscop website and/or as SI of our papers and/or as preprints and/or on data repository

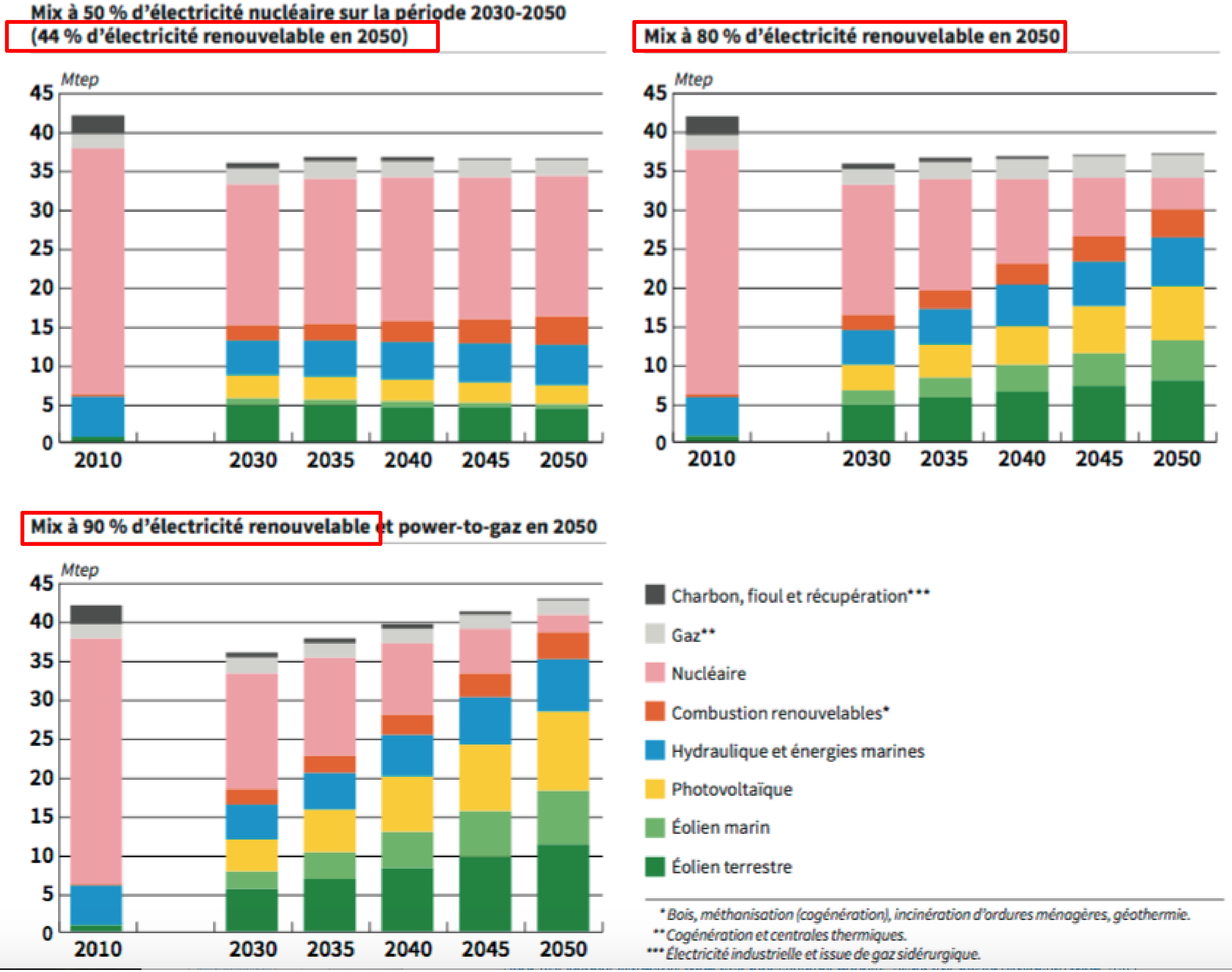
- **Background material**

Also in France…

France: from 20-65% **fluctuating** power in 2050 (Ademe, 2017)



ADEME 2017



Residual biomass : acknowledged prioritization in circular economy

D.A. Teigiserova et al. / Science of the Total Environment 706 (2020) 136033

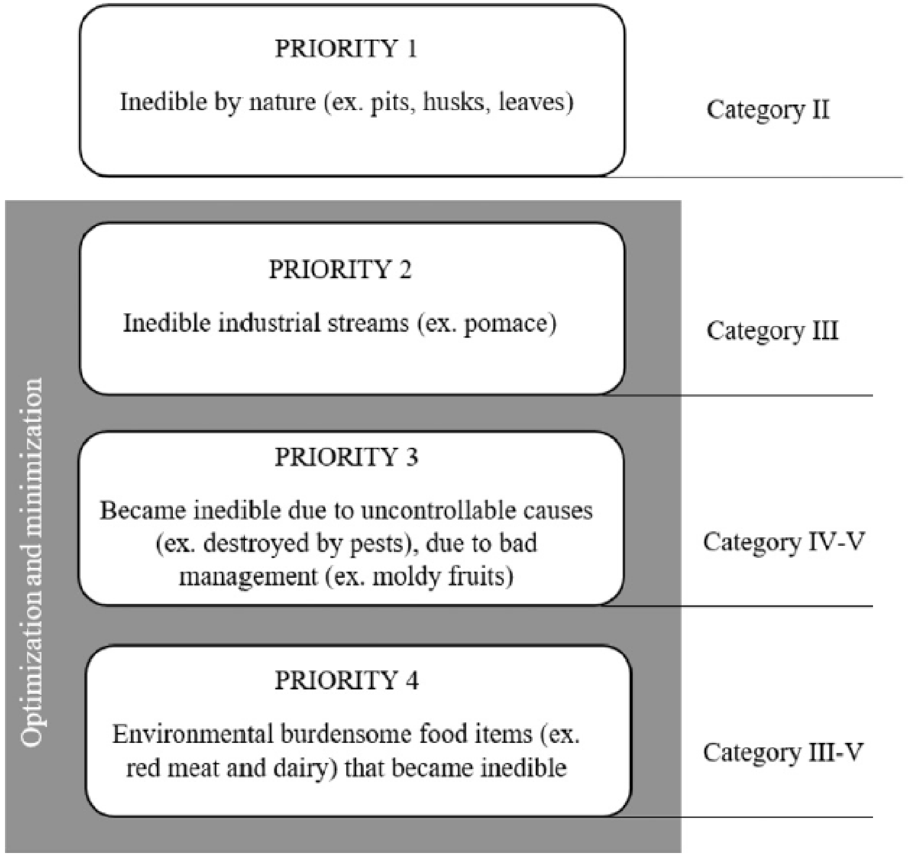


Fig. 3. Ranking proposed to prioritize which inedible food waste stream to use in future food waste biorefineries. Linked to categor

Table 3
Categorization of FSWL in connection with edibility and possibility of avoidance.

Edible	Inedible		Other
Avoidable	Unavoidable	Partly avoidable	
I. All edible food	II. Naturally inedible (ex. bones, pits, leaves) III. Processing waste residues (ex. apple pomace, tea leaves)	IV. Became inedible due to natural causes (crops damaged due weather) V. Became inedible due to inefficient management a. poor functioning of the FSC (lack of proper refrigeration, inadequate infrastructure, etc.) b. avoidable negligence	VI. Not accounted for
Surplus food	Food waste		Food loss

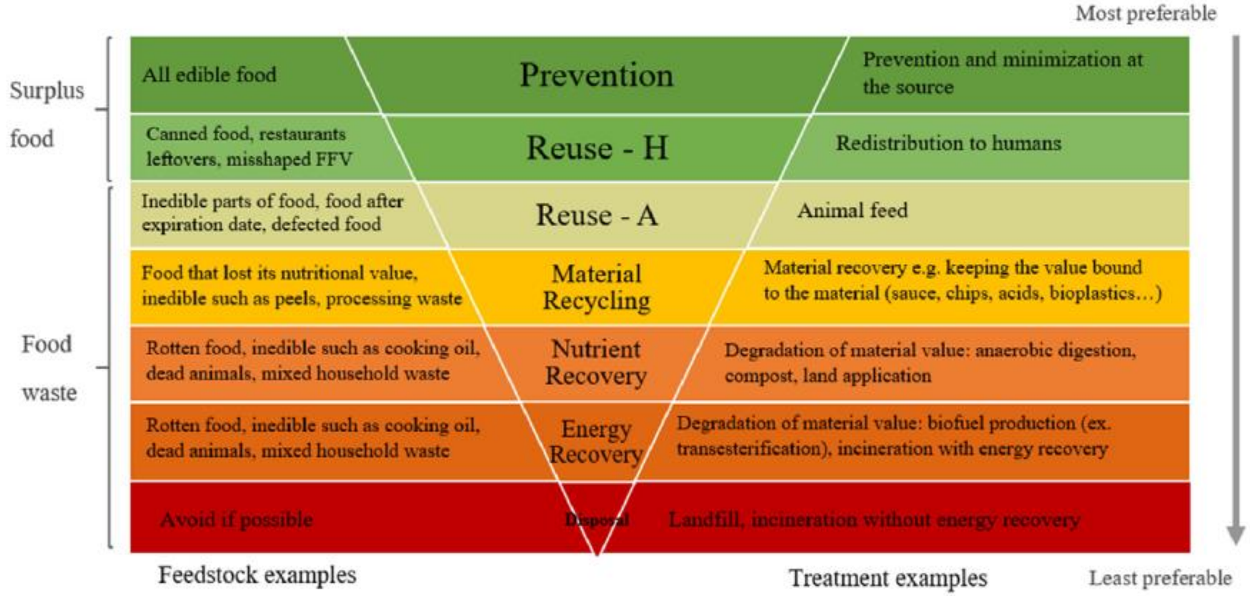
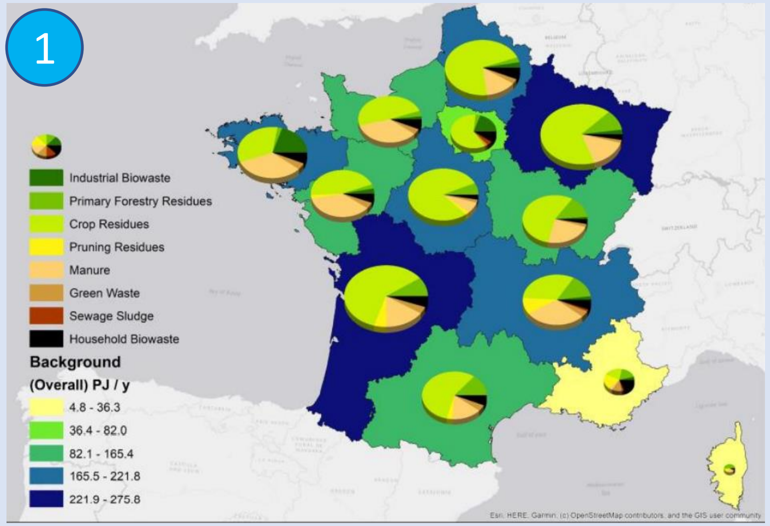


Fig. 1. Updated hierarchy for food surplus and waste proposed herein building on terminology from major European and national projects (UNEP, 2014; WRAP, 2013; FUSIONS: Östergren et al., 2014). *FFV fresh fruits and vegetables.

Source: Teigiserova et al. (2020); doi.org/10.1016/j.scitotenv.2019.136033

Key output

1

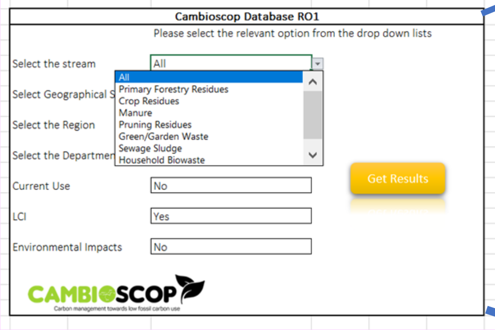


Spatially-explicit residual biomass inventory
~2300 PJ residual biomass in France (56% crop residues), of which >90% is managed as waste

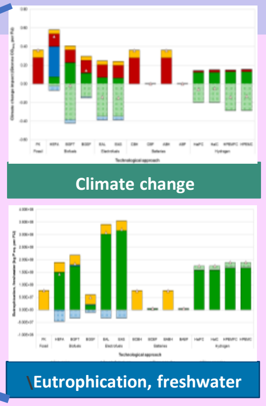
DOI: 10.1016/j.rser.2020.110350
DOI: 10.1016/j.resconrec.2020.105211

2

Life Cycle Assessment **Methodology Development**: Dynamic, prospective & parametric



Make choice, View Impact (16 in total)



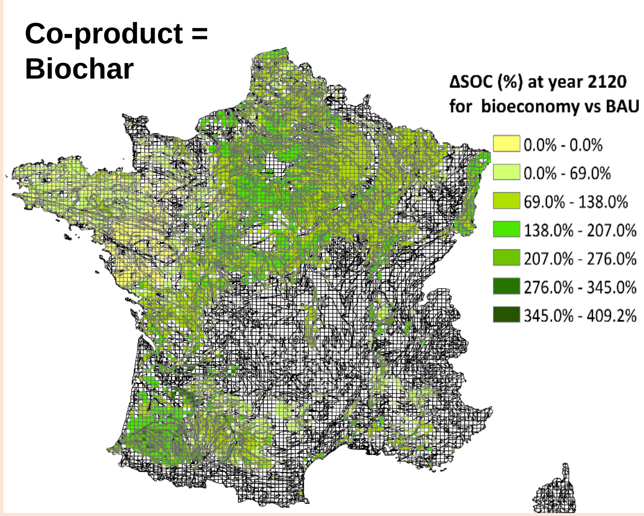
- ✓ Bio-based materials
- ✓ Bio-based oil
- ✓ Bio-based gas
- ✓ Aviation
- ✓ Ingredients
- ✓ Chemicals

Modular Life Cycle Inventories available for more than 500 processes in open access

DOI: 10.1038/s43016-022-00621-9
DOI: 10.1016/j.scitotenv.2022.157331
DOI: 10.1016/j.apenergy.2022.119568
DOI: 10.1016/j.scitotenv.2021.152574
DOI: 10.1016/j.rser.2020.110549
More on Google Scholar

3

Co-product = Biochar



- ✓ Bio-char
- ✓ Gas-char
- ✓ Hydro-char
- ✓ Digestate
- ✓ Bio-ethanol molasses

Maintaining long-term soil organic carbon stocks: Where to harvest crop residues considering 5 bioeconomy co-products return

DOI: 10.1016/j.apenergy.2022.120192

Key findings

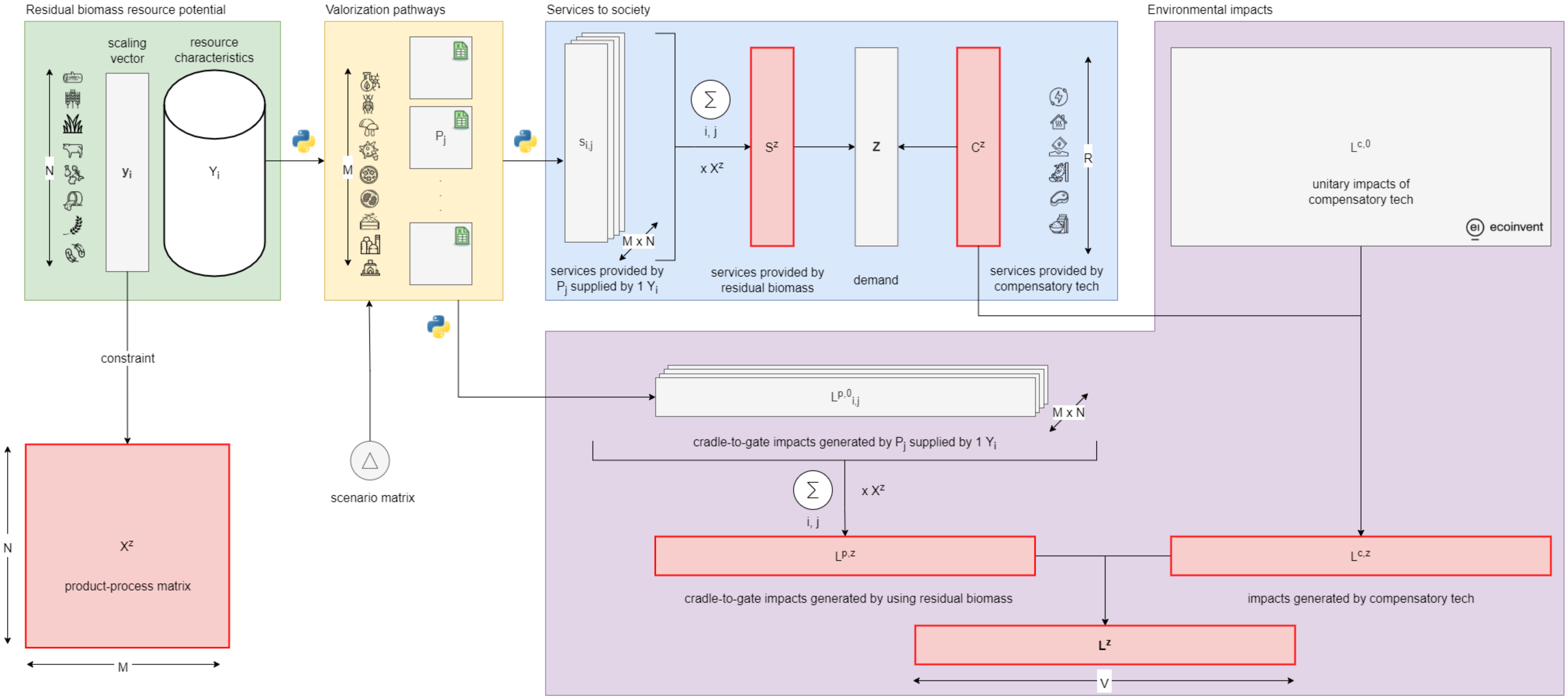
Bio-based materials: Avoiding current construction materials is paramount; this outweights negative emissions. Focus on low-C lands & long life products.

Waste-to-ingredients: Benefits of avoiding crop ingredients are compensated by process emissions; worth under ideal conditions only (e.g. renewable power)

Aviation: **E**lectrofuels: forget; **B**atteries: invest; **H_2**: invest with caution, beware of power source. **B**iofuels: acceptable only if from forestry residues (no waste oil)

Crop residues: Harvestable amounts of 100% for **P**yrolysis & **G**asification, 98% for **H**tL, 53% for **B**iogas, 0% for 2G **E**tOH. No need to lose 70 – 225 PJ to atmosphere.

Next step towards prioritization: scale up to France and optimization considering resources and demands



Which resource allocation z minimize the system's environmental impacts → (multi-)objectives optimization ← Impacts for managing available residual biomass while providing demanded services

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