Life cycle assessment and material flow analysis of **urban biochar applications**

A case study in Uppsala, **Sweden**

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VINNOVA
Sweden's Innovation Agency

Disclaimer

- This presentation includes all the results from our study on biochar use in the urban environment.

- A shorter version will be presented during the live session, focusing on aspects relevant for carbon inventory and management of biomaterials.

Part 1 – Life cycle assessment of urban biochar applications

What are the environmental impacts & benefits of biochar-based products?

Background – Rationale – Research questions

- Biochar use in urban environments is the most mature market segment in Sweden, and new applications are being developed.

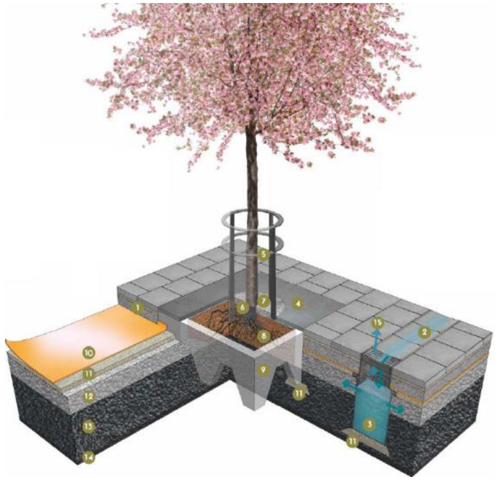
- Biochar products for urban areas are meant to replace other products. How does the environment footprint of biochar and reference products compare? Are there any burden shifts?

- Biochar may be produced from different biomass, in different reactors, resulting in different properties. How do differences in biochar supply-chain affect the footprint of a biochar product?

- A common critique to biochar use in soil is that it could be also be burnt for producing fossil-free steel. What is the most “climate-smart” use of biomass/biochar?

5 biochar urban applications

1. Tree in hard-surface area



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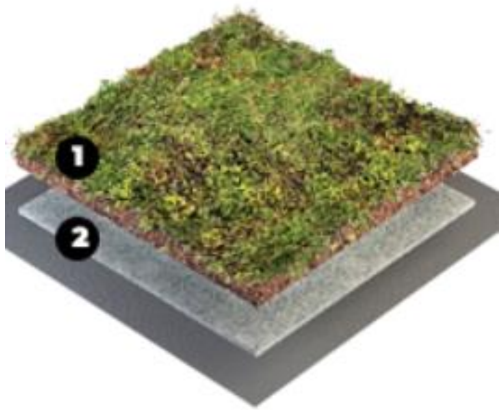
2. Extensive green roof



© VegTech AB

3. Planting soil

© Hasselfors AB

4. Concrete elements

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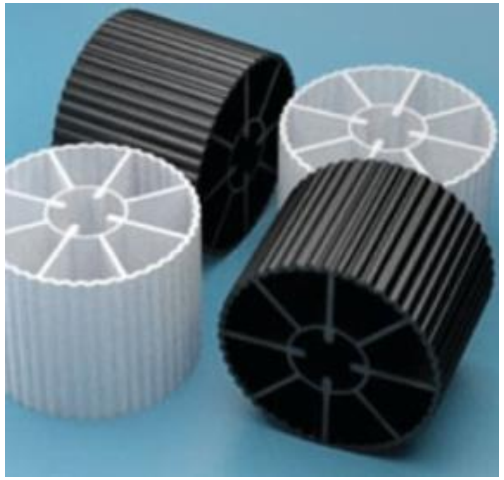
5. Biofilm carrier



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6. Pig iron (for steel)

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- Different technology readiness levels
- For each product, several designs, formulations, and dimensions may exist
- Pig iron – no carbon dioxide removal, but fossil fuel substitution (benchmark)

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7 biochar supply chains

4 biomass types

Wood pellets – WP
from sawmill residues,
alt. combusted for
district heat

Garden waste – GW
from urban areas,
alt. combusted for
district heat

Logging residues – LR
from SE forests,
alt. left to decay
in forest

Willow chips – WL
grown on fallow land,
alt. not cultivated land

© FAO, P. ARONSSON

3 reactor types, with pre-drying

Syngas-heated reactor – S
representative of Pyreg
or BioMaCon units

© BioGreen

Electricity-heated reactor – E
representative of BioGreen units

© EarthSystems

Mobile reactor – M
representative of Charmaker MPP

- In LCA jargon, the “alternative fate of a biomass or land” is called **RLBU** = Reference Land or Biomass Use.
- Biochar yield set to **25% (dry weight)** for all supply-chains
- Reactors S & E co-produce heat, for biomass drying and district heating.
- Biochar **carbon content** and **bulk densities** depends on the biomass type, only.
- Biochar **stability** depends on final application: in soil 80%, in concrete 95%

2 background energy systems

S1 – Swedish average energy system

District heat
from
Forest woodchips

Electricity
from
Swedish average mix

Transport fuel
from
70% diesel, 30% HVO (waste)

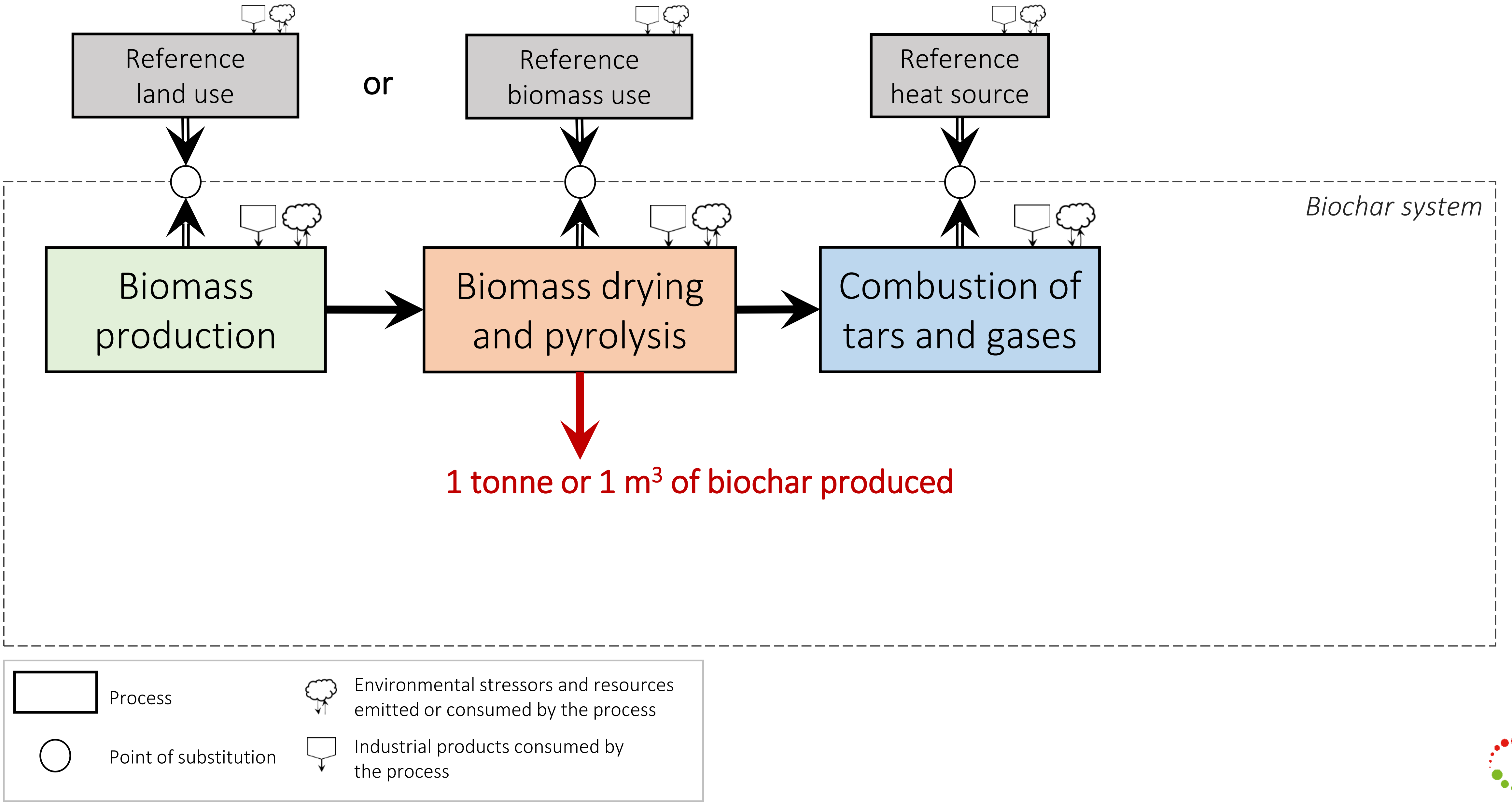
S2 – Fossil energy system

District heat
from
Natural gas

Electricity
from
Natural gas

Transport fuel
from
100% diesel

R1 – Cradle-to-gate LCA of biochar production

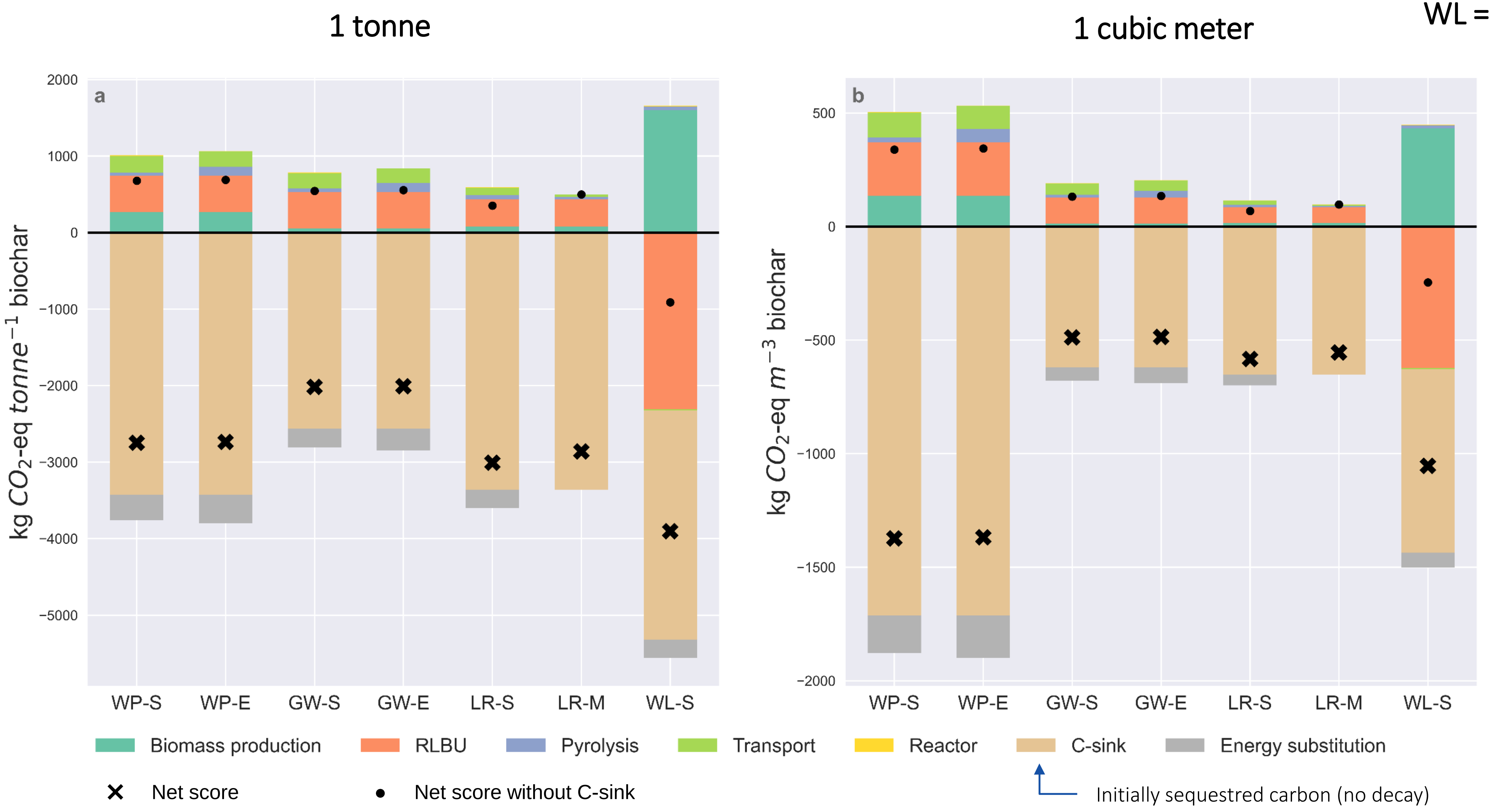


R1 – Cradle-to-gate LCA of biochar production

WP = Wood Pellets
GW = Garden Waste
LR = Logging Residues
WL = Willow chips

S = Syngas
E = Electricity
M = Mobile

In S1 – Swedish average energy system



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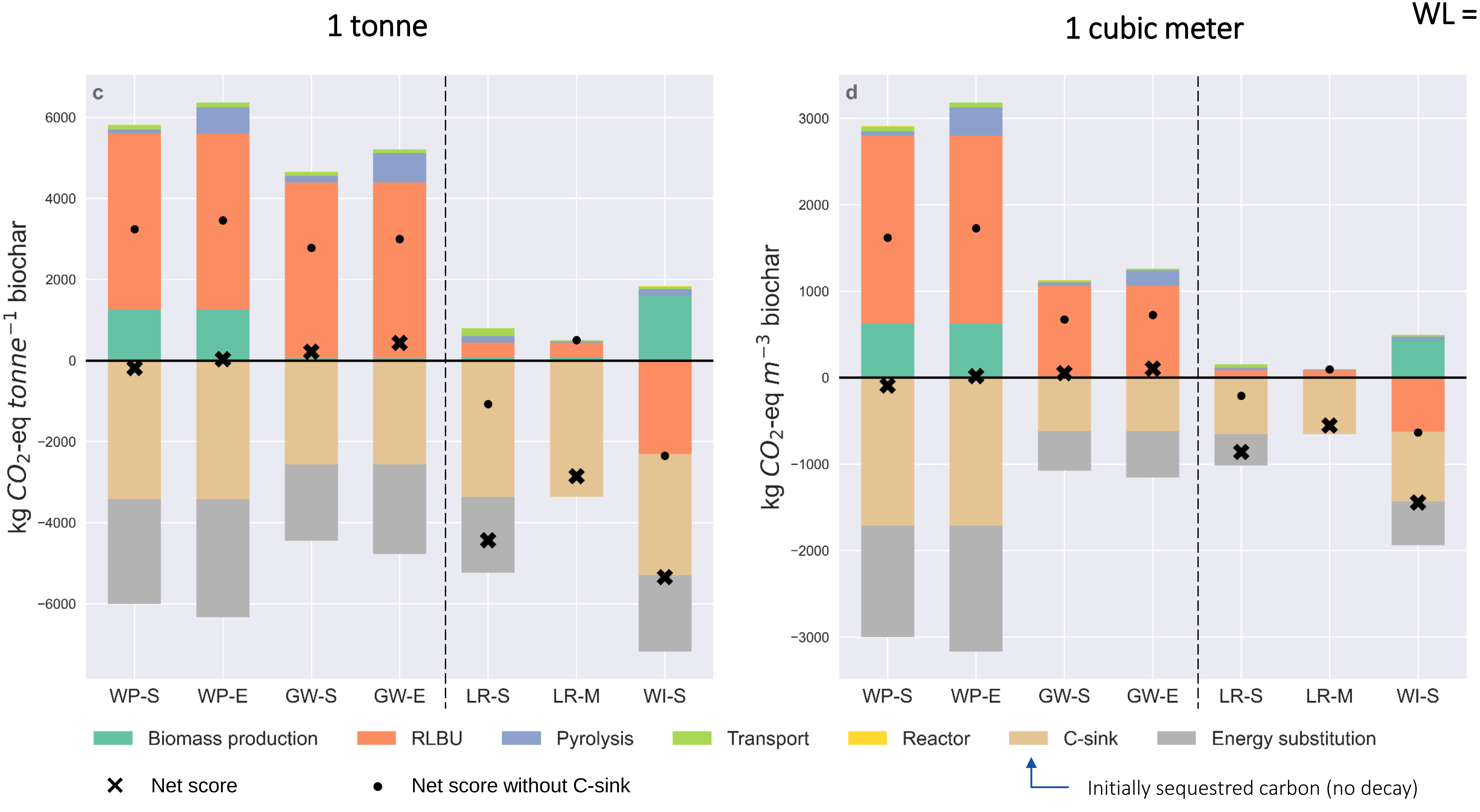
R1 – Cradle-to-gate LCA of biochar production

WP = Wood Pellets
GW = Garden Waste
LR = Logging Residues
WL = Willow chips

S = Syngas
E = Electricity
M = Mobile

In S2 – Fossil energy system



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Cradle-to-gate LCA of biochar production - Conclusions

- Difference in **biochar C-sink** between two types of biochar:
  - Per **mass**: $C_1 \,/\, C_2 \longrightarrow$ WP/GW ≈ 1.3
  - Per **volume**: $\rho_1 C_1 \,/\, \rho_2 C_2 \longrightarrow$ WP/GW ≈ 2.8

- It is **not "climate-smart"** to produce biochar **in a fossil energy system** (e.g. with natural gas as heat and electricity source, as in S2)

- In S1, the main differences between biochar supply-chains come from: **biomass type**, **reference land or biomass use**.

- The climate impact of producing biochar, excluding C-sink, varied in the range:
  - 350 – 700 kg CO_2-eq per tonne biochar (WP, GW, LR)
  - 70 – 340 kg CO_2-eq per cubic meter biochar (WP, GW, LR)

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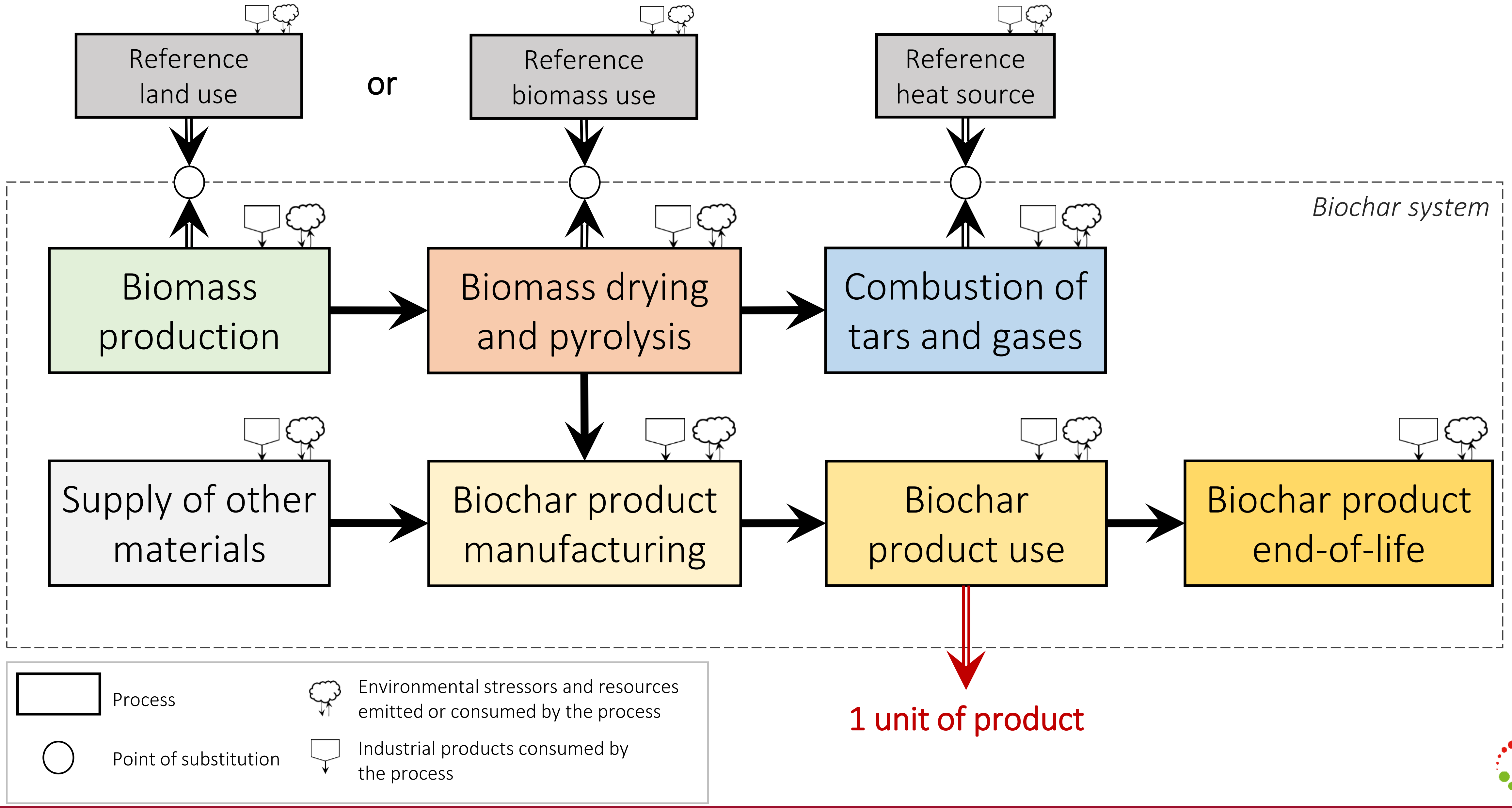
R2 – Comparing biochar products to reference products



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1- Tree in hard surface area, on open sub-base layers

Data/Inputs from:
- Stockholm Stad (handbook)
- Edges
- Hasselfors

Unit: 1 new tree planted, with a 2-year establishment period

Description:
- 15 m^3 root volume, covering about 10 m^2 road
- Manufacturing ⟶ Use ⟶ Disposal

Biochar vs reference product:
- Biochar-compost-macadam 32-64 mm *replaces* planting soil-macadam
- Biochar-compost-macadam 2-4 mm *replaces* planting soil

Biochar content: set by volume ⟶ 1000 L biochar per tree

Excluded here:
- Effects on stormwater quality (divergent results in literature)
- Difference in tree growth between biochar/reference tree
- Difference in fertilisation during establishment and use phase

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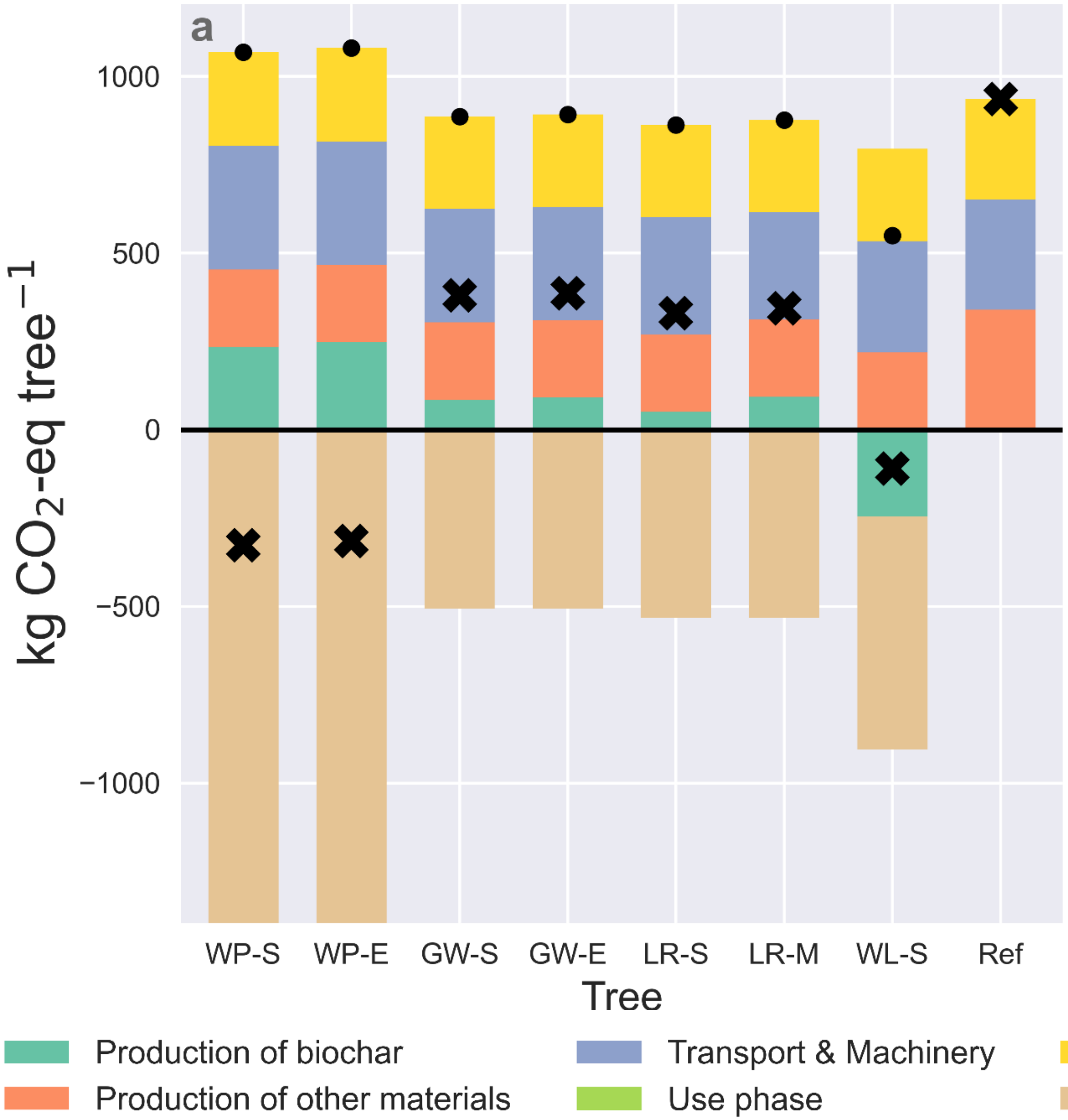
1- Tree in hard surface area, on open sub-base layers



Comments:

- Net score:
  - Always lower than reference
  - Not always below 0
- Net score, without C-sink:
  - Not always lower than reference
- Transport/Disposal: despite different mass, contribution not significantly affected.
- Carbon-sink: volume-based content of biochar

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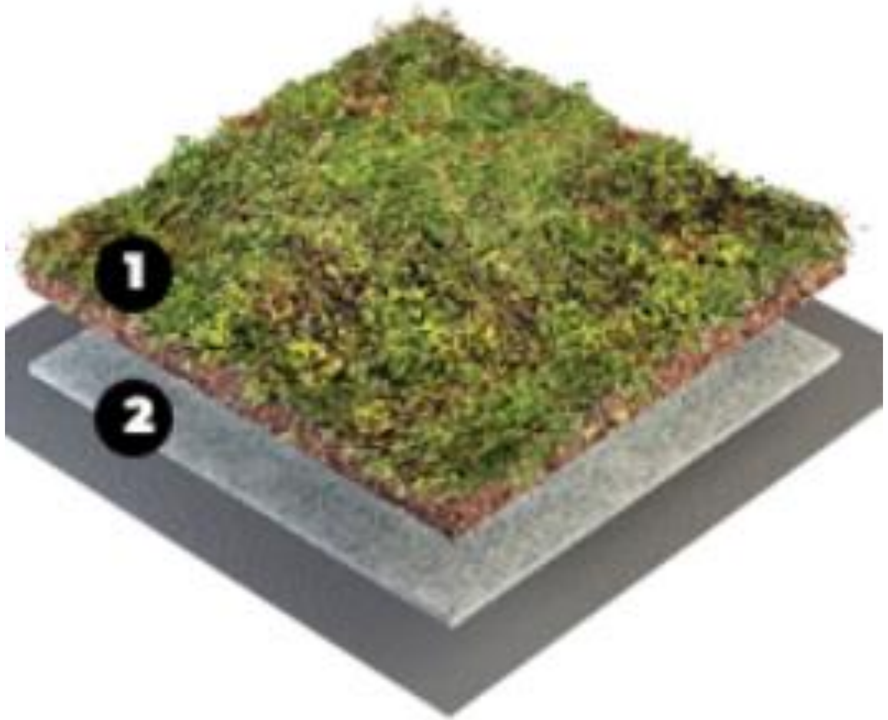
2- Extensive green roof, sedum mats



Unit: 1 m^2 roof covered, for 50 years

Description:
- 1 cm synthetic water holding layer layer, 3 cm lightweight mineral soil layer, cultivated for 2 years with sedum
- Manufacturing ⟶ Use ⟶ Disposal

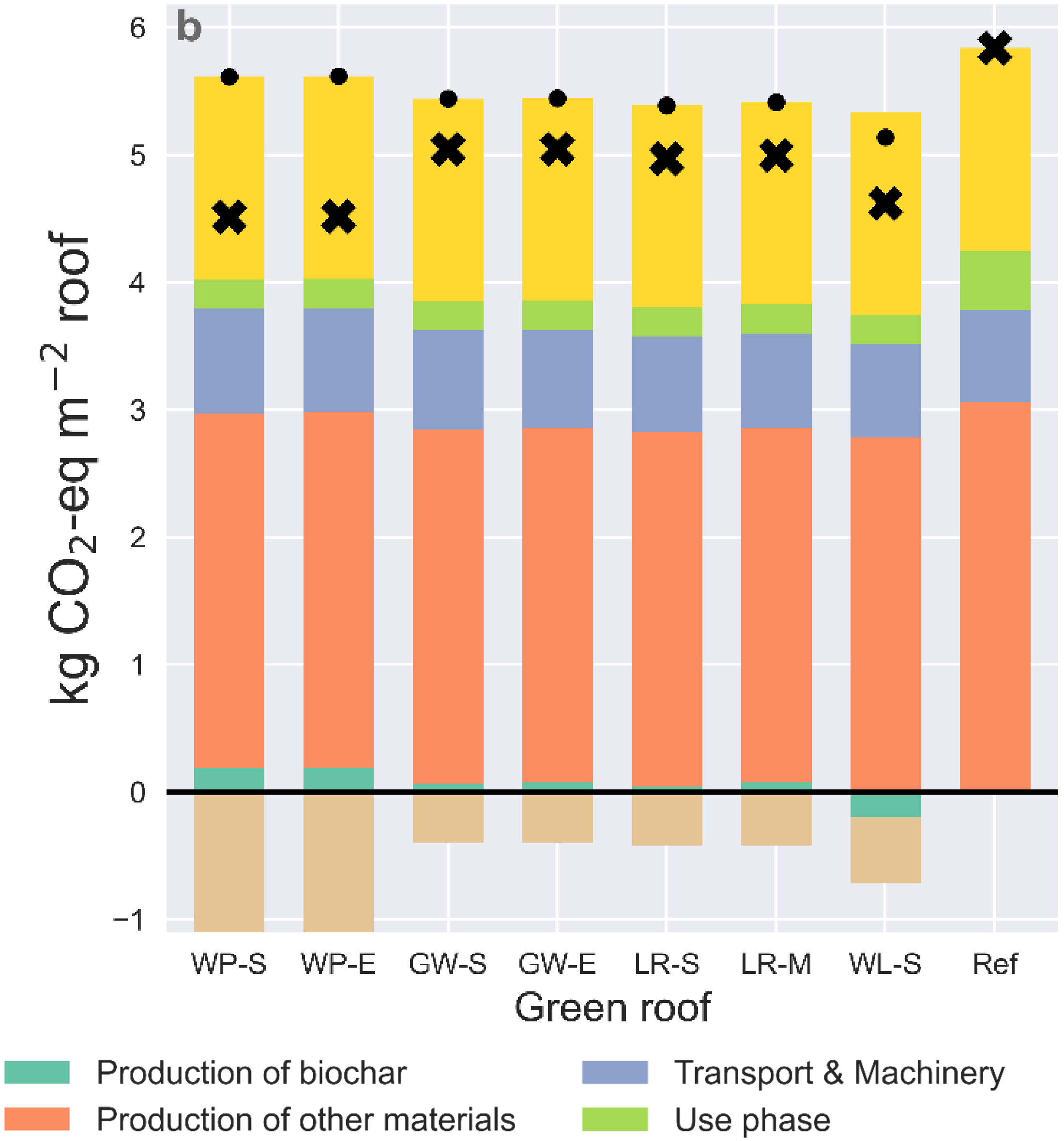
Biochar vs reference product:
- Reference mineral soil is made of pumice, peat, crushed rock, and clay, while the biochar mineral soil was made of pumice, peat, crushed rock, clay, compost and biochar. In different proportions.
- Fertiliser use during use phase (half)

Biochar content: set by volume ⟶ 1.5 L biochar per m^2 roof

Excluded here:
- Difference in lifetime, water runoff effects, building energy savings

Data/Inputs from:
- VegTech AB

2- Extensive green roof, sedum mats



Comments:

- Net score (with & without C-sink)
  - Always lower than reference
  - Never below zero

- Low biochar content

- Transport/Disposal: despite different mass, contribution not significantly affected.

- Carbon-sink: volume-based content of biochar

3- Landscaping soil – Planting soil type A

Unit: 1 m^3 soil delivered

Description:
- Landscaping soil, sold in bulk, used for planting bushes and trees
- Manufacturing ⟶ (Use ⟶ Disposal)

Biochar vs reference product:
- 35%v sand, 30%v clay, 35%v peat, 1250 kg m^{-3} (wet)
- 35%v sand, 30%v clay, 20%v biochar, 15%v compost, 910 kg m^{-3} (wet)

Biochar content: set by volume ⟶ 144 L biochar per m^3 soil

Data/Inputs from:
- Hasselfors AB

Excluded here:
- Use and disposal stages

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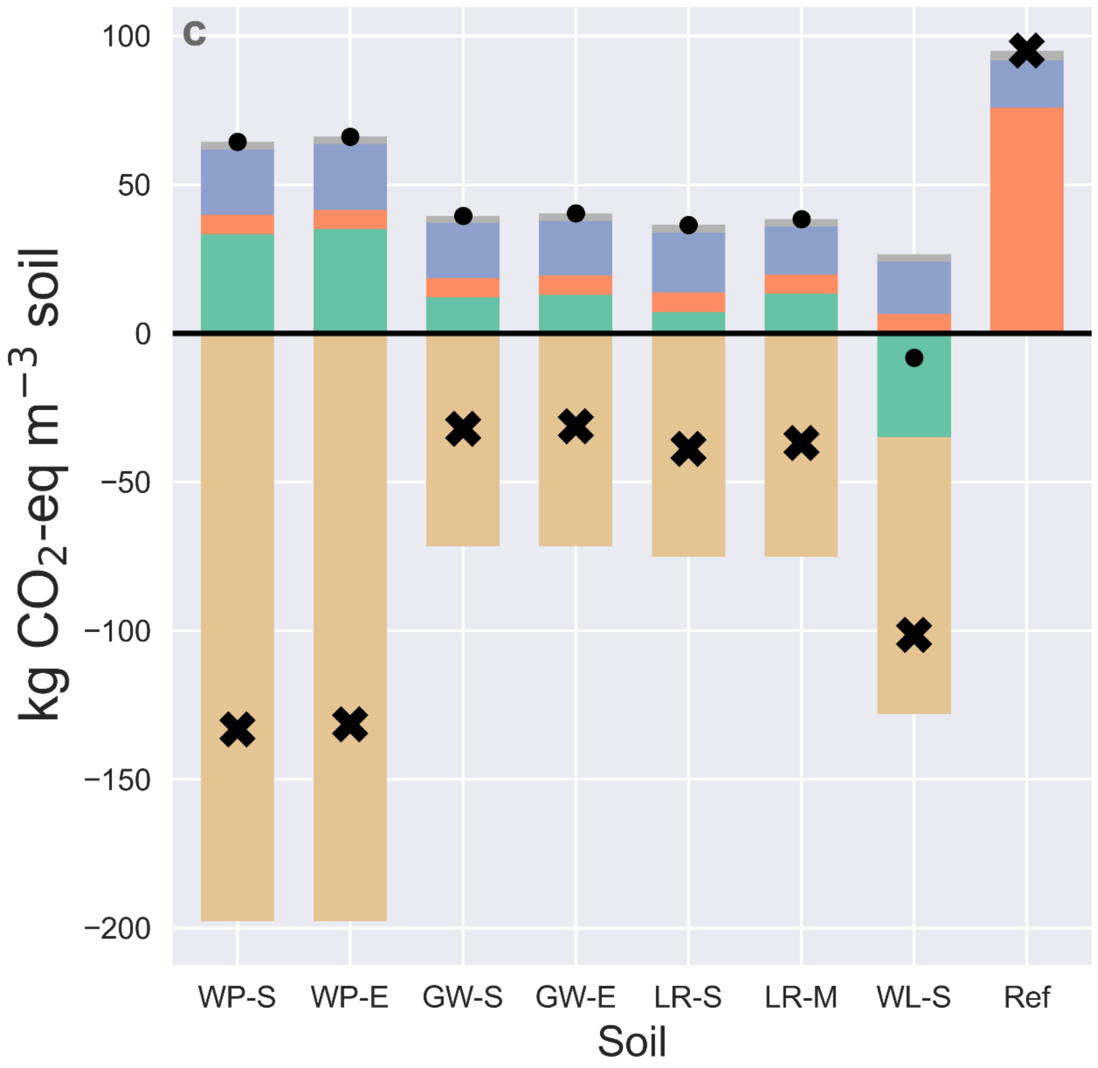
3- Landscaping soil – Planting soil type A



Comments:

- Net score:
  - Always lower than reference
  - Always below zero (not many other inputs, simple product)

- Carbon-sink: volume-based content of biochar

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4- Paving tiles & tree pits

Unit: 1 charcrete element delivered (paving tile, tree pit)

Description:
- Paving tiles: 40 cm x 40 cm x 4 cm
- Manufacturing ⟶ (Use) ⟶ Disposal

Biochar vs reference product:
- Biochar *replaces* some sand and gravel
- Charcrete *consumes more* cement than reference concrete

Biochar content: set by mass ⟶ 110 kg biochar per m^3 concrete

Excluded here:
- Fine grinding of biochar

Data/Inputs from:
- Biokol Produkter AB

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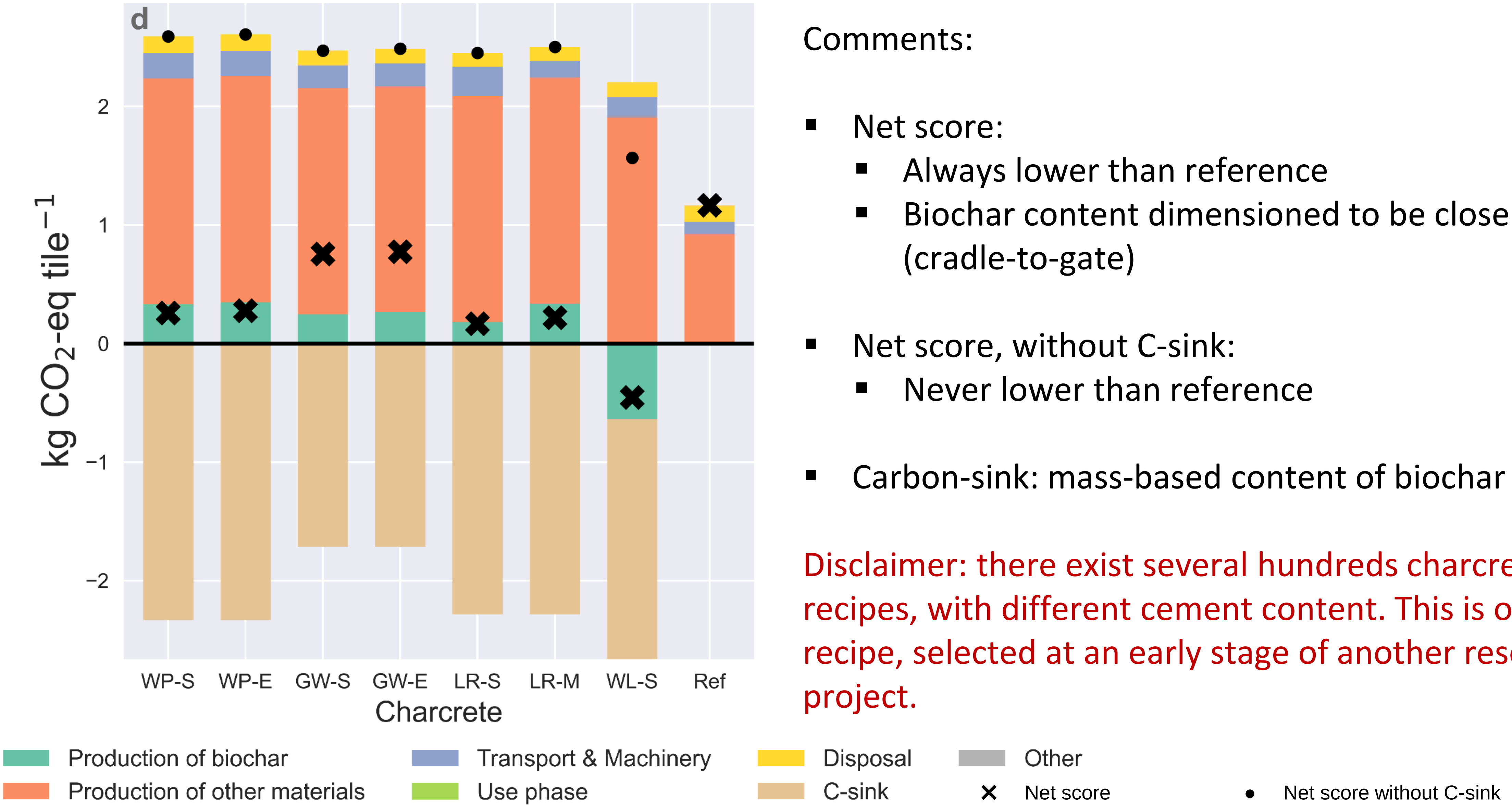
4- Tree pits & paving tiles



Comments:

- Net score:
  - Always lower than reference
  - Biochar content dimensioned to be close to zero (cradle-to-gate)

- Net score, without C-sink:
  - Never lower than reference

- Carbon-sink: mass-based content of biochar

Disclaimer: there exist several hundreds charcrete recipes, with different cement content. This is only one recipe, selected at an early stage of another research project.

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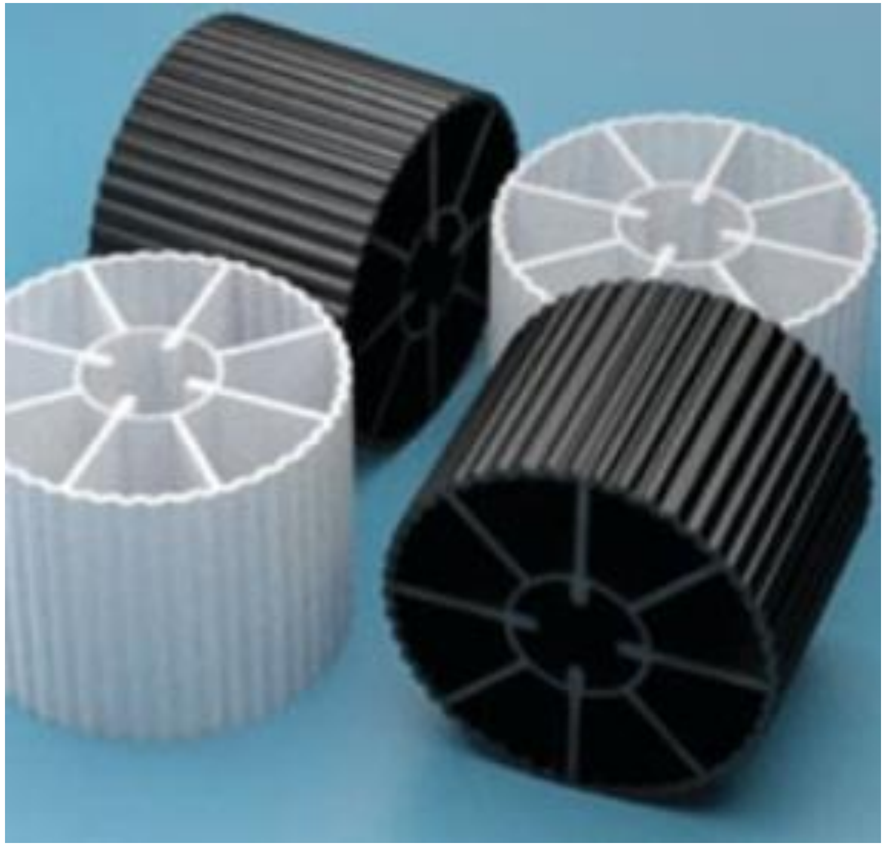
5- Biofilm carrier for BOD removal



Unit: 1 m^3 water pre-treated

Description:
- Use case: biofilm reactor used as a pre-treatment in a drinking water plant, to remove BOD, before a nano-filtration process.
- Manufacturing ⟶ Use ⟶ Disposal

Biochar vs reference product:
- Reference: a 1100 m^3 moving bed reactor, filled at 60% with K1 AnoxKaldnes plastic carrier, treating 7 million m^3 water per year, for 10 years, then incinerated
- Biochar: a 1100 m^3 reactor, filled at 100% with biochar, with a 10-year lifetime, then re-used as soil amendment or landfilled.

Data/Inputs from:
- Uppsala Vatten och Avfall AB

Biochar content: set by volume ⟶ 15 L biochar per 1000 m^3 water

Excluded here:
- Rest of the water treatment process (electricity use, mainly)

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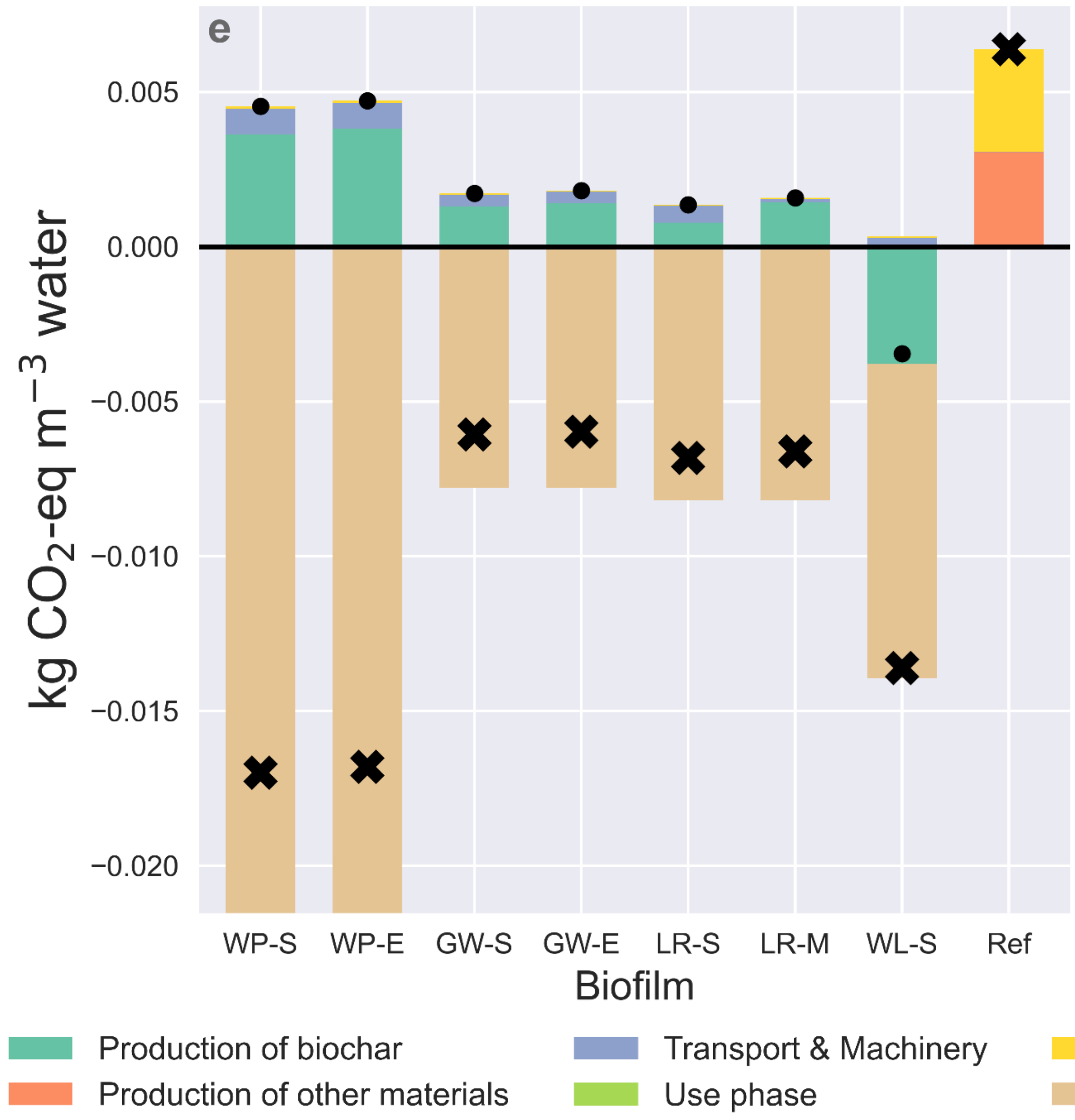
5- Biofilm carrier for BOD removal



Comments:

- Net score:
  - Always lower than reference
  - Always below zero (because not many other inputs in the product, simple product)
- Disposal of fossil plastic via incineration
- Carbon-sink: volume-based content of biochar

6- Pig iron production

Unit: 1 kg pig iron produced (intermediate product in the production of steel in a blast furnace)

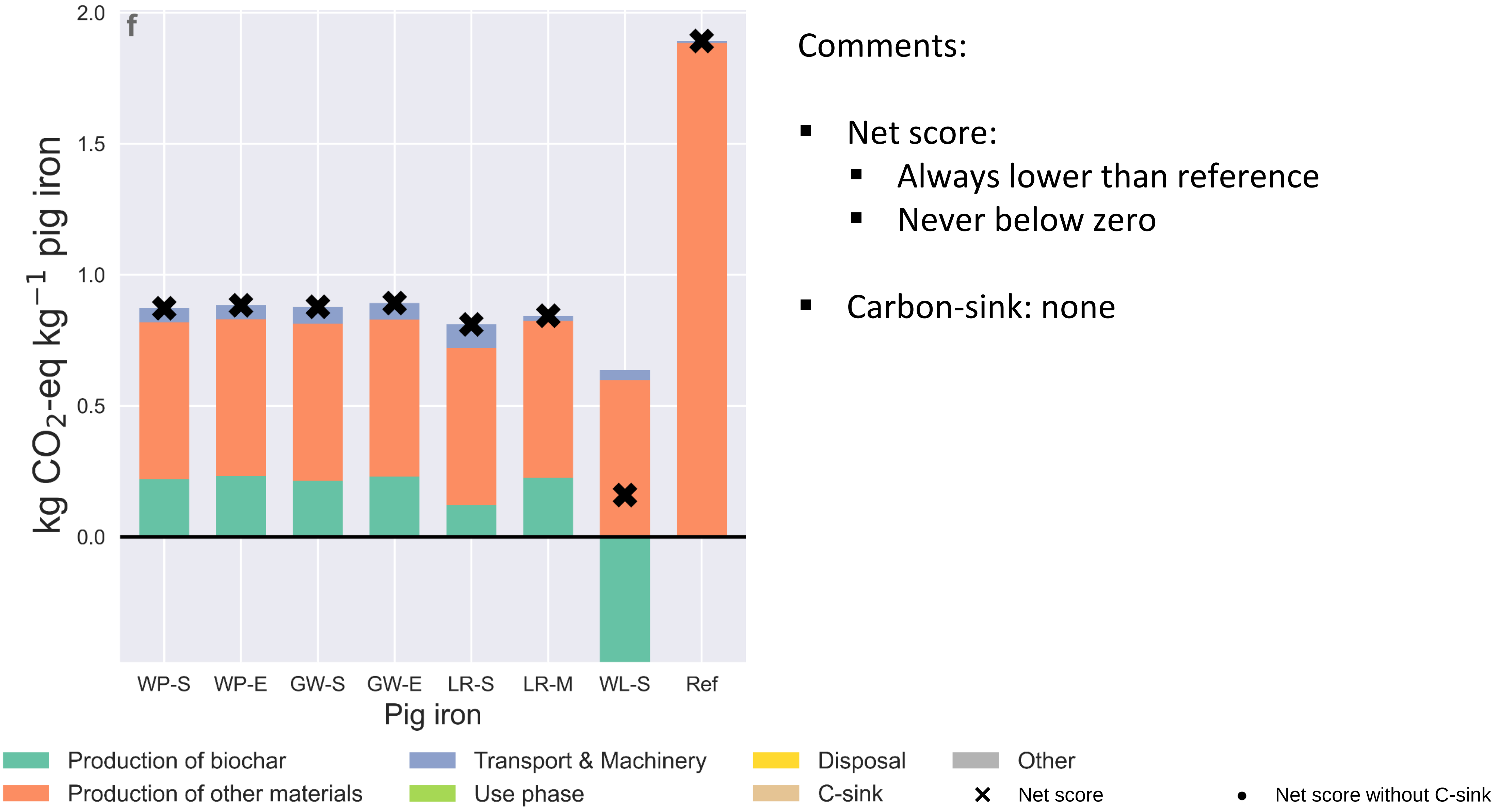
Description:
- Producing 1 kg of pig iron requires
  - 15 MJ thermal energy
  - 0.44 kg of C (as reducing agent)
- Manufacturing ⟶ (Use ⟶ Disposal)

Biochar vs reference product:
- Biochar *replaces* hard coal and coke

Biochar content:
set by carbon/energy ⟶ 0.48 – 0.62 kg biochar per kg pig iron

Data/Inputs from:
- Ecoinvent
- Literature

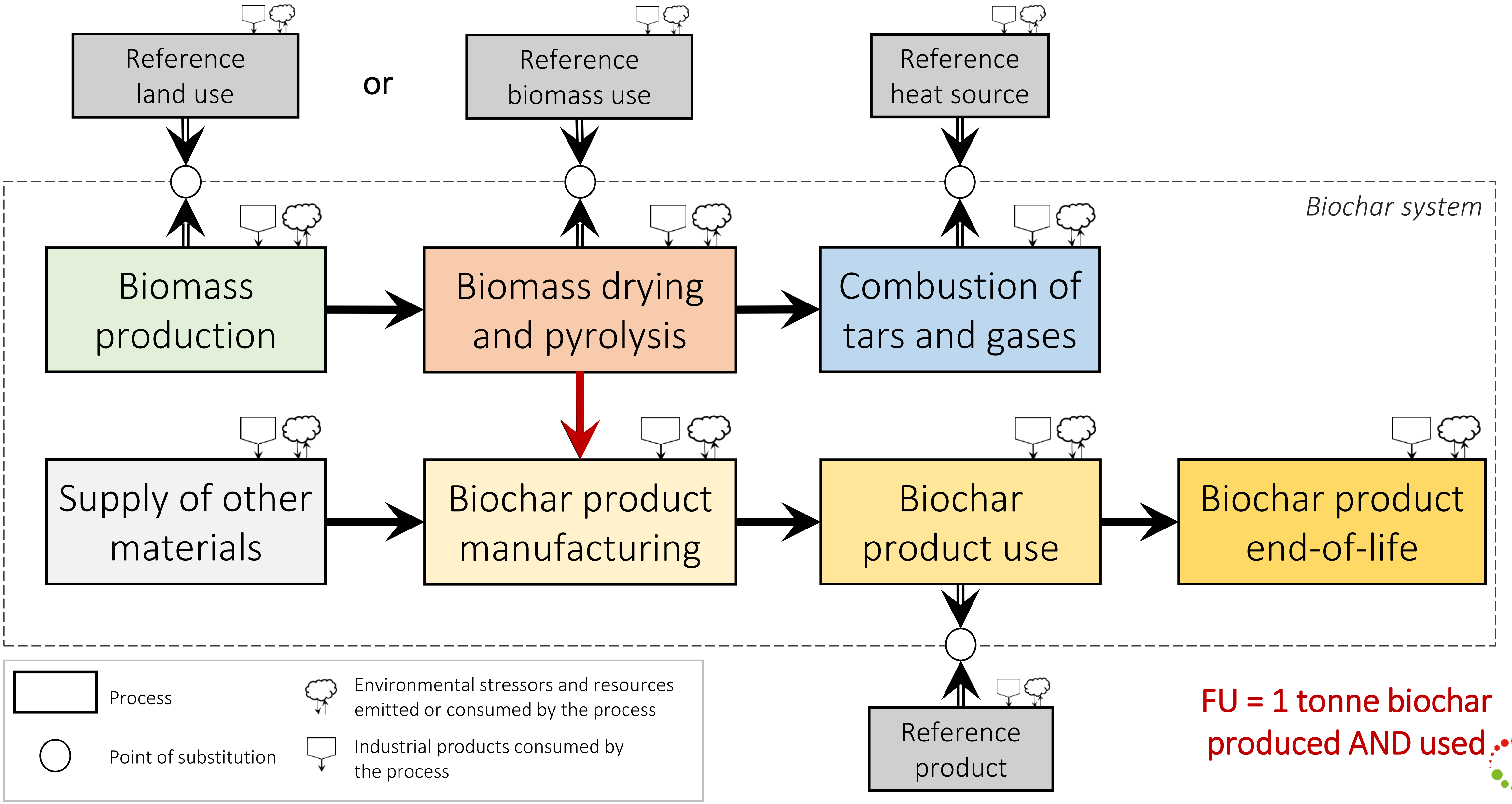
6- Pig iron production



Comments:

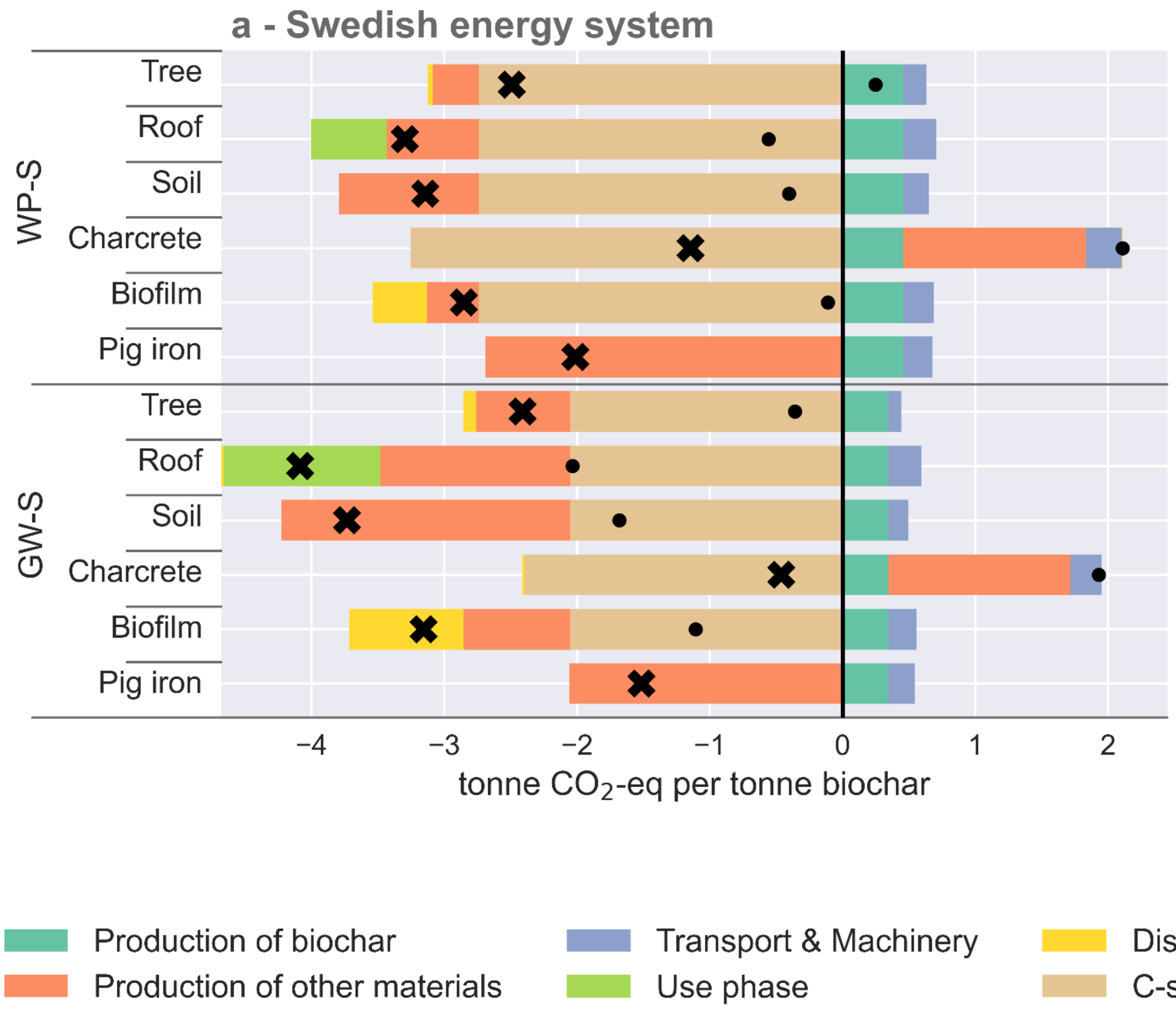
- Net score:
  - Always lower than reference
  - Never below zero
- Carbon-sink: none

R3 – Is there a "smartest" way of using biochar?



FU = 1 tonne biochar produced AND used

Is there a "smartest" way of using biochar?



How to read this graph: *if net score is…*

- *below zero*: product gives net GHG emission reductions ☺
- *above zero*: product gives increased GHG emissions ☹

In S1 (low-carbon heat and electricity system):

- For WP-S (wood-pellet biochar), all applications give net GHG emission reductions ☺ when accounting for C-sink.
- For GW-S (garden waste biochar), substitutions benefits are doubled compared to WP-S in volume-based biochar applications (1 tonne biochar, x2 more volume, x2 more product)
- Except for charcrete, all biochar applications outperform biomass use for pig iron production. This result is valid IF:
  - Other materials (peat, plastic) are substituted
  - Biochar stability is high (>80%)

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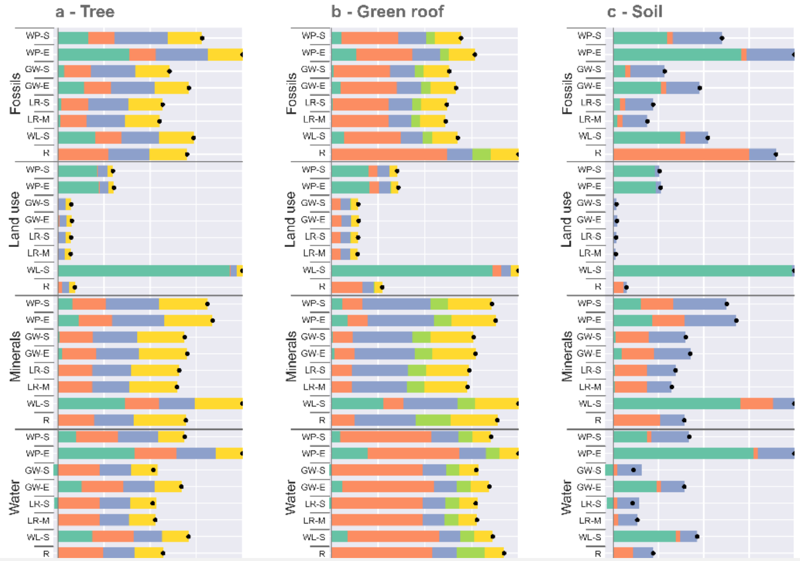
R4 – Other environmental impacts

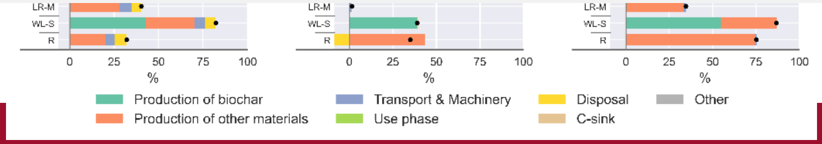
Resource use,
Human toxicity,
Ecotoxicity

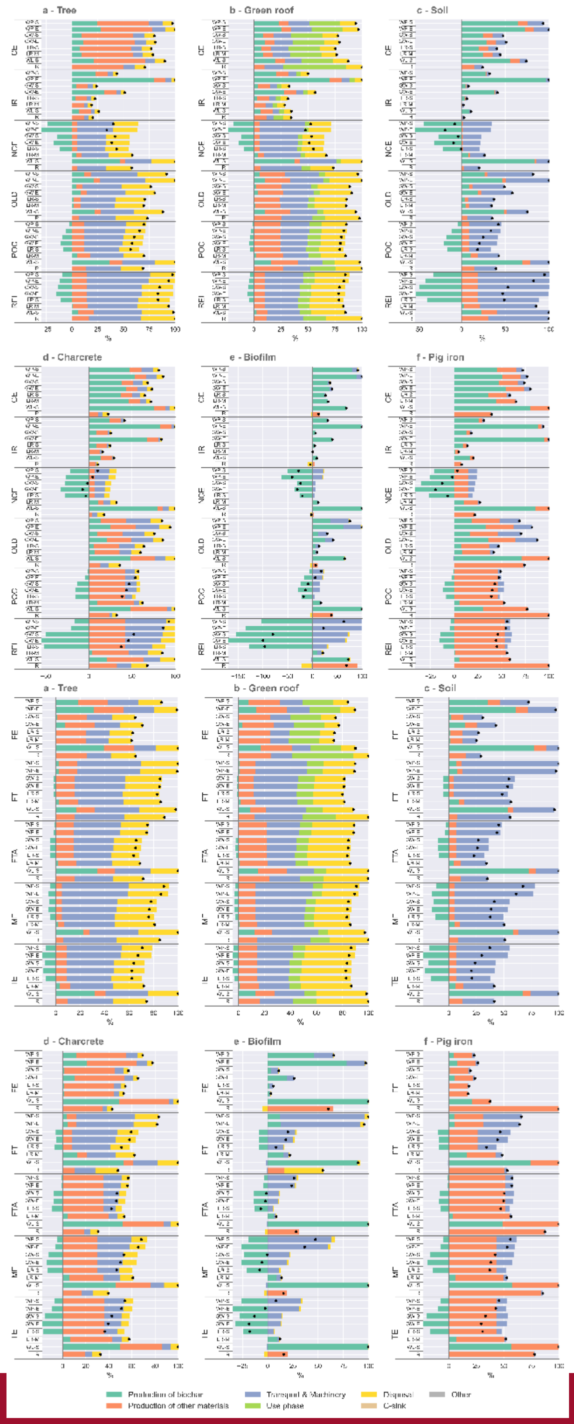


Picture much less clear than for climate impact

Biochar products can have either higher or lower environmental impacts than the reference products.

It is essentially due to biomass supply and biochar production, and material substitution.





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Discussion & limitations of LCA

- Biochar yield set to 25%, i.e. 1 tonne of biochar (dry) requires from 4 tonnes of biomass (dry)

- Biochar stability set to either 80% or 95%. What if it is 50%?

- LCA data for other materials (peat, clay, cement…) is as important as LCA data for biochar. Biochar landscaping soil appears "better" because it is compared to peat-based soils. The reference product matters when making comparisons.

- Design variability for each product was not investigated. Biochar & Reference product had same design. Model is rather well parametrized and can be modified.

- Difference in "use-phase" effects between biochar and reference were discussed, but rarely included because of lack of quantified information, unreliable or variable results, or non-significant differences.

- Product lifetime and disposal – kept simple, because fate is unknown.

LCA conclusions

R1 – Do not produce biochar if you have a fossil heat/electricity supply.

R2 – All biochar applications had lower climate change impact than their reference alternative. **Some achieved that even when excluding biochar carbon sequestration** ☺

R3 – Using biochar for C-sequestration can provide as much or more climate change mitigation benefits than its use for fossil-fuel substitution in steel production, **only if biochar stability is high (80%)** and **when other materials are substituted (peat & plastic)**.

R4 – Beside climate change, biochar products can have either increased and reduced environmental impacts (resource use, toxicity, ecotoxicity). *To be further analysed.*

Part 2 – Material flow analysis at the district scale

How much biochar could be used in Uppsala’s new city district?

Background – Rationale – Research questions

In Part 1, we checked the LCA climate impact of 5 biochar products
Put simply, it is worth using biochar products:

- if energy system is rather decarbonised
- if biochar stability is high (e.g. 80%)
- if biochar replaces other materials (e.g. peat, plastic,…)

In a city, how much biochar can be used?

- Roof space is rather limited
- Trees planted one time, then nothing for several decades
- Water consumption is set

In a city, how to manage the biochar C-sink when products reach end-of-life?

⟶ We performed a case study in Uppsala's new city district to quantify these flows of biochar over the coming century (2020 to 2100).

Uppsala SÖS – For those who don't know it…

- Construction: 2020 to 2050
- Population: 57 000
- Accommodation: 20 000
- Jobs: 10 - 15 000

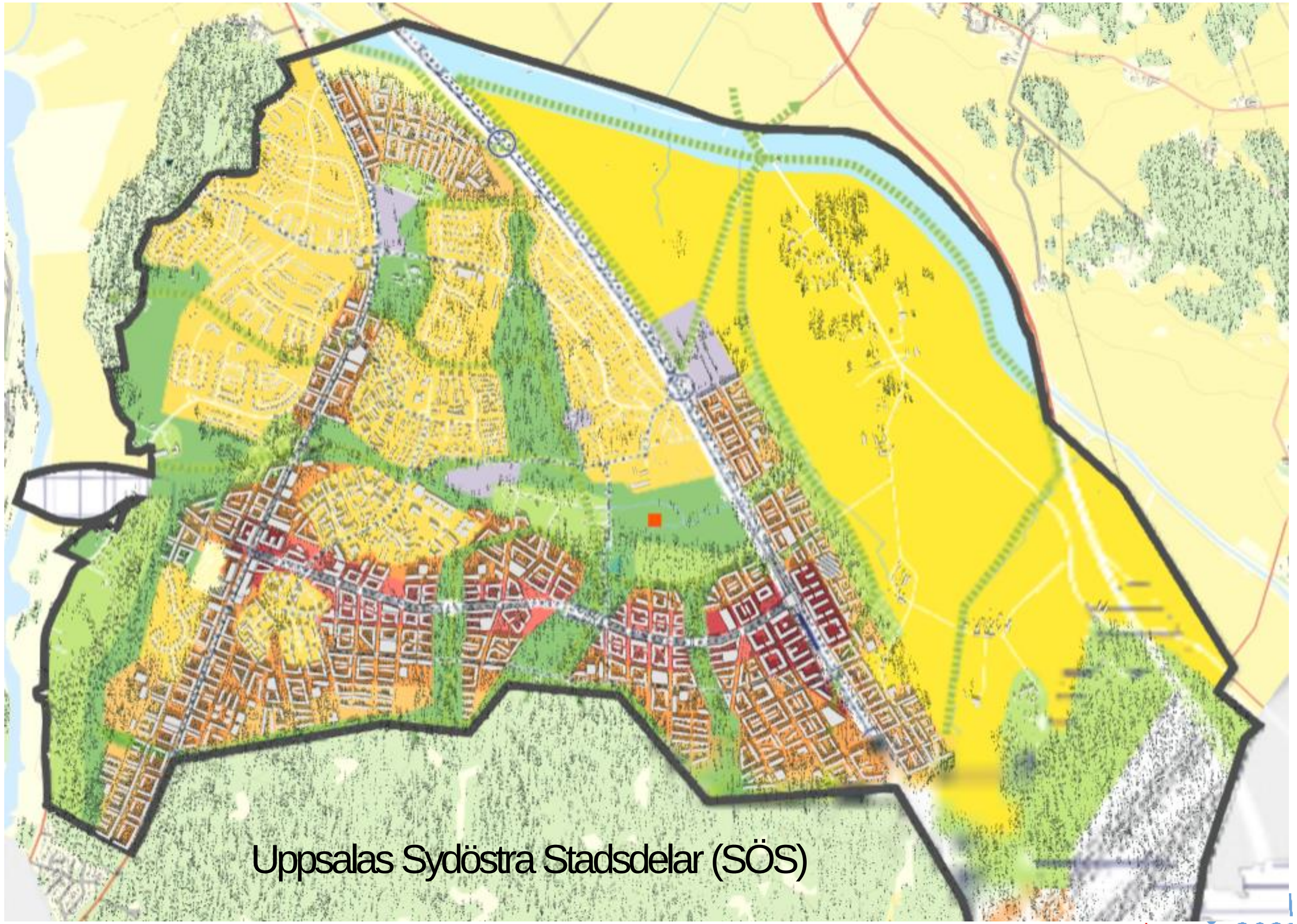
- Road area: 1 200 000 m^2
- Road length: 50 000 m

- Rooftop area: 837 800 m^2

- Residential yards: 1 000 000 m^2
- 6 new public parks: 230 000 m^2

- Forest area cleared: 182 ha, with ca 30 000 m^3 standing wood

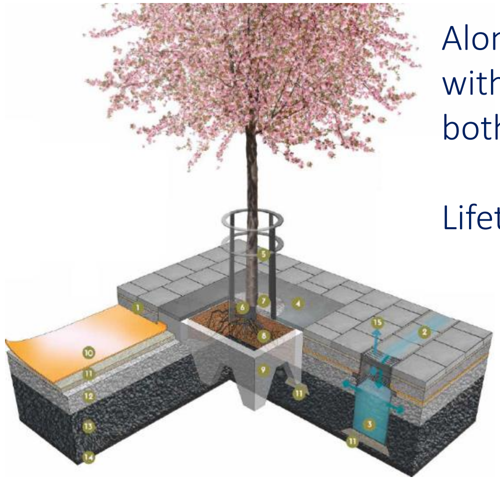
How much biochar can be used?



2021

The 5 biochar urban applications *in SÖS*

1. Tree in hard-surface area

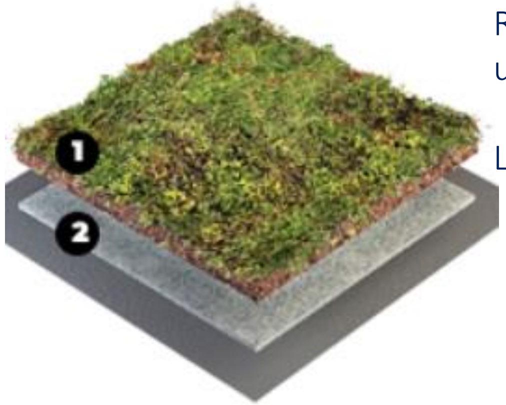


Along 50 km of road, with 10 m spacing, both sides

Lifetime 50 years

© Stockholm city

2. Extensive green roof



On 50% of roof area, Rest for PV or not-usable

Lifetime 50 years

© VegTech AB

3. Planting soil

In residential yards, and public parks

for trees, bushes, and lawns

at a rate of 0.33 m^3 per m^2 planted area, for establishment

at a rate of 1 $L/m^2/yr$ for maintenance

© Hasselfors AB

4. Concrete elements

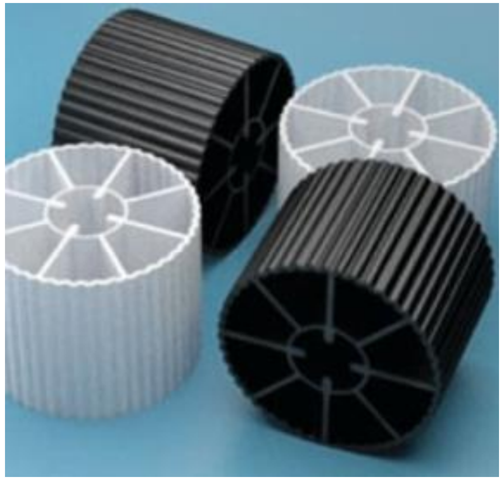
One pit per tree

10 decorative tiles, around trees (rain gardens)

Lifetime 100 years

© StockholmsTreePits Co., St Eriks AB

5. Biofilm carrier



Population: 57 000
Water use: 140 L/day

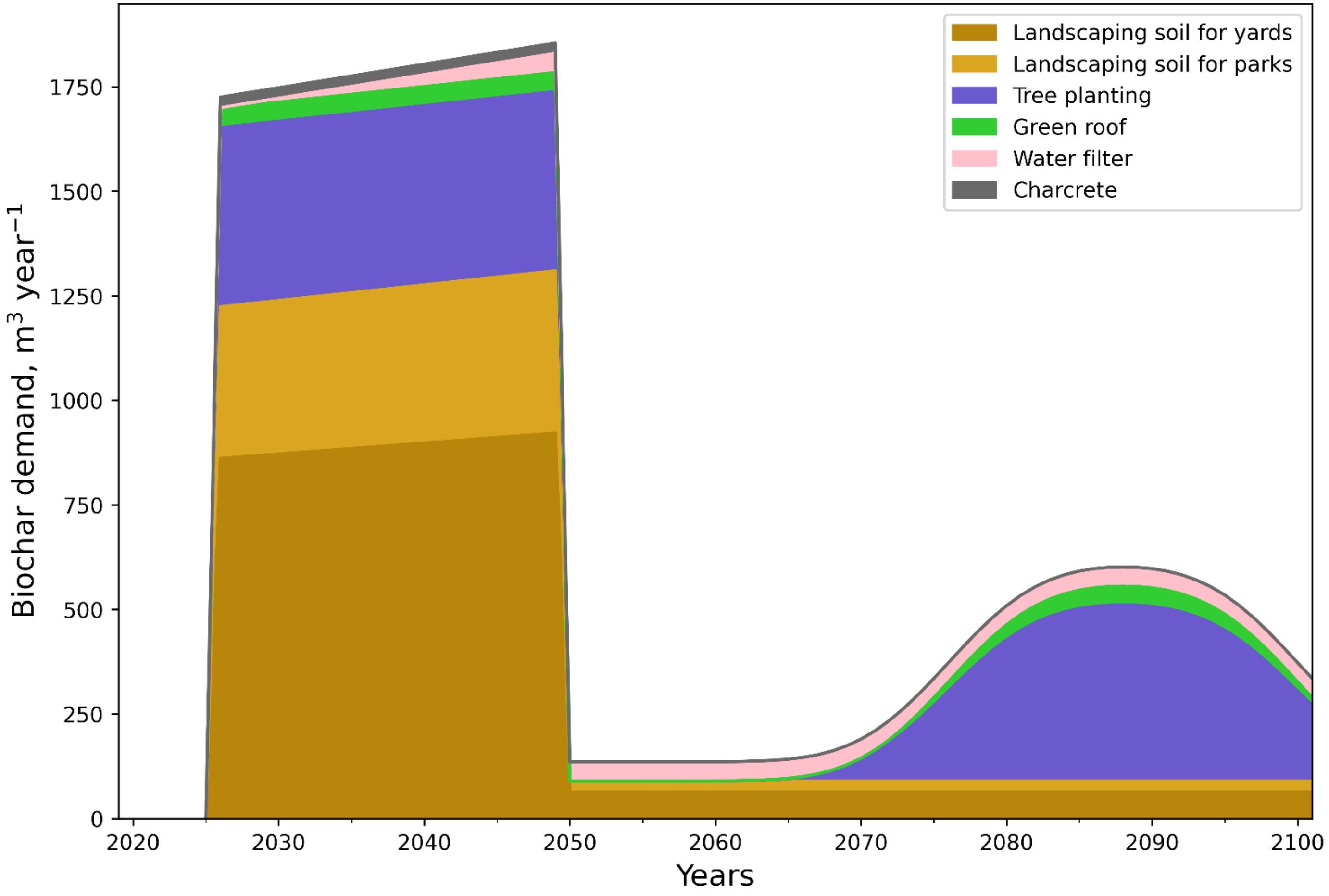
© Wikipedia Commons

Note: biochar volume and mass demand vary with biochar type and application.

Equation for stock-driven dynamic material flow

$$i(t) = \frac{dS(t)}{dt} + \sum_{c<t} i(c) \cdot sf(t,c)$$

Biochar demand



Mass & Volume requirement

Biochar	Construction	Maintenance
any, m^3	**43 600 m^3**	18 700 m^3
WP, t	21 500 t	9 300 t
GW, t	10 600 t	4 500 t
LR, t	8 500 t	3 600 t
WL, t	11 800 t	5 000 t

Biomass and land demand

Wood pellets – WP

Annual Swedish consumption: 1 250 000 t
(Pelletsförbundet, 2020)
⟶ 7% of 2020's consumption, spread over 25 years

Garden Waste – GW

Uppsala Vatten och Avfall collects about 1700 of wood waste annually
⟶ roughly equal to the annual demand during construction

Logging Residues – LR

In Swedish forests, at final felling, we can harvest between 0.3 and 0.7 dry tonnes ha^{-1} $year^{-1}$ (North/South) (Hammar, 2015)
⟶ 68 400 ha of forest at final felling, harvested one time

Willow Woodchips – WL

Willow yield: 2.3 dry tonnes ha^{-1} $year^{-1}$
(Hammar, 2016)
⟶ 820 ha of willow, cultivated for 25 years

Biomass requirement (dry tonnes)

Biochar	Construction	Maintenance
WP	86 200 t	37 300 t
GW	42 300 t	18 100 t
LR	34 200 t	14 500 t
WL	47 100 t	20 200 t

Forest land cleared in the district

182 ha
about 30 000 m^3 standing wood,
i.e. about 10 000 dry tonnes

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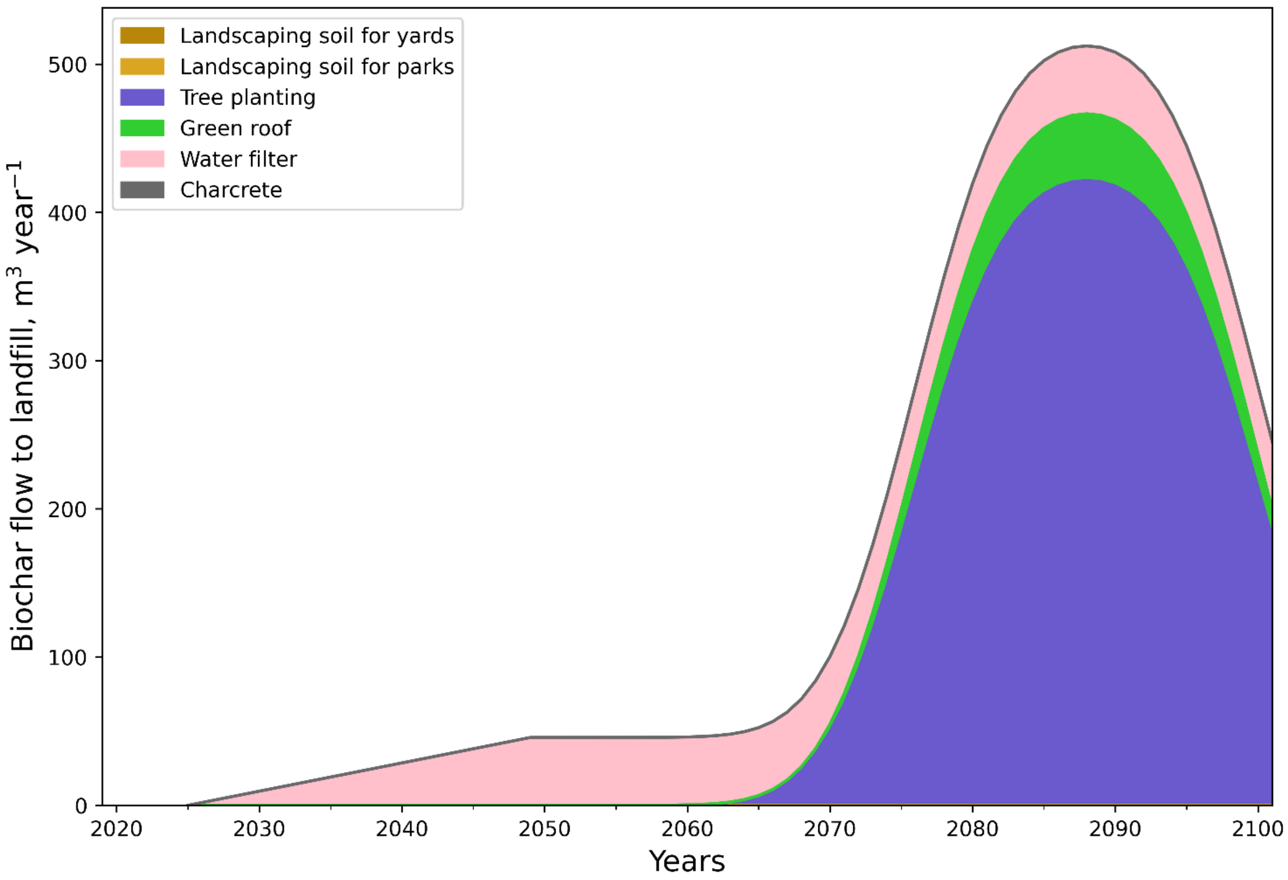
Biochar end-of-life, who will manage it and *when*?



Note: flow in biochar volume, most biochar is in fact blended with macadam, mineral soil.

Note: landscaping soil assumed to remain in parks and yards.

At period end, in 2100, of all biochar produced:
- 57% remaining in parks
- 20% in-use stock (tree, roof, charcrete, filter)
- 23% landfilled

"landfilled" is default case – but one could see it as secondary material for backfill.

Secondary applications, lifetime extensions (e.g. green roof) reduce future "primary" biochar demand

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How much carbon sequestration for the city ?

- Current estimate, over 25 years of construction:
  ca 40 000 m^3 biochar
  ca **20 - 60 000 t CO_2-eq** sequestered in total
  ca **800 – 2400 t CO_2-eq $year^{-1}$** sequestered

Biochar carbon sink (t CO_2-eq)

Biochar	Construction	Maintenance
WP	59 200 t	25 600 t
GW	21 800 t	9 300 t
LR	23 100 t	9 700 t
WL	28 300 t	12 000 t

*Per-capita GHG-emissions, Sweden, 2018 = 8 t CO_2-eq/pers/year

- Compared to:

  (i) expected emissions for the construction of the residential buildings of the new district, estimated by the municipality: 20 000 tonnes CO_2 $year^{-1}$ (for 25 years)

  (ii) emissions of Uppsala municipality as reported for 2020: 1 million tonnes CO_2-eq per year

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Final word

1. **Design recommendation: biochar products should have a better environmental performance than reference product even without accounting for the C-sink, because:**
   - Biochar stability is still uncertain (precautionary principle)
   - Many persons want to claim the rights for biochar C-sink
   - Globally, we need to reduce emissions AND deploy carbon removal

2. **In this study, tangible co-benefits to CDR were mainly related to:**
   - Peat substitution (in all 3 soil applications)
   - Plastic substitution (filter)

3. **Biochar supply-chain variability**
   - Producers should document in detail biomass type and origin, conversion process, biochar properties
   - Product manufacturer should document dry mass and volume content of biochar in their products,
     - For environmental accounting reasons
     - For waste management phase

4. **At-scale the city scale:**
   - Large amounts of biomass needed – may be available in Sweden, but elsewhere?
   - Biochar CDR may be equivalent to few percent of current emissions
   - Market mixes & market segmentation

Keywords:
Industrial ecology
Life cycle assessment
Energy, agriculture and climate
Biochar

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Previous work

Case study 1 – Prospective large-scale biochar production in Stockholm, and use in dairy farming
https://pubs.acs.org/doi/10.1021/acs.est.9b01615

Case study 2 – On-farm small-scale biochar production at Lindeborgs farm
https://doi.org/10.1016/j.jclepro.2020.124873, https://github.com/ntropy-esa/P2_farm_biochar

Case study 3 – Biochar from wood waste used for contaminated soil remediation
https://doi.org/10.1016/j.scitotenv.2021.145953

Methodology – Assessing the diverse side-effects of biochar
https://doi.org/10.1016/j.jenvman.2021.112154

2019 Webinar – Overview of biochar deployment in Sweden & related life cycle assessments
https://www.youtube.com/watch?v=Wd1aSp3Fp-E

2021 Webinar – Life cycle assessment of 6 urban applications of biochar & case study in Uppsala
https://www.youtube.com/watch?v=PfIGIUWJnkw

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