A CIRCULAR BIOECONOMY

WITH BIOBASED PRODUCTION FROM NUTRIENT AND CO₂ SEQUESTRATION BY SEAWEED

MARIANNE THOMSEN, MICHELE SEGHETTA, ANNETTE BRUHN, SIMONE BASTIANONI, BERIT HASLER AD THE WHOLE MAB3 TEAM
ECOSYSTEM SERVICES

Definition:
Benefit that human obtain from an ecosystem (MEA, 2005)

Seaweed cultivation +
Ecoindustrial system =

____________________________

Engineered ecosystem services mimicking the natural system

Fig. modified from Metrovancouver.org
CONCLUSION

- Seaweed production and biorefinery systems may deliver **supporting and regulatory services**, e.g. restoration of aquatic water quality and mitigation of climate change, while producing biobased products for biobased societies.

- **Climate regulation** = **Delivery of net negative GHG emission**, e.g. carbon capture and storage + carbon capture and use
  - 0.1-1.3 ton CO$_2$e bioassimilated per ton dw seaweed harvested

- **Nutrient cycling** = **Net removal of excess nitrogen and phosphorous from the aquatic system** re-entering the economic system.
  - 5-43 kg N is removed from the aquatic system per ton dw seaweed harvested
CONCLUSION

- Harmonised methodologies for quantifying the services delivered by seaweed cultivation and biorefinery systems are needed!

- The monetary value of the services obtained from biorefinery systems producing biogas, protein, ethanol and fertilizer constitutes 5-30% of the Return on Investment (RoI).

- The break-even point in productivity are in the range of 2.2-5.8 ton dw seaweed/ha, excluding investment and maintenance cost of the biorefinery plant.

- RoI of the macroalgal biorefinery systems analysed varies between 126-11,100 EUR/ha
CONTENT

- MAB3 systems analysed
- Variability in productivity and units of measure
- Services, policies and environmental performance
- Product portfolio – a glimpse
- Return on investments from MAB3 biobased production systems
- Conclusion
Protein, Ethanol & Fertilizer Products

Macroalgae production system
- Seed lines
- Deployment
- Maintenance
- Harvest

Transport

Biorefinery
- Pretreatment
- Hydrolysis
- Fermentation
- Distillation/separation

Ethanol
Proteins
Fish feed prod.
Fish feed

Liquid fertilizer
BIOGAS AND PROTEIN

Macrosalgae production system
- Seed lines
- Deployment
- Maintenance
- Harvest

Energy production pathway
- Biogas production
- Digestate storage
- Digestate transport
- CO₂ conversion
- CHP unit

Protein production pathway
- Chopping
- Hydrolysis
- Microalgae growth
- Dewatering

Transport
Partial drying
Ensilage

Electricity
Heat
organic NPK fertilizers
Proteins
CIRCULAR NUTRIENT MANAGEMENT

- Industrial ecology!
- Use of emissions as a resource for seaweed production
  - Biobased products & services

Seghetta et al., 2016
There are 7 registered seaweed cultivation plants in Denmark. Hjarnø Havbrug (Horsens) is the biggest, Seaweed Société ApS owns 3 plants; each 10-30 ha. The remaining 3 seaweed cultivation plants are below 10 ha.

**Horsens:**
13 ton N harvested/year < yearly emission supply of 740 ton

**Limfjorden:**
0.4 ton N harvested/year < yearly emission supply of 9 ton

(33-130 kg N/ha, 3-12 kg P/ha, 1000-4000 kg/ha)

Seghetta et al., 2016
### PRODUCTIVITY

<table>
<thead>
<tr>
<th></th>
<th>Saccharina latissima &amp; Laminaria digitata, WW</th>
<th>Saccharina latissima, DW</th>
<th>Laminaria digitate, DW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Productivity</strong></td>
<td>Lowa</td>
<td>Highb</td>
<td>Average</td>
</tr>
<tr>
<td>Dry matter content</td>
<td>21.6%</td>
<td>14.8%</td>
<td>28.3%</td>
</tr>
<tr>
<td>[kg/m HL]</td>
<td>6.1</td>
<td>12.0</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>[kg/m SL]</td>
<td>1.4</td>
<td>2.6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>[Mg/ha]</td>
<td>6.8</td>
<td>13.2</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

a) Based on productivity measured in Limfjorden
b) Based on productivity measured in Horsens Fjord

Seghetta et al., 2016
NON-MONETARY VALUE OF THE SERVICES

Climate Change mitigation

<table>
<thead>
<tr>
<th>Regulating service: Climate regulation</th>
<th>kg CO$_2$e assimilated / ton dw seaweed harvested</th>
</tr>
</thead>
<tbody>
<tr>
<td>The cultivation step</td>
<td>990-1,300</td>
</tr>
<tr>
<td>The whole biorefinery value chain</td>
<td>123-190</td>
</tr>
<tr>
<td>The whole value chain of biogas and fertilizer production</td>
<td>170-1,247</td>
</tr>
</tbody>
</table>

Mitigating Aquatic Eutrophication

<table>
<thead>
<tr>
<th>Supporting services: Nutrient cycling</th>
<th>kg N assimilated / ton dw seaweed harvested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivation step</td>
<td>5-43</td>
</tr>
<tr>
<td>The whole biorefinery value chain</td>
<td>7-57</td>
</tr>
<tr>
<td>The whole value chain of biogas and fertilizer production</td>
<td>1-30</td>
</tr>
</tbody>
</table>

Quantification of the regulatory services from macroalgae production and biorefinery systems should be based on the net result of the whole value chain

Thomsen et al., 2016
“If we are to limit global warming to 2 °C, all sectors in all countries must reduce their emissions of GHGs to zero not later than 2060–2080.”

- Today, investments in zero-emission technologies are rapidly catching up with investments in fossil energy
- The development and market growth of potential zero-emission technologies such as wind and solar power, electric transport systems, zero-energy buildings and advanced biofuels have been impressive and the co-benefits of mitigation are widely recognized (IPCC, 2014).
- In contrast to these advances, the energy-intensive industries (EII) are facing greater challenges.
- EII produce basic materials such as steel, cement, aluminium, fertilizers and plastics, and account for a large share of global GHG emissions. The best available technologies (BATs) can only reduce emissions by 15–30% in these industries, even if they are applied on a large scale
- May BBI catch up with the investments in EII?
- What are the climate performance of the BBI sector?
BC: Average productivity 1.5 ton dw seaweed /ha, harvest summer (high ethanol), high dw percent (*Laminaria digitata*)

A2: High productivity scenario, harvest summer (high ethanol), high dw percent (*Laminaria digitata*)

A6: Low CO₂ footprint of the cultivation design main reason for carbon negative, i.e. CC mitigating results!

Seghetta et al., 2016
BIOGAS, PROTEINS & CLIMATE REGULATION

System boundaries are important!

Cradle to Cradle vs. Cradle to Gate

Sequestering of recalcitrant carbon is important!

Seghetta et al., 2016
PROTEIN, ETHANOL & FERTILIZER PRODUCTS

Seawater → Macroalgae production system
- Seed lines
- Deployment
- Maintenance
- Harvest

Transport → Biorefinery
- Pretreatment
- Hydrolysis
- Fermentation
- Distillation/separation

Ethanol → Human
Proteins → Fish feed prod.
Liquid fertilizer → Fish feed

atmosphere

soil

WWTP
CARBON CYCLE – TIME VARIATION

1 production cycle

9-13% of C is sequestrated

100 production cycles

Seghetta et al., 2016
CARBON CYCLE – SEASONAL VARIATION

Carbon cycle simulations for 100 seaweed cultivation cycles evaluated after 100 years

Seghetta et al., 2016
WATER QUALITY POLICIES

-seaweed as an instrument for water quality restoration
- close existing resource leakage gaps by recycling excess nutrients from aquatic system
- An alternative to land-based instruments

Nutrients bioextracted

<

Nutrient emission supply

Seghetta et al., 2016
WATER QUALITY RESTORATION - BIOREF

Nitrogen limited

Phosphorus limited

Saccharina latissima harvested in spring

Laminaria digitata harvested in spring

Seghetta et al., 2016
WATER QUALITY RESTORATION - BIOGAS

Nitrogen limited

Phosphorus limited

Seghetta et al., 2016
TAKE HOME MESSAGE

Seaweed production and biorefinery systems may perform net negative, i.e. contributing climate regulation and water quality restoration by nutrient recycling.

Biogas and fertilizer production delivers higher mitigation of CC compared to biorefineries; i.e. producing recalcitrant carbon sequestering in soil.

The more treatment steps included in the value chain, the higher risk of performing with a net positive GHG emission, i.e. contributing to climate change.

Low/zero carbon energy sources and increased resource utilization efficiency may counterbalance this tendency.

Zero or net negative balances for non-market services = for environmental sustainability

Net positive values for provisional services (goods) = for economic sustainability
ANNUAL PRODUCTION COSTS - PHASES

IMMATURE TECHNOLOGY
- Nursery 43%
- Deployment 25%
- Maintenance 9%
- Harvest 23%

MATURE TECHNOLOGY
- Nursery 17%
- Deployment 40%
- Maintenance 17%
- Harvest 26%

Thomsen et al., 2016
Seaweed as instrument for circular nutrient management

<table>
<thead>
<tr>
<th>Technology scenarios</th>
<th>Limfjorden</th>
<th>Horsens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Immature</td>
<td>Mature I</td>
</tr>
<tr>
<td>Productivity <em>Saccharina latissima</em> (15% dry matter content) [kg/ha]</td>
<td>1,000</td>
<td>1,500</td>
</tr>
<tr>
<td>Productivity <em>Laminaria digitata</em> (29% dry matter content) [kg/ha]</td>
<td>1,959</td>
<td>2,894</td>
</tr>
<tr>
<td>N assimilation - <em>Saccharina latissima</em> [kg N/ha]</td>
<td>33</td>
<td>64</td>
</tr>
<tr>
<td>N assimilation - <em>Laminaria digitata</em> [kg N/ha]</td>
<td>53</td>
<td>78</td>
</tr>
</tbody>
</table>

Immature: low productivity

Mature I: Stone rope technology, optimum productivity, first year harvest

Mature II: Two season cultivation – nursery and deployment each second year

Mature III: Two season cultivation and double productivity

Financial costs of supporting service 27-365 EUR/kg N harvested

Thomsen et al., 2016
SPATIAL CONFIGURATION OF THE COST-EFFECTIVE SOLUTION, 4165 TONS REDUCTION

Measures
- Blue: Set aside
- Light brown: No measures
- Green: Catch crops etc.
- Red: Norm reductions etc.

Costs
- Brown: 0
- Teal: 0 - 100
- Blue: 100 - 1,000
- Dark blue: Over 1,000

Hasler et al., 2015
MARGINAL COSTS OF N LOAD REDUCTIONS

Opportunity costs of the supporting service
91-183 DDK/kg N = 12-25 EUR/kg N harvested

Set aside
Afforestation
Constructed wetlands

Buffer zones
Catch crops

Hasler et al., 2015
### Monetary Value of the Services

#### Climate Change Mitigation

<table>
<thead>
<tr>
<th>Regulating service: Climate regulation</th>
<th>kg CO₂e assimilated/ton dw seaweed harvested</th>
<th>Shadow price: EUR/kg CO₂e harvested</th>
<th>Opportunity cost: EUR/ton dw seaweed harvested</th>
</tr>
</thead>
<tbody>
<tr>
<td>The cultivation step</td>
<td>990-1,300</td>
<td>0.07-0.13</td>
<td>65-176</td>
</tr>
<tr>
<td>The whole biorefinery value chain</td>
<td>270-430</td>
<td></td>
<td>8-26</td>
</tr>
<tr>
<td>The whole value chain of biogas and fertilizer production</td>
<td>170-1,247</td>
<td></td>
<td>12-169</td>
</tr>
</tbody>
</table>

#### Mitigating Aquatic Eutrophication

<table>
<thead>
<tr>
<th>Supporting services: Nutrient cycling</th>
<th>kg N assimilated/ton dw seaweed harvested</th>
<th>Shadow price: EUR/kg N harvested</th>
<th>Opportunity cost: EUR/ton dw seaweed harvested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivation step</td>
<td>5-43</td>
<td>12.2-24.6</td>
<td>61-1,056</td>
</tr>
<tr>
<td>The whole biorefinery value chain</td>
<td>7-57</td>
<td></td>
<td>90-1404</td>
</tr>
<tr>
<td>The whole value chain of biogas and fertilizer production</td>
<td>1-29</td>
<td></td>
<td>11-727</td>
</tr>
</tbody>
</table>
### A GLIMPSE OF THE PRODUCT PORTFOLIO

<table>
<thead>
<tr>
<th>Product Category</th>
<th>Market Volume [Euro/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phycobiliproteins (PBP)</td>
<td>&gt;800</td>
</tr>
<tr>
<td>Pharmaceuticals, bioactive peptides, Polyphenols</td>
<td>10-800</td>
</tr>
<tr>
<td>Food</td>
<td>0.1-135</td>
</tr>
<tr>
<td>Phycocolloids (agar, carrageenan, alginate)</td>
<td>1-10</td>
</tr>
<tr>
<td>Polysaccharides-prebiotics</td>
<td>1-10</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>3-8</td>
</tr>
<tr>
<td>Chemicals</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Biogas, bioethanol</td>
<td>0.5-3</td>
</tr>
</tbody>
</table>
The break-even point is obtained by an increase in the seaweed productivity of 4.5-6 ton dw seaweed/ha.
RETURN ON INVESTMENT – STILL UGLY

The break-even point is obtained by seaweed productivity of 4.2-5.3 ton dw seaweed/ha.
The break-even point is obtained by seaweed productivity of 3.2–4.4 ton dw seaweed/ha.
RETURN ON INVESTMENT - GOOD

1. Optimized protein production with microalgae conversion of seaweed sugar content
2. Combined succinic acid and CO₂ conversion, with TPC and fertilizer as biproducts
3. Combined protein, bioethanol and fertilizer production in spring (L.d. > S.l.)

Break-even point: 2.5-5.8 ton dw seaweed / ha

Thomsen et al., 2016
RETURN ON INVESTMENT – EVEN BETTER

1. Optimized protein production with microalgae conversion of seaweed sugar content
2. Combined succinic acid and CO$_2$ conversion, with TPC and fertilizer as biproducts
3 and 4. Combined protein, bioethanol and fertilizer production in spring (L.d. > S.l.)

Break-even point: 2.2-4.4 ton dw seaweed / ha

Thomsen et al., 2016
CONCLUSION

- Seaweed production and biorefinery systems may deliver ecosystem services and biobased products for biobased societies.

- Climate Regulation = Delivery of net negative GHG emission, i.e. climate change mitigation by carbon capture and storage + carbon capture and use
  - Net negative values of 170-1,247 kg CO$_2$e per ton dw seaweed biorefined

- Nutrient cycling = Net removal of excess nitrogen and phosphorous from the aquatic system re-entering the economic system
  - Net negative value for reduction in eutrophication level, 1-57 kg N is removed from the aquatic system per ton dw seaweed biorefined
CONCLUSION

- Harmonised methodologies for quantifying the services delivered by seaweed cultivation and biorefinery systems are needed.

- The monetary value of the services obtained from biorefinery systems producing biogas, protein, ethanol and fertilizer constitutes 5-30% of the Return of Investment (RoI).

- The break-even point in productivity are in the range of 2.2-5.8 ton dw seaweed/ha, excluding investment and maintenance cost of the biorefinery plant.

- RoI of the macroalgal biorefinery systems analysed varies between 126-11,100 Euro/ha.

- More high value products and a biorefinery pilot plant to be realised in MAB4.
Funded by the Innovation fund Denmark
http://www.mab3.dk/

Thanks for input to the MAB3 consortium and a special thank to
Michele Seghetta, Annette Bruhn, Per Dolmer, Ditte Bruunshøj Tørring & Berit Hasler
Marianne Thomsen mth@envs.au.dk
REFERENCES – MAB3


5. Seghetta, M., Romeo, D., D'este, M., Bastianoni, S., Alvarado-Morales, M., Angelidaki, I. & Thomsen, M., 2016. Macroalgae as a new source of energy and feed in Denmark: evaluating the environmental impacts through LCA. *Journal of Cleaner Production*. In review.


Scientific papers are/will be available at [http://pure.au.dk/portal/en/mth@envs.au.dk](http://pure.au.dk/portal/en/mth@envs.au.dk)
REFERENCES – MORE...


