Biogenic Carbon accounting modelling: State of the art, limitations, and global trends towards the integration of realistic modelling in LCA.

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Coupling Soil Organic Carbon modelling into LCA framework

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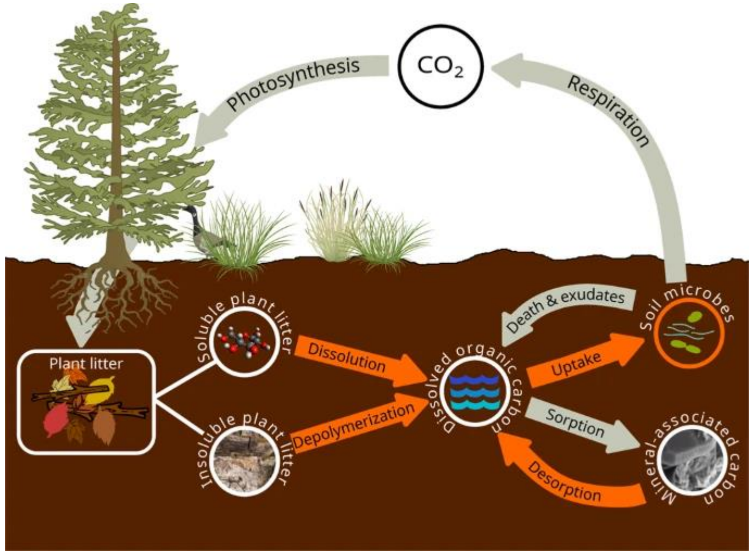
Crop residues are key to supply renewable carbon

- Abundant
- Flexible to supply several bioeconomy pathways
- No land or food competition

However…

- Crop residues are a source of carbon to maintain the soil organic carbon (SOC) stocks balance



Source: Woolf and Lehman, 2019 https://doi.org/10.1038/s41598-019-43026-8

- Crop residues harvest is often limited to 15 -60 % of the theoretical potential

To harvest or not to harvest crop residues for supplying renewable carbon to the bioeconomy?

Aims of the study

- **Determine the amount of crop residues that can be harvested to supply bioeconomy pathways while maintaining SOC stocks.**
- **Determine trade-offs between SOC sequestration and the full environmental impacts of bioeconomy strategies regarding the management of crop residues.**

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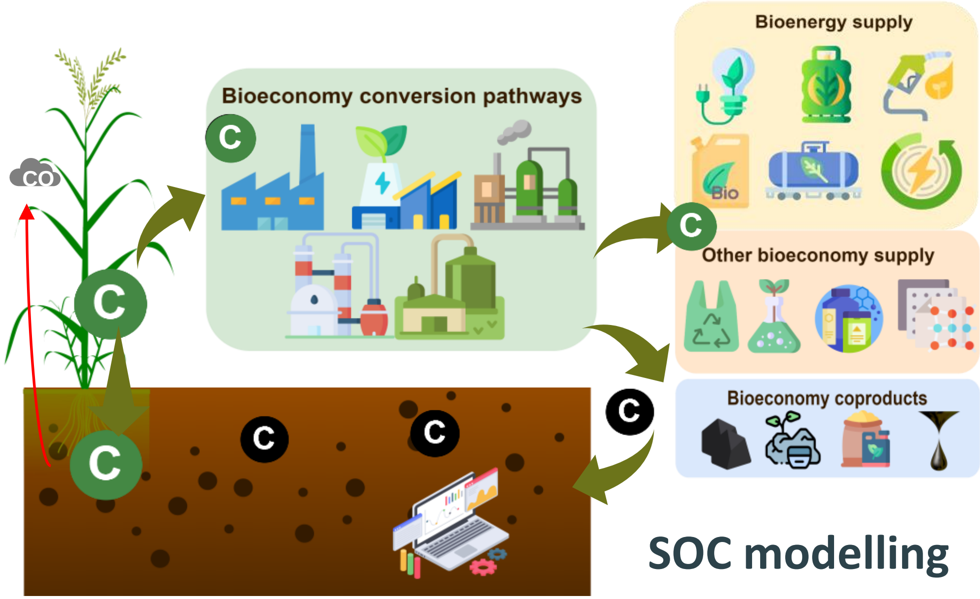


SOC modelling

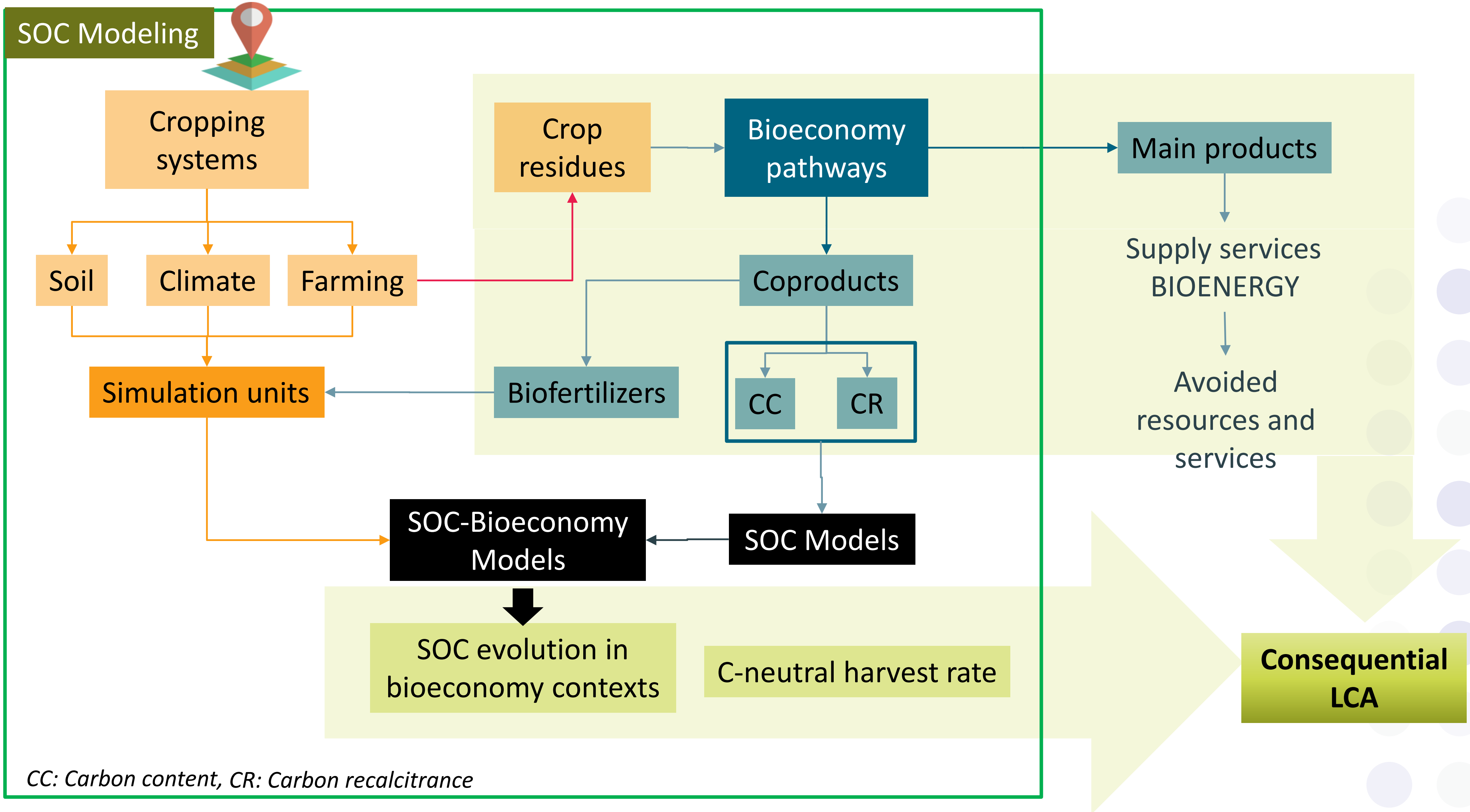
Ⓒ Carbon in raw crop residues (labile+recalcitrant)

Ⓒ Carbon in bioeconomy coproduct (recalcitrant)

SOC modeling for recalcitrant bioeconomy coproducts

+

LCA of the full supply chain for the bioeconomy pathways



Details in *https://doi.org/10.1016/j.apenergy.2022.120192* *https://doi.org/10.21203/rs.3.rs-3093300/v1*

https://doi.org/10.1016/j.rser.2023.113890

Maximum amount of crop residues that can be supplied to the bioeconomy if the recalcitrant coproducts are returned to soils as biofertilizers

C-neutral harvesting rate

Bioeconomy scenarios

Conversion pathways	Coproducts
Pyrolysis	Biochar (pyrochar)
Gasification	Char (gaschar)
Hydrothermal liquefaction (HTL)	Hydrochar
Anaerobic digestion (AD)	Digestate

Reference scenario

- Business as usual (**BAU**) → Crop residues not harvested

Temporal scope: 20 – 50 -100 years

Geographical scope

Temperate: France	Tropical: Ecuador

	Temperate: France	Tropical: Ecuador
Baseline	INRAE	This study
Soil model	AMG	ROTH-C
Simulation units	>60,000	>15,000

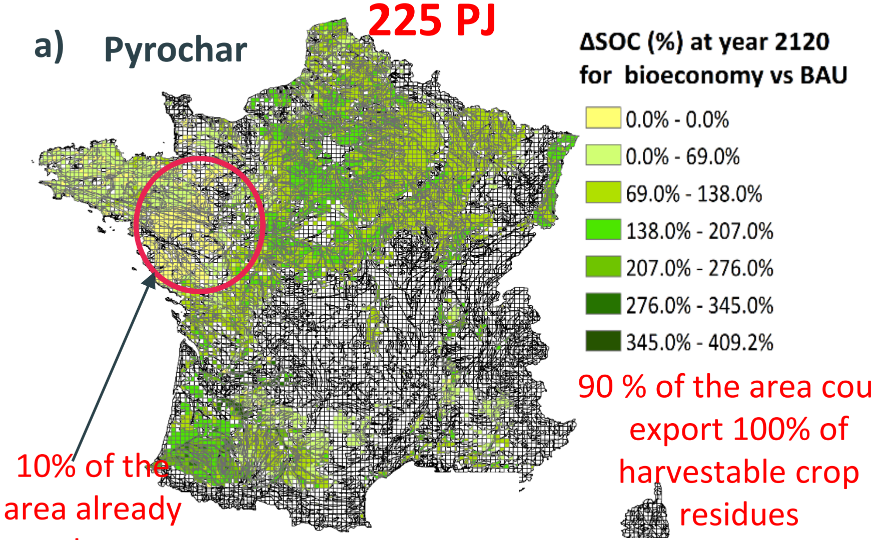
Andrade Díaz et al., 2023 *https://doi.org/10.1016/j.apenergy.2022.120192*

Andrade Díaz et al., 2023 https://doi.org/10.21203/rs.3.rs-3086337/v1
Andrade Diaz et al., 2023 10.5281/zenodo.7984822

C-neutral harvest in French croplands

✓ Bioeconomy vs BAU 2120

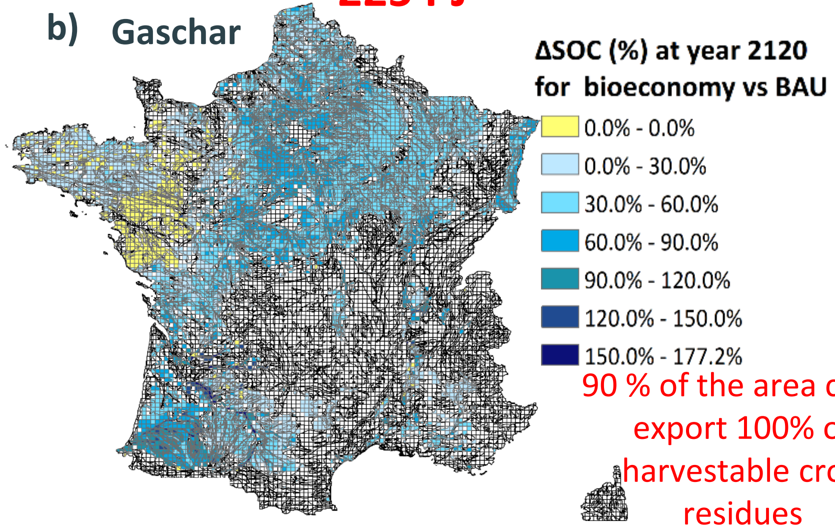
a) Pyrochar **225 PJ**



90 % of the area could export 100% of harvestable crop residues

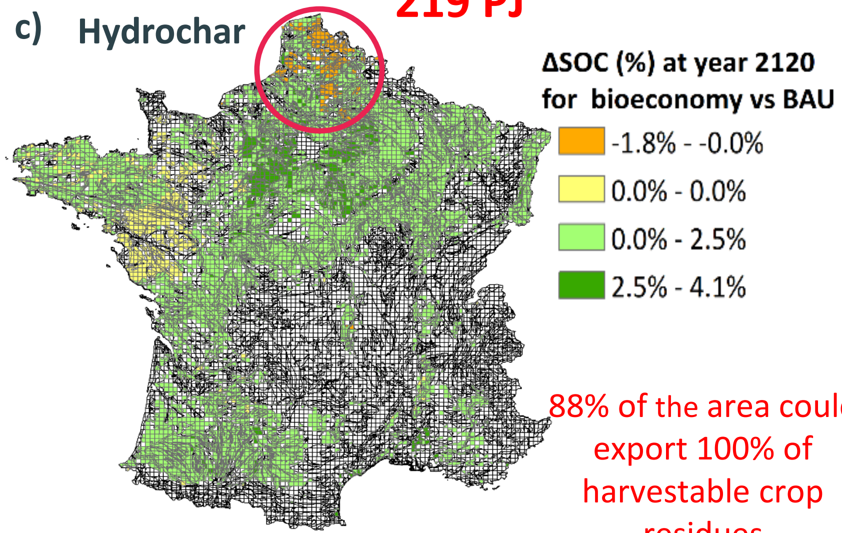
10% of the area already use the crop residues

b) Gaschar **225 PJ**



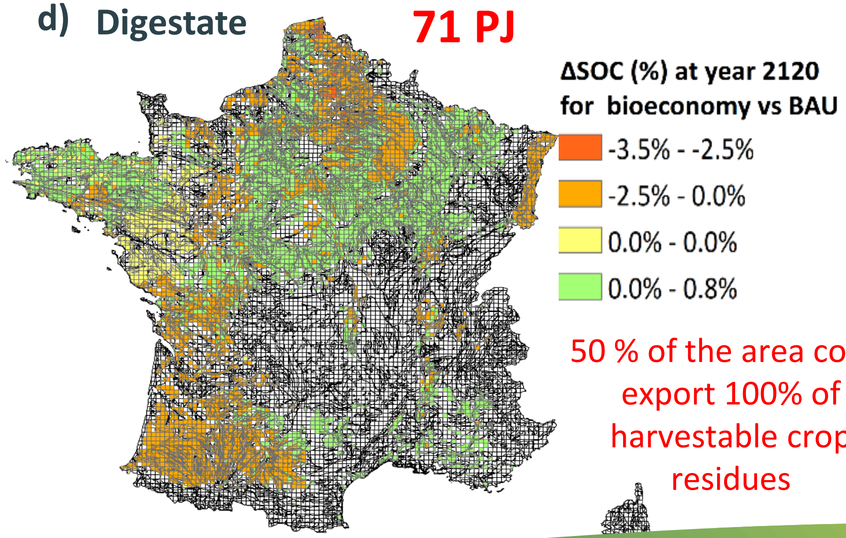
90 % of the area could export 100% of harvestable crop residues

c) Hydrochar **219 PJ**



88% of the area could export 100% of harvestable crop residues

d) Digestate **71 PJ**

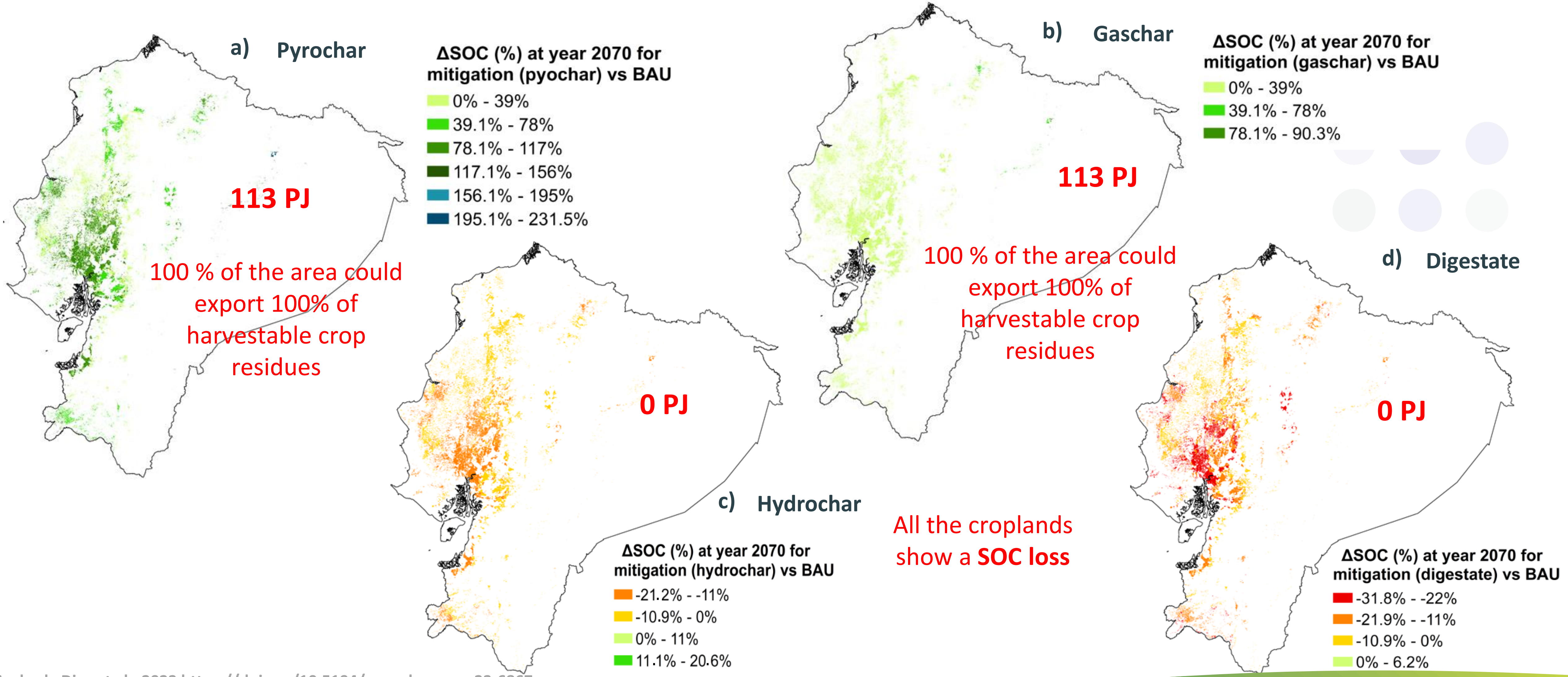


50 % of the area could export 100% of harvestable crop residues

Published in: Andrade Diaz et al., 2023. https://doi.org/10.1016/j.apenergy.2022.120192

C-neutral harvest in Ecuadorian croplands

✓ Bioeconomy vs BAU 2070



Andrade Diaz et al., 2023 https://doi.org/10.5194/egusphere-egu23-6867;
Andrade Diaz et al., 2023 10.5281/zenodo.7984822

LCA on a relevant case – Maritime biofuels

Sea transport represents ca. 80% of international trade, consuming **330 Mt of maritime fuels** per year, of which **77% is heavy fuel oil** (HFO).

Sustainable maritime fuels (SMF) are an alternative towards the GHG emission reduction goal

Crop residues used for the bioeconomy

- **Main product** → **SMF**
- **Coproduct** → **Biofertilizers**

Two extreme cases selected

- **Pyrolysis** → **Biooil**, **Biochar**
- **Anaerobic digestion** → **Biomethane**, **Digestate**

Scope

- ❑ France
- ❑ Future optimal performance

Consequential LCA

Goal

❑ Reveal trade-offs between the C-neutral harvest potential and overall environmental impacts of the full supply chain to identify the best management option.

Functional unit

"The management of one wet tonne of harvestable crop residues per year".

❑ **Well-to-wake** **Emissions from the fuel production to the end-use by a ship**

Raw materials acquisition → Fuel production → Fuel use onboard → Utilities

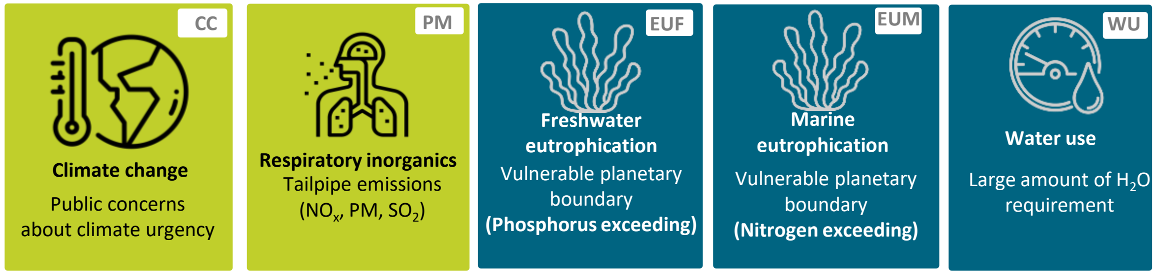
Coproducts management

Waste management

Avoided products and services

Emissions associated to each life stage of the process

Environmental Footprint v3.1



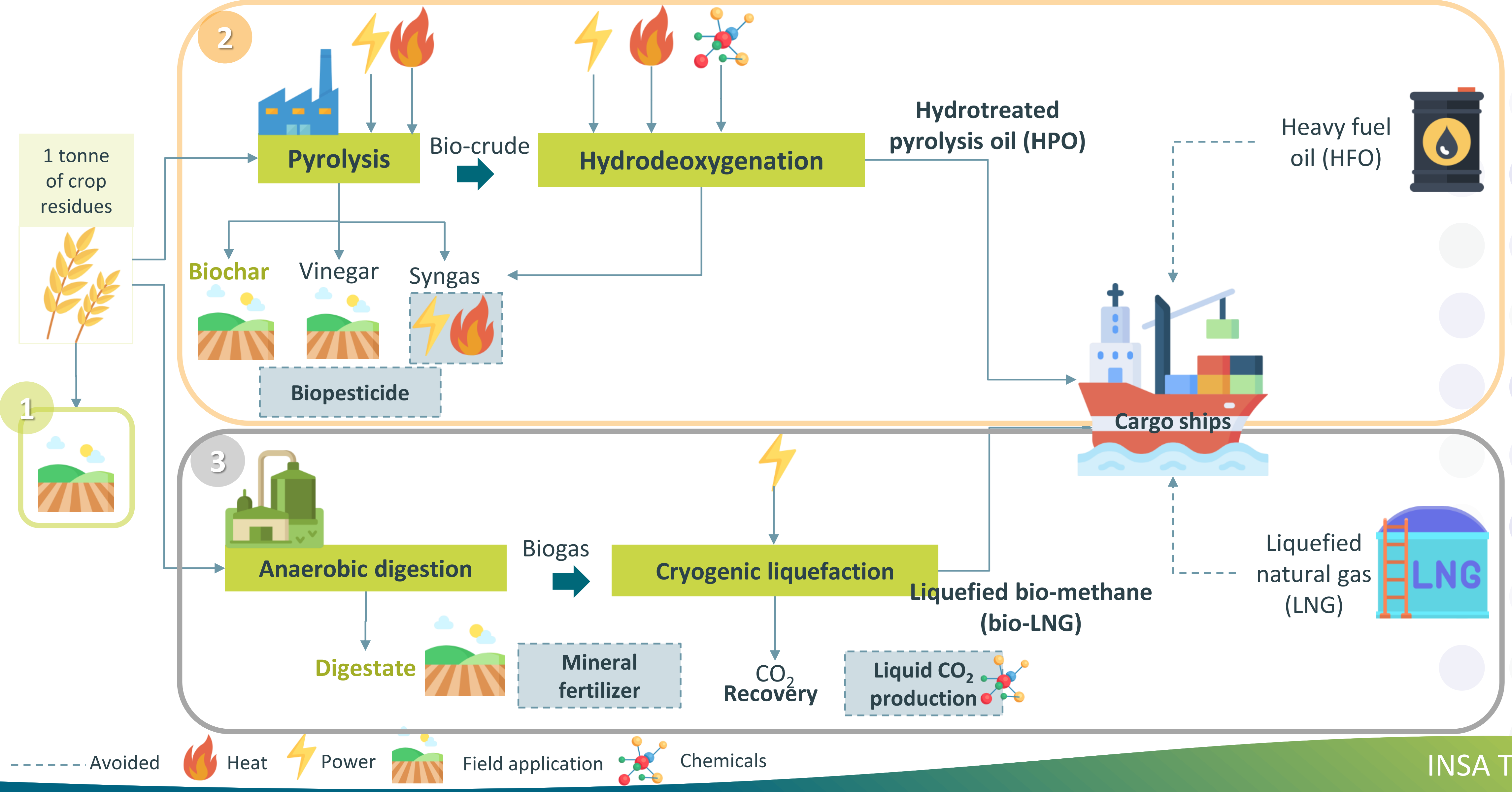
ecoinvent

Brightway

Biogenic CO_2

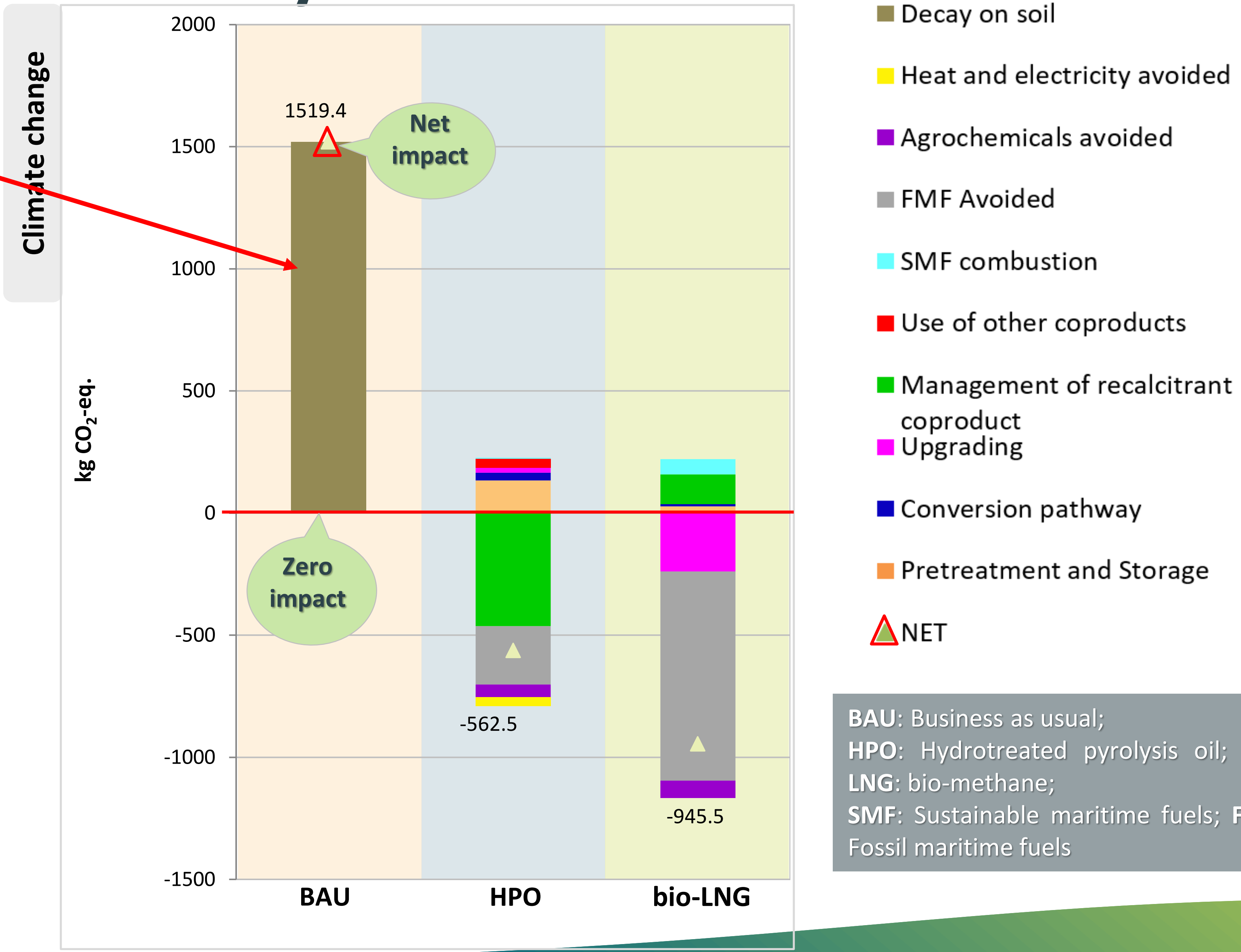
❑ 0/0 approach

System boundaries



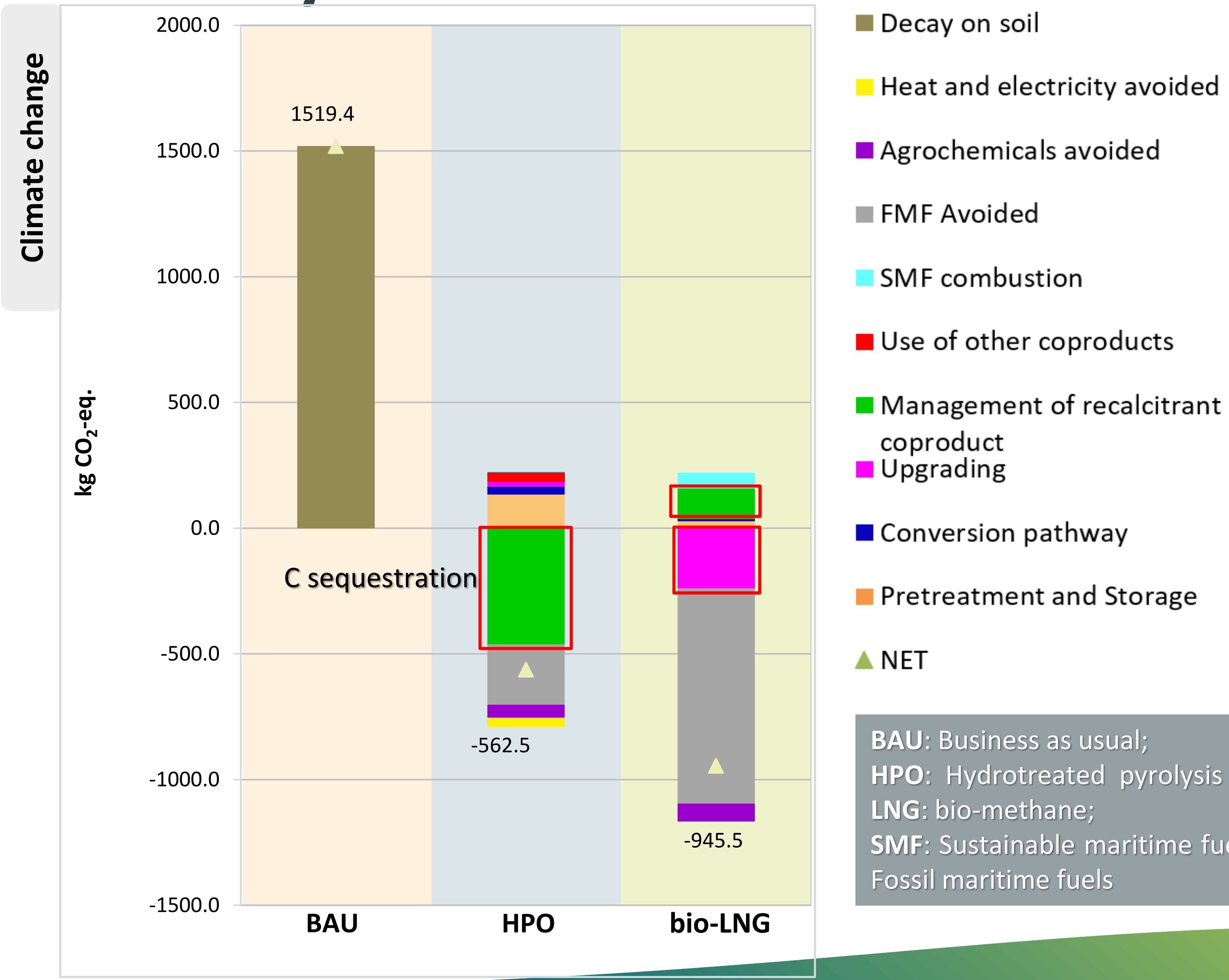
Contribution analysis

Biogenic C
Shown only for illustrative purposes



BAU: Business as usual;
HPO: Hydrotreated pyrolysis oil; **bio-LNG**: bio-methane;
SMF: Sustainable maritime fuels; **FMF**: Fossil maritime fuels

Contribution analysis



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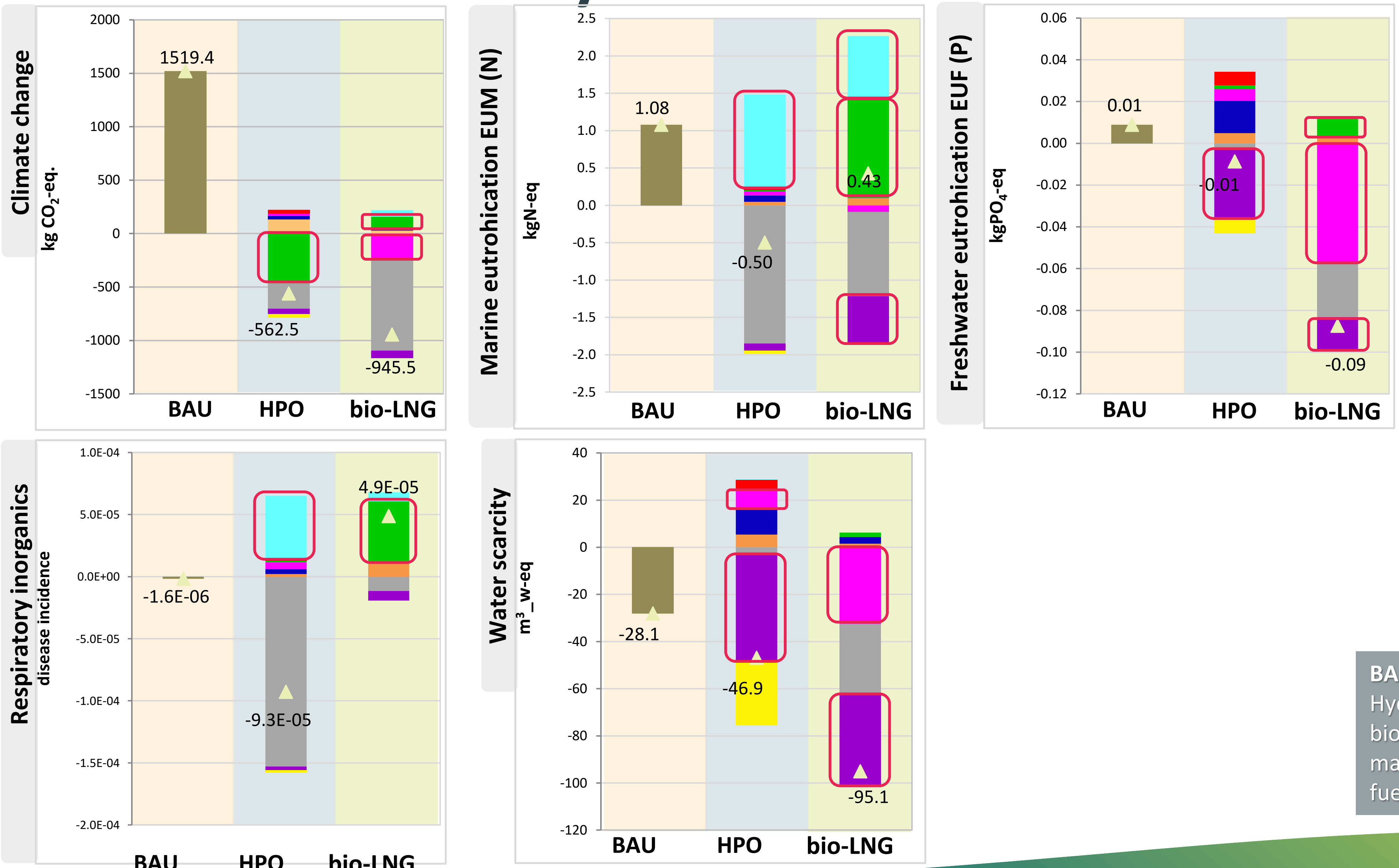

- Decay on soil
- Heat and electricity avoided
- Agrochemicals avoided
- FMF Avoided
- SMF combustion
- Use of other coproducts
- Management of recalcitrant coproduct
- Upgrading
- Conversion pathway
- Pretreatment and Storage
- NET

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SOC–Environmental impacts tradeoff:

Scale up

	BAU	Pyrolysis	Anaerobic Digestion
C sequestered in soil (kt C) *100 years (Bioeconomy vs BAU)*	-178.0	7740.0	7.6
C-neutral harvest potential per technology (Mt D.M.) *13.24% w.c.*	18.7	18.7	10.0

Conclusions

Gross electricity generation in

Greece Austria

- The C-neutral harvest rate allows to supply **extra 71 – 225 PJ and 113 PJ** for **France and Ecuador**, respectively, while maintaining and even increasing SOC stocks, compared to the BAU.
- If the goal is to maintain or enhance the SOC stocks compared to the BAU, 100% of crop residues can be harvested for pyrochar and gaschar, 88% for hydrochar, and 50% for digestate for the French context.
- While for pyrochar and gaschar both France and Ecuador cases can harvest 100% of crop residues, hydrochar and digestate showed no SOC sequestration potential in Ecuador.
- HPO and bio-LNG can **offset 90% of the GHG emissions** of traditional fossil maritime fuels.
- For France, **no tradeoffs** were found between the SOC conservation goals and the environmental performance of pyrolysis and anaerobic digestion to produce sustainable maritime fuels

Take-home message

- Coupling spatially explicit SOC modeling and LCA studies allows **finding hotspots** where crop residues can be harvested to supply a given bioeconomy pathway while ensuring the best environmental performance and soil carbon conservation.
- Scaling the environmental impacts to the national **C-neutral potential** of the country can reveal a different optimal pathway compared to the management of 1 tonne of crop residues.
- Despite low SOC sequestration potential, a given technology can be more attractive if the overall scaled environmental impacts are considered.
- **Defining a C-neutral harvesting rate ensures to supply the bioeconomy while maintaining SOC stocks and reduce environmental impacts, compared to a BAU situation where crop residues are directly incorporated into soils.**

Limitations / challenges of the study

- **Lack of data!** Spatial-explicit studies require gathering data with fine granularity, which is difficult to find in most countries. LCAs require data for the supply chain which most of the time is difficult to find and proxies are used.
- **Upscaling laboratory studies** to represent real environments is still a challenge.
- **Sources of uncertainty**: Baseline data, coproducts characteristics, and way of integrating the coproducts within the soil models.
- Big **computing power** is needed. Modeling SOC stocks and using the results in LCA studies can take a long time and use heavy loads of computer memory.
- **Time consuming**! Results are required to be faster than produced
- Returning recalcitrant coproducts to croplands may **alter soil functions beyond the carbon balance**. Nutrients and microorganisms' interactions with the new recalcitrant carbon may change the fertility of soils and future yields. These changes are difficult to include in LCA studies.

Perspectives

- Improving the inclusion of the SOC model results within the LCA model by using the observed SOC change as the C sequestration potential of the biofertilizers instead of just an expected retained C potential.

- Average characterization factors for SOC depletion can be used in LCA methodologies. These factors can be improved based on spatial-explicit SOC modeling results for a given spatio-temporal context. Currently, the project "*ACV Carbonne*" is dedicated to developing a methodology to derive such factors to include SOC changes in LCAs for France.

- SOC-LCA coupled studies are time-consuming, developing automatized tools that can integrate the SOC model results within the life cycle inventories is therefore envisioned.

- Simultaneous implementation of various pathways are needed to evaluate the competitions and synergies among them and derive the best management alternative.

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Thank you for your attention

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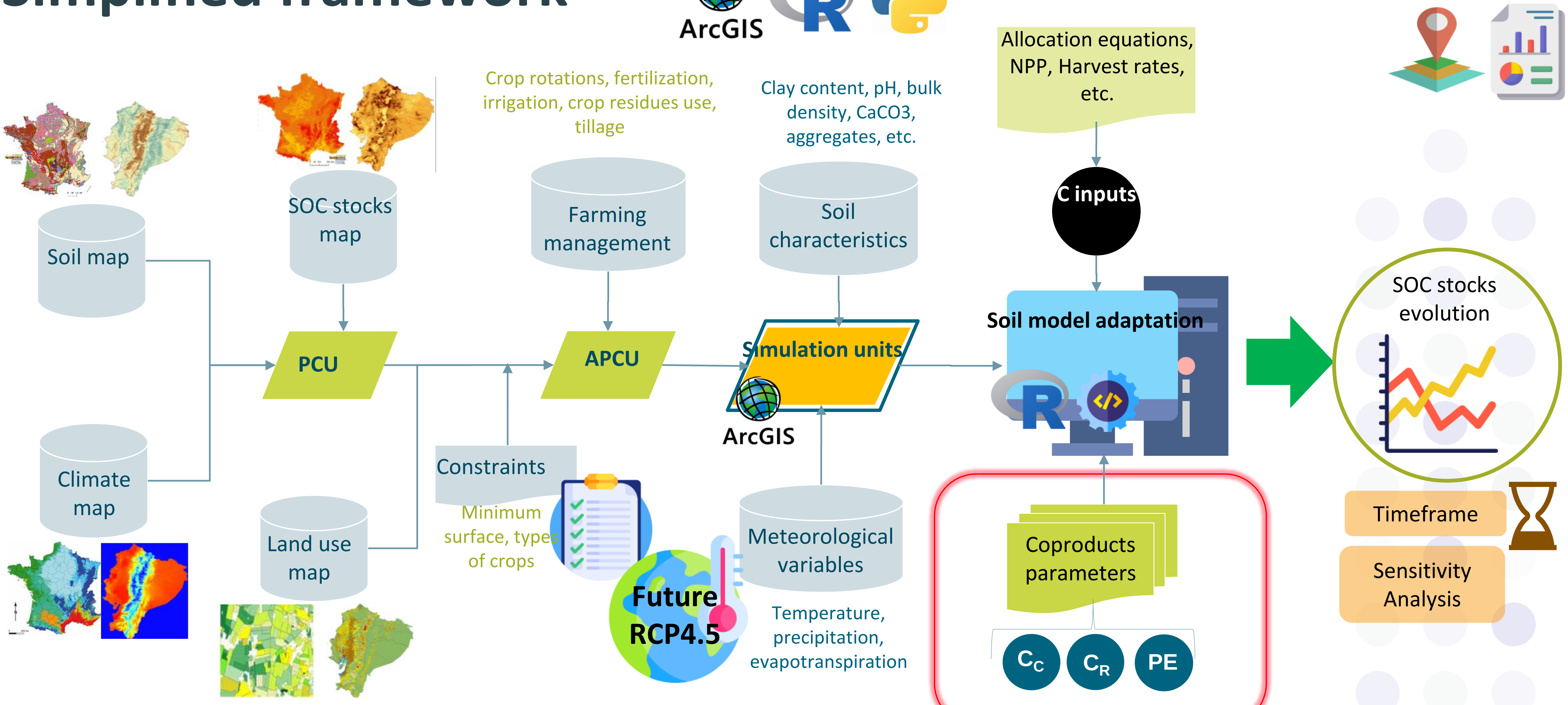
06 Supplementary Information

Simplified framework



Adapted from Launay et al., 2021 DOI: 10.1111/gcb.15512

Pedoclimatic unit (**PCU**), Agricultural pedoclimatic unit (**APCU**), Carbon conversion (**C_C**), Carbon recalcitrance (**C_R**), Priming effect (**PE**), Net primary production (**NPP**), Soil organic carbon (**SOC**)

Scope

France

- ❑ Future optimal performance

Background data

- ❑ Ecoinvent 3.9.1 consequential database

Foreground inventories

- ❑ Built on previous similar works and expanded based on published literature and stoichiometry balances

- ❑ Only marginal suppliers reacting to a change in demand were considered.

Marginal heat and electricity

- ❑ Heat → Electrically supplied
- ❑ Electricity: Mix for France already implemented in Ecoinvent 3.9.1 for medium or high voltage (13% wood, 84% wind,3% others)

Brightway

Environmental Footprint v3.1

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