# Bio-Economic aspects of off-shore seaweed cultivation - food and energy security

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# Macroalgae as food and energy security – is it true?

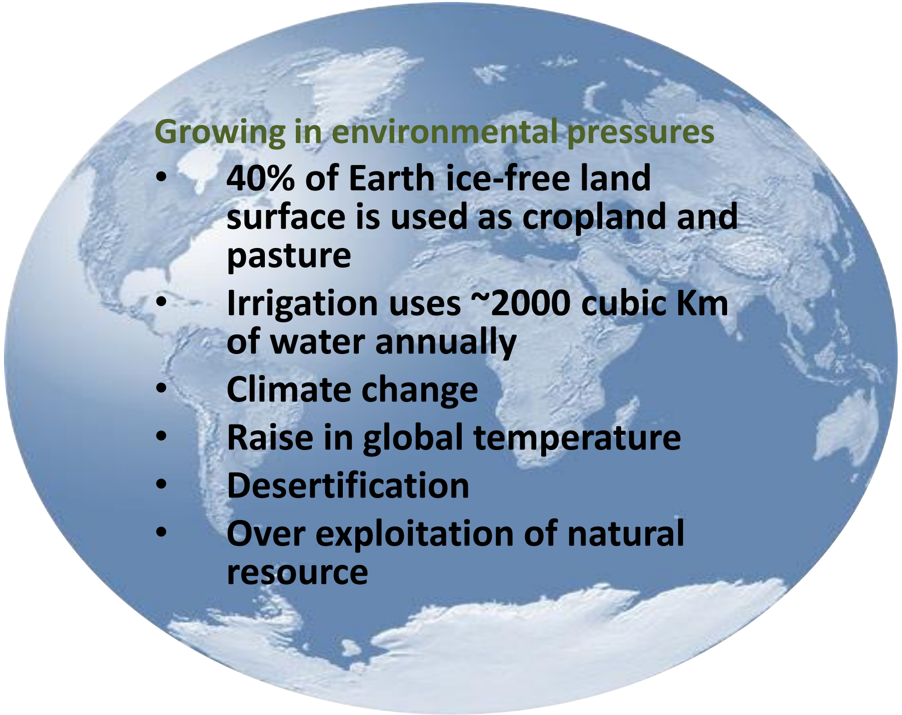
## By 2050:

**9.1 billion people on earth**

Continued increase in food demand would require raising of annual food production by **70%** (World Bank; FAO & HOW forum 2016).

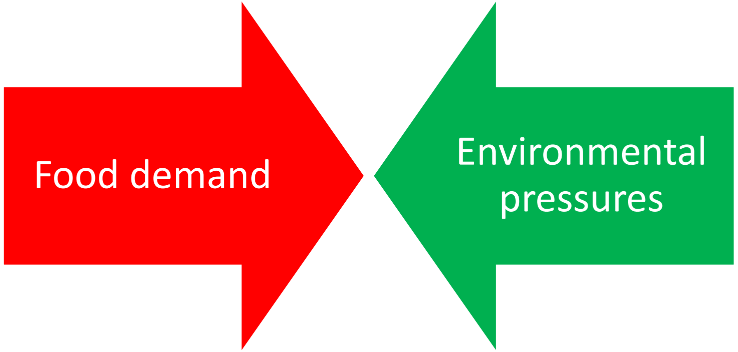

| WORLD PROTEIN PRODUCTION OUTLOOK (Million metric tons) | | | |
|---|---|---|---|
| **Protein source** | **2015** | **2050** | **% change** |
| Bovine | 67.9 | 107.5 | 63% |
| Poultry | 111.8 | 201.9 | 55% |
| Pigs | 119.4 | 150.3 | 79% |
| Aqua | 78 | 113.7 | 69% |
| Milk | 804.5 | 1119.7 | 72% |
| **Total** | **1181.6** | **1693.1** | **70%** |
| **Source: IFIF; FAO** | | | |

# Food demand and environment are in a collision course



Growing in environmental pressures

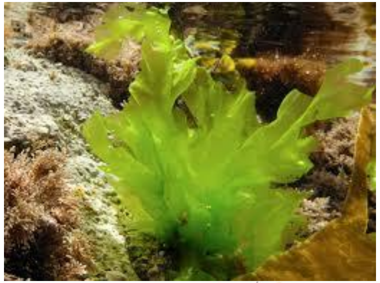
- 40% of Earth ice-free land surface is used as cropland and pasture
- Irrigation uses ~2000 cubic Km of water annually
- Climate change
- Raise in global temperature
- Desertification
- Over exploitation of natural resource




- Shortage in fresh water supply
- Soil nutrient depletion
- Reduced terrestrial yields

# Offshore biomass production

## Macroalgae - A viable biomass source

## Ocean - A huge un-exploited marine area

for Industrial Macroalgae cultivation.

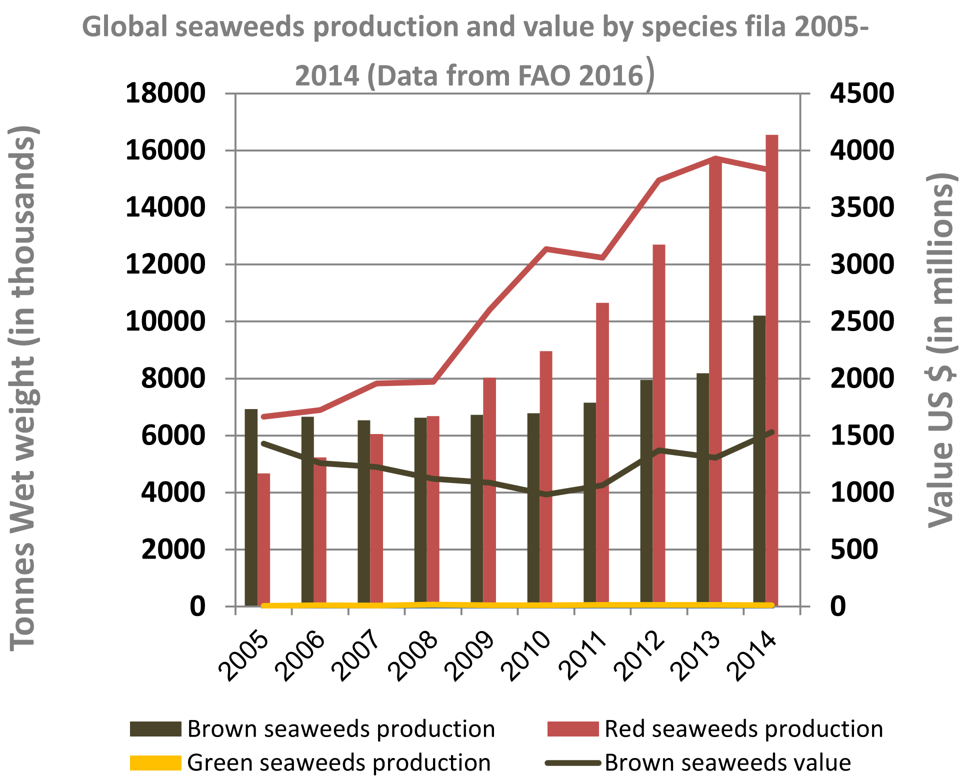
Ocean farming of seaweeds has the potential to produce ~40 tone dry weight biomass per hectare per annum

# Why Macroalgae (Seaweeds)

- Minimal use of arable land and freshwater
- Fast growth rate – up to 50% $day^{-1}$.
- possess unique compositions of proteins, lipids and carbohydrates, variety of vitamins, essential amino acid, minerals and trace elements

# Macroalgae - A viable biomass source

- Exponential growth of worldwide Macroalgae industry production over the last 50 years.
- Between 2005 -2014 average annual growth was 9.28% in quantity and 6.1% in monetary value.
- In 2014 – Over 26 million ton (FW) of Macroalgae were produced from aquaculture, valued more than 5 billion US$.
- To date Macroalgae farming is practiced in ~50 countries – An expansion of 8% per annum in the last decade (FAO, 2016)

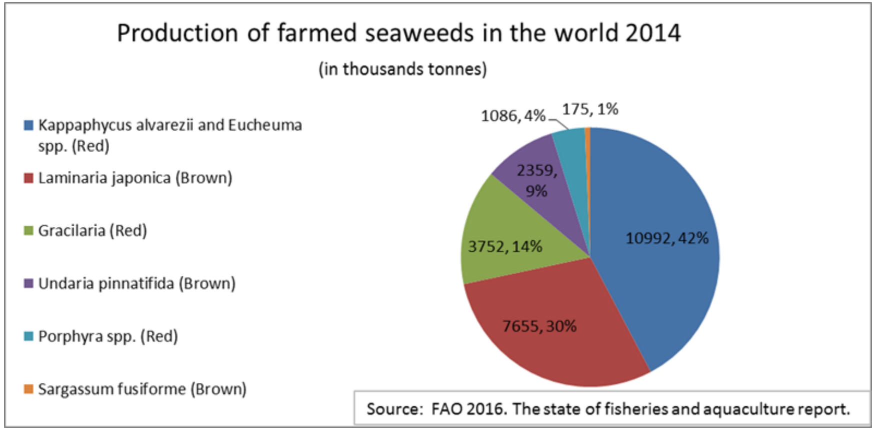


# Macroalgae uses

- **~80%** of total seaweed production is for direct human consumption and hydrocolloid extraction
- **~20%** is for food additives, feed, pharmaceuticals, cosmetics, fertilizers, water purifier, green chemicals  and bioenergy
- Using a biorefinery approach for bioenergy applications suggest to utilize the entire seaweed biomass for different purposes:

| Sugar/ polysaccharide | Mineral residues | Proteins |
|---|---|---|
| Substrate for fermentative processes | for fertilliser Applications | Food, feed, non food applications |

Van den Burg, et al., (2013).



# Hydrocolloids and bio-ethanol prices

Porse & Rudolph (2017)

**Table 1** Seaweed hydrocolloid sales volumes

| Seaweed hydrocolloid | 2009 sales (t) | 2015 sales (t) | Aagr %[a] |
|---|---|---|---|
| Agar | 9, 600 | 14,500 | 7 |
| Alginates[b] | 26,500 | 24,644 | −7 |
| Carrageenans | 50,000 | 57,500 | 2 |
| Total | 86,100 | 93,035 | 1 |

[a] Annual average growth rate

[b] Food–pharma–PGA grades only

**Table 3** Seaweed hydrocolloid sales values

| Seaweed hydrocolloid | 2009 sales (million USD) | 2015 sales (million USD) | % Change |
|---|---|---|---|
| Agar | 173 | 246 | 6 |
| Alginates | 318 | 345 | 8 |
| Carrageenans | 527 | 518 | −1 |
| Total | 1018 | 1058 | 2 |

Table 3.A1.8. **World biofuel projections**

OECD/FAO 2016

| | | Average 2013-15est | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ETHANOL** | | | | | | | | | | | | |
| **World** | | | | | | | | | | | | |
| Production | mln L | 111.5 | 119.3 | 122.0 | 123.2 | 124.2 | 125.1 | 125.1 | 125.7 | 126.4 | 128.0 | 128.4 |
| of which maize based | mln L | 59.2 | 62.9 | 64.9 | 64.8 | 64.4 | 64.2 | 63.3 | 63.1 | 63.0 | 63.4 | 62.6 |
| of which sugar cane based | mln L | 26.9 | 29.5 | 29.9 | 30.3 | 31.1 | 31.8 | 32.4 | 33.0 | 33.4 | 34.1 | 34.6 |
| of which biomass based | mln L | 0.4 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 |
| Consumption | mln L | 111.5 | 119.9 | 123.1 | 124.4 | 125.3 | 126.1 | 126.0 | 126.6 | 127.3 | 128.8 | 129.2 |
| of which fuel use | mln L | 89.0 | 96.5 | 99.4 | 100.3 | 100.8 | 101.2 | 100.7 | 101.0 | 101.2 | 102.4 | 102.3 |
| Exports | mln L | 7.3 | 7.7 | 7.8 | 8.0 | 7.8 | 8.2 | 8.0 | 7.8 | 7.7 | 7.4 | 6.9 |
| Price[1] | USD/t | 57.8 | 46.7 | 48.8 | 49.5 | 50.5 | 52.7 | 54.0 | 56.5 | 58.2 | 60.9 | 60.3 |

# Macroalgae – important protein source for high value market

- A transition from commoditized biomass to valuable bioactive compound and high value market development is needed for the future of seaweeds industry.
- This industry will require:

  Selection of improved cultivars

  Domestication of new species

  Refinement of cultivation technique

  Improve quality control and traceability of products.

(Hafting et al 2015)

- **Protein Ingredients Market worth 58.49 Billion USD by 2022**
  marketsandmarkets.com (2017)
- **Protein** – major factor when assessing health benefit.
- Out of 22 amino acid 9 considered essential for humans.
- Livestock provides ¼ of all the protein (and 15% of energy) consumed in food, but also creates substantial environmental impacts
- **The chemical score of seaweeds protein ranged from 0.75to 1** – superior to most terrestrial plants (based on individual amino acids residues following acidic hydrolysis)

# Macroalgae – High protein score

Mæhre et al (2014)

**Table 2.** Total amino acids in ten macroalgae species ($n = 5$)

Chemical Score did not consider protein digestibility

| | *A. esculenta* | *L. digitata* | *L. hyperborea* | *F. vesiculosus* | *P. canaliculata* | *C. rupestris* | *E. intestinalis* | *U. lactuca* | *P. palmata* | *V. lanosa* |
|---|---|---|---|---|---|---|---|---|---|---|
| Essential amino acids (EAA) | | | | | | | | | | |
| Threonine | 5.1 ± 0.4c | 3.8 ± 0.3b | 3.5 ± 0.3b | 3.4 ± 0.4b | 3.5 ± 0.1b | 2.2 ± 0.3a | 8.0 ± 0.8def | 6.2 ± 0.3d | 7.1 ± 0.2e | 7.8 ± 0.3f |
| Valine | 5.5 ± 0.3c | 3.6 ± 0.3b | 3.5 ± 0.2b | 3.7 ± 0.6ab | 3.9 ± 0.2b | 2.4 ± 0.3a | 8.4 ± 1.3cde | 7.1 ± 0.1d | 9.6 ± 0.4e | 7.6 ± 0.3d |
| Methionine | 2.4 ± 0.3cde | 1.8 ± 0.1bc | 1.6 ± 0.1b | 1.5 ± 0.2b | 1.4 ± 0.1b | 0.9 ± 0.1a | 2.3 ± 0.4bcde | 2.2 ± 0.1d | 3.1 ± 0.2e | 1.8 ± 0.2bcd |
| Isoleucine | 3.8 ± 0.5bc | 2.7 ± 0.1b | 2.2 ± 0.2a | 2.7 ± 0.3ab | 3.0 ± 0.0b | 1.6 ± 0.4a | 5.9 ± 1.0cde | 4.4 ± 0.2c | 6.5 ± 0.1d | 7.2 ± 0.2e |
| Leucine | 7.5 ± 0.9c | 5.2 ± 0.1b | 4.5 ± 0.5b | 5.0 ± 0.7b | 5.2 ± 0.3b | 2.7 ± 0.5a | 9.5 ± 1.2cde | 8.5 ± 0.3c | 11.3 ± 0.3e | 9.9 ± 0.2d |
| Phenylalanine | 4.8 ± 0.5c | 3.4 ± 0.3b | 3.1 ± 0.1b | 3.3 ± 0.4b | 3.4 ± 0.1b | 2.1 ± 0.3a | 7.4 ± 1.1 cdef | 6.0 ± 0.2d | 7.1 ± 0.2e | 8.2 ± 0.2f |
| Lysine | 5.3 ± 0.5c | 3.7 ± 0.2b | 3.4 ± 0.3b | 4.3 ± 0.6bcd | 3.7 ± 0.2b | 2.1 ± 0.4a | 6.4 ± 0.9c | 5.1 ± 0.2c | 8.9 ± 0.4d | 12.6 ± 0.3e |
| Histidine | 1.6 ± 0.2bcde | 1.2 ± 0.1b | 1.2 ± 0.1bc | 1.1 ± 0.1b | 1.0 ± 0.1ab | 0.7 ± 0.2a | 2.1 ± 0.4bcde | 1.6 ± 0.1 cd | 1.8 ± 0.1de | 2.0 ± 0.0e |
| Tryptophan | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Non-essential amino acids (NEAA) | | | | | | | | | | |
| Aspartic acid[a] | 8.4 ± 0.7c | 6.2 ± 0.2b | 5.9 ± 0.4b | 8.3 ± 1.1bc | 5.9 ± 0.3b | 3.5 ± 0.4a | 14.6 ± 1.8de | 9.0 ± 0.3c | 13.1 ± 0.3e | 12.3 ± 0.2d |
| Serine | 5.2 ± 0.4c | 3.6 ± 0.1b | 3.5 ± 0.3b | 3.5 ± 0.5ab | 3.6 ± 0.1b | 2.2 ± 0.3a | 7.8 ± 1.1cde | 5.9 ± 0.3c | 8.4 ± 0.2e | 7.7 ± 0.3d |
| Glutamic acid[a] | 20.1 ± 1.1e | 8.5 ± 0.6b | 8.6 ± 0.6b | 17.9 ± 2.2 cde | 15.0 ± 1.2 cd | 5.7 ± 0.8a | 18.2 ± 2.0de | 12.2 ± 0.5c | 21.3 ± 0.5e | 16.3 ± 0.4d |
| Proline | 5.1 ± 0.8abc | 3.9 ± 0.2b | 3.5 ± 0.5ab | 3.1 ± 0.5ab | 3.2 ± 0.2a | 2.9 ± 0.3a | 6.6 ± 1.0c | 5.8 ± 0.5c | 9.7 ± 0.3d | 10.8 ± 0.5d |
| Glycine | 5.7 ± 0.6b | 4.1 ± 0.2a | 3.8 ± 0.2a | 3.8 ± 0.5a | 4.1 ± 0.2a | 3.3 ± 0.4a | 8.5 ± 0.9 cd | 7.3 ± 0.2c | 9.6 ± 0.4d | 8.9 ± 0.2d |
| Alanine | 18.9 ± 1.1 g | 5.2 ± 3.0abcef | 6.2 ± 0.5b | 5.0 ± 0.7b | 5.5 ± 0.3b | 3.1 ± 0.5a | 14.7 ± 1.8dg | 10.1 ± 0.3de | 12.2 ± 0.5df | 7.6 ± 0.5c |
| Cysteine | n.d.a | n.d.a | n.d.a | n.d.a | n.d.a | 0.5 ± 0.2bd | 1.4 ± 0.4cef | 1.0 ± 0.2de | 0.5 ± 0.1bc | 2.1 ± 0.1f |
| Tyrosine | 2.9 ± 0.4c | 1.8 ± 0.2b | 1.6 ± 0.1ab | 1.5 ± 0.2ab | 1.4 ± 0.1a | 1.5 ± 0.3ab | 3.8 ± 0.5 cd | 3.4 ± 0.4c | 4.7 ± 0.2de | 5.4 ± 0.4e |
| Arginine | 4.8 ± 0.6 cd | 3.4 ± 0.2bc | 3.0 ± 0.1ab | 3.2 ± 0.4ab | 3.2 ± 0.2ab | 2.5 ± 0.3a | 7.4 ± 1.2def | 6.0 ± 0.3d | 8.6 ± 0.3f | 7.0 ± 0.4e |
| Sum TAA | 107.2 ± 6.6c | 62.2 ± 4.2b | 58.9 ± 3.3b | 71.2 ± 8.4b | 66.8 ± 3.2b | 40.1 ± 5.0a | 132.9 ± 17.1 cd | 101.5 ± 3.9c | 143.6 ± 3.7d | 135.1 ± 2.7d |
| Relative amount EAA (%) | 33.5 ± 1.4a | 40.9 ± 2.2cdefg | 38.9 ± 0.3 cd | 35.0 ± 1.1ab | 37.7 ± 0.6bc | 36.7 ± 0.9abcd | 37.5 ± 0.4be | 40.3 ± 0.4 g | 38.6 ± 0.2c | 42.3 ± 0.1f |
| Chemical score | 0.84 | 1.00 | 0.89 | 0.80 | 0.82 | 0.96 | 0.91 | 0.92 | 0.75 | 0.87 |

# Seaweeds provide variety of ecosystem – services that should be valued and monetized

- Primary producer
- Contribute ~ 50% of the world's carbon fixation
- Natural means for GHG emissions
- Nutrient cycling and waste purification
- Offshore farm create new habitat for diverse species
- Job creation
- Healthy source of nutrition

# Challenges of offshore cultivation

- **which seaweeds species should producer cultivate**
- **what should be the biomass volume before harvesting**
- Seasonality deviation in bioactive compounds
- Optimal farm size and location
- Technology availability
- Hatchery to planting to harvest to processing efficiency.
- Complex interaction between different factors: (water temperature, light, nutrients, salinity, pH, currents, waves, winds)

**Levant basin in the Mediterranean Sea**

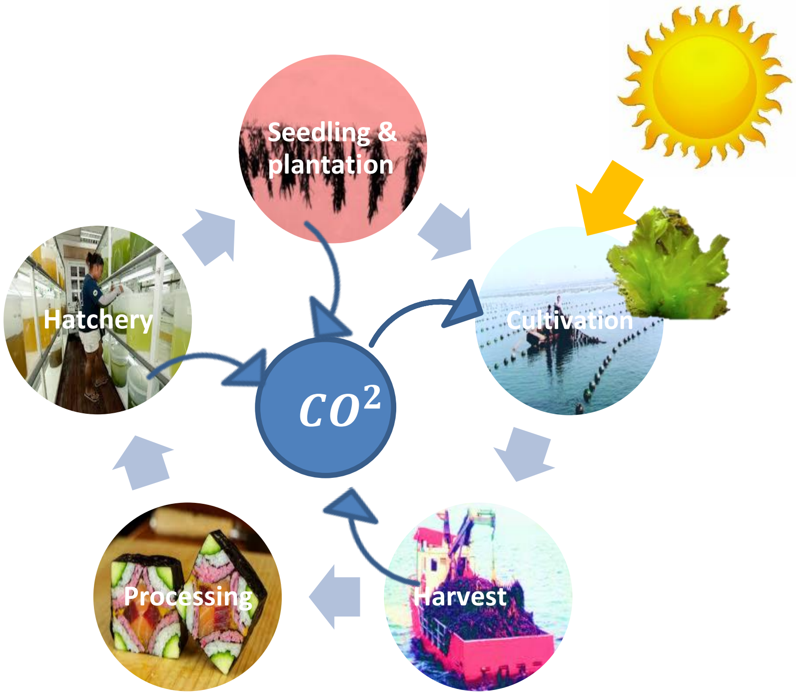
**The warmest, saltiest and nutrient-poorest water, most energetic winter waves, occur in the Israeli coastal shoreline**

**There is a need for viable source of biomass and cultivation medium for mass production to achieve food and energy security**

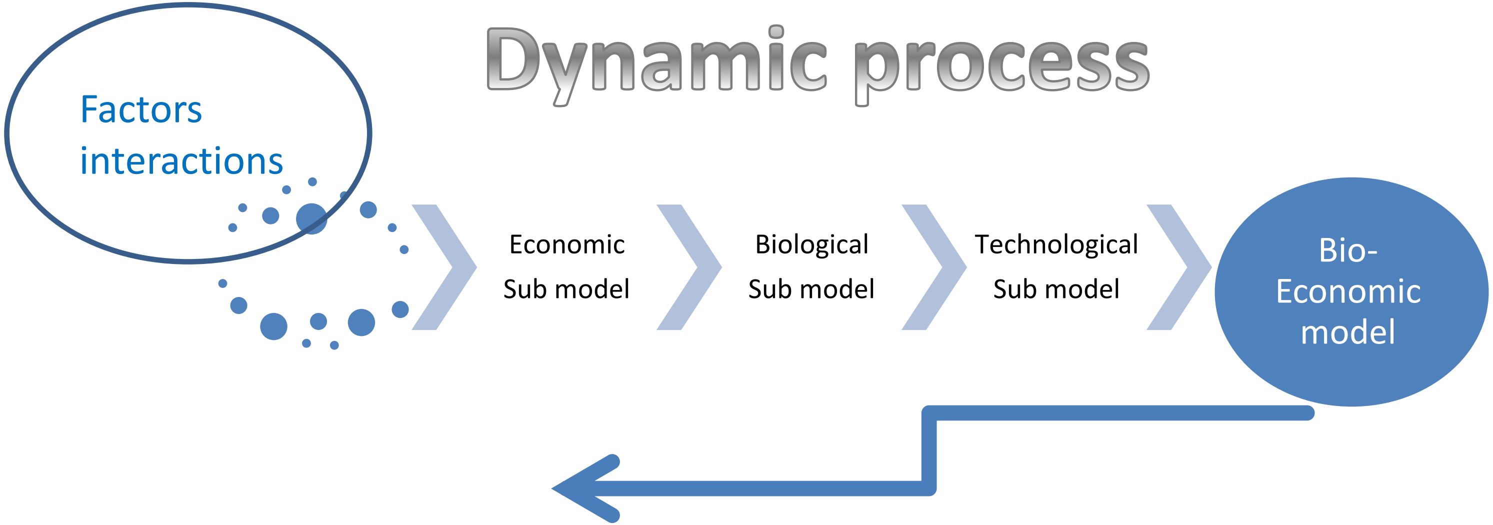
- It must be sustainable and economic feasible
- economic valuation and feasibility :

\- Cost Benefit Analysis **(CBA)**

\- Life Cycle Assessment **(LCA)**

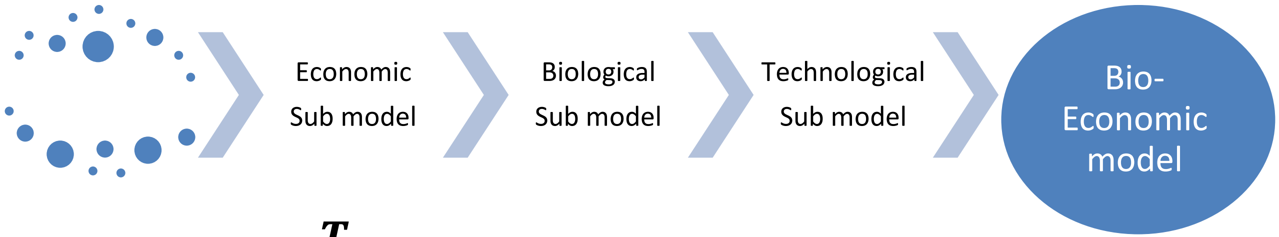


# Bio-Economic model




**which seaweeds species should producer cultivate**
**what should be the biomass volume before harvesting**

# Bio-Economic Model




**(1) Max** $\pi H_t = \sum_t^T \{P_t((W_{t,}\ H_{t,}\ Q_{i,t})(W_t H_t\ (PP_t\ PD_t))$ **-**

$(C_{PPC,} C_{PD,}\ C_{HC})H_t$ **-** $C_{VC_t} H_t) \cdot \frac{1}{(1+r)^t}\}$ **-** $A_0$ **+** $E_{j,t}(ES_j, P_{ESj})$

**Subject to:**

$P_t = P_t\ (W_{t,}, H_{t,}\ Q_{it})$

$W_t = f(\mathrm{NUBR}_t, \mathrm{AV}_t(\mathrm{GR}_t))$

$E_{j,t} = EX(ENV_j, ES_j, P_{ESj})$