



Valuation of ecosystem services provided

SEAMARK DELIVERABLE 9.4

Sjókovin – Blue Resource



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SEAMARK DELIVERABLE 9.4: VALUATION OF ECOSYSTEM SERVICES PROVIDED

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Abstract:

This report (Deliverable 9.4) reviews and applies methods for valuing key ecosystem services (carbon sequestration, nutrient bioextraction, biodiversity enhancement) provided by cultivated seaweed, using approaches beyond direct market pricing. It builds on previous quantification work to estimate monetary values at three SeaMark project sites and sets the stage for developing payment mechanisms for these services.

This report builds on earlier SeaMark deliverables and literature to identify suitable monetary valuation methods for seaweed-related ecosystem services. It presents the monetary valuation methods, such as market price, production function, contingent valuation, then uses a multicriteria decision analysis to select the best methods, presents the valuation results, and concludes with a discussion of related challenges and opportunities.

The value of nutrient bioextraction, using the replacement cost methodology, is estimated at €65 for ORF, €62 for ALG, and €27 for OF per ton of wet weight (WW). The differences in value reflect the differences in nitrogen (N) and phosphorus (P) content. For the total 2024 harvest, this translates to €12,454 for ORF, €8,305 for ALG, and €2,141 for OF. The estimated potential total CO₂eq sequestration values for 2024 are €531–€986 at ORF, €378–€702 at ALO, and €394–€732 at OF, depending on whether Gold Standard (€42/t CO₂) or EU ETS (€78/t CO₂) carbon pricing is applied. These figures are based on site-specific potential carbon sequestration data. Biodiversity enhancement data was only available for the ORF sites, but the collected data did not allow to value the benefit seaweed aquaculture on biodiversity with methods like contingent valuation or choice experiments.

The study finds that nutrient bioextraction by seaweed offers notable economic value, especially at ORF, though current methods may overestimate benefits without linking to actual environmental outcomes. Potential carbon sequestration shows measurable value, but seaweed is not yet included in formal carbon markets due to regulatory and methodological gaps. Biodiversity enhancement, demonstrates ecological potential, yet monetary valuation is limited by data gaps and methodological challenges. To fully realize the ecosystem values of seaweed, coordinated research, robust monitoring, and supportive EU policies are essential.

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LIST OF ABBREVIATIONS

Abbreviation	Description
DW	Dry weight
ES	Ecosystem services
MCDA	Multicriteria decision analysis
N	Nitrogen
P	Phosphorous
POC	Particulate organic carbon
UNGC	United Nations Global Compact
WTP	Willingness to pay
WW	Wet weight

1. INTRODUCTION

Ecosystem services (ES) are described as the links between nature and the economy (TEEB, 2010), or as benefits humans gain from ecosystems. Ecosystems provide humans for example with clean water, good air quality, nutritious food, they also contribute to regulating the climate and are therefore key for human life. Recreation, spiritual and cultural value are also fundamental to humans and have gained recognition in global ecosystem assessment (IPBES, 2022). The benefits humans get from ecosystems are directly related to ecosystem functions such as pollination, cycling of nutrients, carbon uptake (IPBES, 2019).

The cascade framework, see Figure 1, is one of various ecosystem frameworks that links ecological (biophysical) processes with elements of human well-being. It visualises how ecosystem services are supplied by biophysical structures and processes. These ecosystem services have benefits for human well-being, that have a value.

The monetary valuation of ES is an approach to theoretically and mathematically demonstrate that ES have a public value that can be expressed in monetary terms. Although assigning monetary value to nature has been highly controversial, due to the anthropocentric and utilitarian view of economic values, assigning value to something economically or in monetary terms can also inform society about the relative level of resource scarcity (TEEB, 2010). Conducting a monetary valuation can serve as a tool to make nature's contribution visible and countable. Also, these valuations can serve as communication tools for raising awareness among diverse stakeholders' groups, as well as informing decision making at managerial and at policy levels and as potential verification means for certification schemes, among others.

Seaweed has been recognized by the European Commission as a valuable sustainable new resource (EC, 2022) that could significantly contribute to EU's blue bioeconomy and the

objectives of the European Green Deal, as it is fast-growing and does not require arable land, fresh water or fertilizers for its growth when cultivated in the sea (Vincent *et al.*, 2020). Seaweed biomass is used for a wide range of applications, such as food, feed, pharmaceuticals, nutraceuticals, cosmetics, bioplastic, biofuels, etc., which fall under the category of provisioning services. Seaweed also provides regulating services, such as nutrient bioextraction and potentially carbon sequestration, habitat creation, or cultural services such as education and learning or cultural heritage (Halpern *et al.*, 2012; Hasselström *et al.*, 2018).

Provisioning services are the ES with the most attainable economic value, directly associated with the cultivated seaweed market price. The value of the provisioning services depends on the use of the biomass, which currently in Europe is still a developing market. The expected strategic market approach for the seaweed industry is to aim for higher value products, according to results within the SeaMark project (Deliverable 8.4 WP8 and WP7 on Go-to market strategies).

This report, Deliverable 9.4, focuses on the value of key ES beyond provisioning services - specifically potential carbon sequestration, nutrient bioextraction and biodiversity enhancement. By examining these non-provisioning services, the report explores monetary valuation methods beyond direct market pricing and considers alternative ways to quantify value beyond simple sales revenue.

The overall objective of this deliverable is to review and apply monetary valuation methodologies of the ES provided by cultivated seaweed and conduct a valuation based on the results of previous work on quantification reported in D9.3. This deliverable presents results of the monetary valuation of ES from cultivated seaweed (T9.2) and provide the groundwork for upcoming task (T9.3) in assessing payment mechanism for the monetized ES. This methodology assessment and valuation exercise will be done for three seaweed cultivations within the SeaMark project: Ocean Rainforest (ORF) in the Faroe Islands, Algoflesko (ALO) in France and Ocean Forest (OF) in Norway.

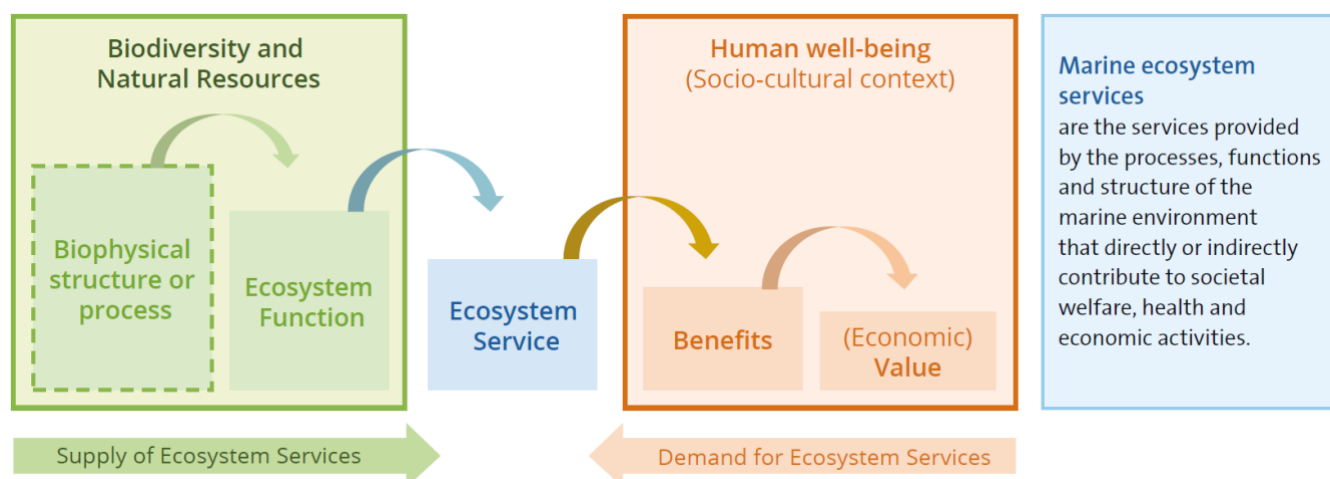


Figure 1: Example of an ecosystem framework: The ecosystem cascade framework (Austen *et al.*, 2019).

The research questions that guided this report are:

- What methods can be used to attain a monetary value for the ES provided by cultivated seaweed?
- What are the most suitable monetary valuation methods for valuing the selected ES in SeaMark?
- What is the monetary value of selected ES provided by cultivating seaweed?

2. METHODOLOGICAL APPROACH

This report builds on previous deliverables within SeaMark (D9.2, D9.3 and D8.3), as well as reviewed literature on monetary valuation methods for ES provided by seaweed cultivation. The deliverable is structured as follows: First, relevant monetary valuation methods for the three selected ES are introduced, followed by a description of several criteria that help to assess the methods for suitability. With the results of the available SeaMark deliverables in mind, a multicriteria decision analysis (MCDA) approach was used to support the choice of the best fitting valuation methods. Several criteria were defined to assess suitability. The monetary valuation of selected ES of the three seaweed production companies in SeaMark is then presented. The report finishes with a discussion on the challenges and opportunities from the monetary valuation methods.

3. MONETARY VALUATION METHODS

Various monetary valuation methods have been employed to capture both the market and non-market values of marine ES (Addamo *et al.*, 2024; Hasselström *et al.*, 2018; IPBES, 2019, 2022; Lopez-Rivas & Cardenas, 2024). As shown in Figure 2, methods can be categorized according to the four main types of coastal ES, including supporting, regulating, provisioning, and cultural services. The selected three ES from D9.3 fall under supporting and regulating categories of ES (Hasselström *et al.*, 2018).

The strengths and weaknesses of each monetary valuation method for the three selected ES are discussed in Table 1. This highlights the trade-offs between the pursuit of accuracy and context-specificity versus the practical constraints.

To select the most appropriate valuation method in a specific context, it is suggested to use the following criteria, representing the multicriteria decision analysis (MCDA).

1. Is there enough time for data collection to adopt this method?
2. Is there enough budget for data collection to adopt this method?
3. Is the required data available from previous deliverables or other sources?

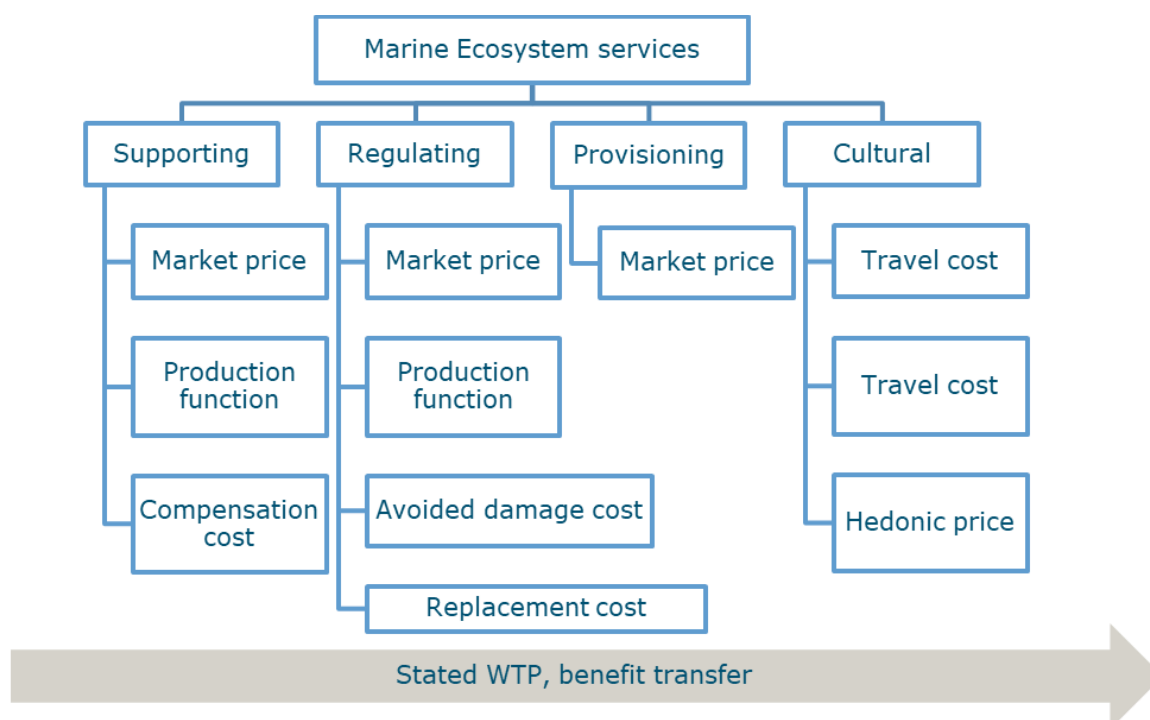


Figure 3: Monetary valuation methods for marine ES.

Table 1: A review on monetary valuation methods for marine ecosystem services.

Method	Description	Strength	Weakness	Benefit valued
Market price	Market prices stemming from a normal production process/Uses observed market prices to value ecosystem goods/services.	• Straightforward. • Real value. • Provides values over time.	• Only applicable to marketed goods/services. • May overestimate value if market prices do not reflect true social costs. • Estimates based on current market prices; subject to change as markets fluctuate. • Values might vary by region.	• Carbon sequestration. • Nutrient uptake. • Seaweed harvesting. • Capture fisheries.
Production function	Values how changes in the quantity or quality of the ecosystem affects ES and ultimately the costs of production of the final benefit.	• Links ecological and economic systems. • Can consider both static (current) and dynamic (future) model. • Applies in micro-economic scale.	• Information must be available to describe the change in a natural ecosystem. • Usual assumption for unrealistic biological growth condition. • May not align well with the macro total reported in the national accounts.	• Water quality in an estuary • Filtration services provided by oyster reef in a bay. • Attracting habitat for fish abundance, provide habitat for crabs, lobsters, fisheries.
Replacement cost	Value is based on the cost of replacing the environmental function.	• Applies in the lack of data on linkage between the initial ecological function, process to facilitate and services to construct a reliable hypothetical scenario.	• May overestimate value as it is using 'costs' as a measure of economic 'benefit'.	• N and P removal. • Waste water treatment.
Contingent valuation	Survey technique asking a representative sample of individuals how much they are willing to pay to prevent loss of, or to enhance, an environmental good or service.	• Value non-market services. • Widely uses.	• Comprehensive hypothetical scenarios. • Can be expensive. • Information must be available to describe the change in a natural ecosystem. • Change in the natural ecosystem must be understandable.	• Protection of a marine species or habitat, marine non-use values, conservation of fish species or habitats.
Choice experiments	Asking respondents to select their preferred package of environmental attributes at different prices and then inferring specific component values.	• Value multiple attributes simultaneously. • Widely uses.	• Comprehensive hypothetical scenarios. • Can be expensive. • Information must be available to describe the change in a natural ecosystem. • Change in the natural ecosystem must be understandable.	• Climate regulation. • Potential use of marine genetic materials. • Fisheries management scenarios.
Benefits transfer	Values estimated in one context and location are used to estimate values in a similar or different context and location.	• Time and budget constraint.	• Depending on availability of relevant studies. • Inaccuracy might arise when the original value was calculated in very different biophysical, ecological and socio-economic characteristics. • Risk of recycling old values.	• Various.

4. SELECTION OF VALUATION METHODS IN SEAMARK

The MCDA analysis was conducted to select the most appropriate valuation method for the three ES selected in SeaMark (see D9.2). Results are presented in sections below, accompanied by further elaboration on the valuation method chosen.

4.1 Nutrient bioextraction

For nutrient bioextraction service, direct market values can be obtained from nutrient trading schemes. This approach provides direct monetary value based on actual market transactions. In the EU, such schemes are currently at the pilot stage, with an example of the NutriTrade nutrient offset pilot scheme in the Baltic Sea (Fammler *et al.*, 2020). In contrast, nutrient trading markets have been more widely implemented in the US, for controlling nitrogen or phosphorus mainly in the US (King & Kuch, 2003).

An alternative approach is the use of the replacement cost method, which calculates the cost of replacing natural nutrient filtering with engineered solutions such as water treatment facilities or industrial filtration systems, like sewage treatment plant (Grabowski *et al.*, 2012). This method is effective because it provides technology-based comparisons and is well-suited for technical services with clear artificial alternatives.

The results of the MCDA to decide which valuation method is most appropriate to use are presented in Table 3 below.

Table 2: Review of valuation methods' applicability to nutrient bioextraction.

Method/Criteria	Availability of		
	Time	Budget	Data
Market price	YES	YES	YES
Production function	NO	NO	NO
Replacement cost	YES	YES	YES
Contingent valuation	NO	NO	NO
Choice experiment	NO	NO	NO
Benefit transfers	YES	YES	NO

As our data was collected in European seaweed sites, and there is currently no nutrient trading market in Europe, the replacement cost method is selected for monetary valuation of nutrient bioextraction through seaweed cultivation. This is calculated by estimating the removal of both N and P, as outlined in the following formula:

$$\text{Nutrient removal value} = (N_{\text{content}} \times N_{\text{price}}) + (P_{\text{content}} \times P_{\text{price}}) \quad (1)$$

For the replacement cost method, N and P removal are valued in €/kg. Specifically, the removal price for N is €20/kg and for P, it is €30/kg. These values are based on the study by Pistocchi *et al.* (2023), which estimated the costs of nutrients removal through wastewater treatment plants in the EU.

4.2 Carbon sequestration

Market-based valuation methods are relevant for both carbon sequestration and nutrient removal services in seaweed farming (Barrett *et al.*, 2022; Racine *et al.*, 2021; Vásquez *et al.*, 2014). For carbon, these include carbon credit markets and offset programs, while nutrient services are valued through water quality trading programs. While market price methods offer a straightforward approach to marketed services, they have limitations including market volatility, regional variations, and potential overvaluation when market prices fail to reflect true social costs (Dominati *et al.*, 2014; Heal, 2000).

Alternative valuation approaches for carbon sequestration include choice experiments, which reveal public preferences for climate action including carbon reduction by presenting respondents with various scenarios and trade-offs (Ncaves and Maia, 2022; Remoundou *et al.*, 2015).

The results of the MCDA to decide which valuation method is most appropriate to use for valuation carbon sequestrations are presented in Table 3 below.

Table 3: Review of valuation methods' applicability to carbon sequestration.

Method/Criteria	Availability of		
	Time	Budget	Data
Market price	YES	YES	YES
Production function	NO	NO	NO
Replacement cost	YES	YES	NO
Contingent valuation	NO	NO	NO
Choice experiment	NO	NO	NO
Benefit transfers	YES	YES	NO

Currently, there is no established carbon offset market specifically for seaweed cultivation. However, carbon credits from seaweed may enter the market in the future, therefore the market price valuation method is selected for carbon sequestration potential. In regulated markets, the EU Emissions Trading System reached €78/t CO₂ in January 2025, its scope remains limited to energy, manufacturing, aviation, and maritime sectors (Statista, 2025). In voluntary carbon markets, international organizations like Verra and The Gold Standard assess and certify carbon offset projects.

Verra has approved a methodology for quantifying net greenhouse gas emission reductions from seagrass cultivation in 2021 and is currently developing standards for seaweed cultivation (Verra, 2021, 2025), with most projects selling carbon offsets between €7 to €27 per ton (IFC, 2023).

The Gold Standard, which commands premium prices because its credits qualify for emission reductions under the Kyoto Protocol, prices its carbon offsets up between €9 to €82/tCO₂, depending on project type (Gold Standard, 2025).

This Gold Standard pricing has been used in recent seaweed ES valuation studies, including (Collins *et al.*, 2022) for *Alaria esculenta* cultivation in Ireland.

The monetary value of potential carbon sequestration is calculated using the formula:

$$\text{Carbon sequestration value} = \text{carbon sequestration rate} \times \text{yield} \times \text{carbon price} \quad (2)$$

Where the potential carbon sequestration rate is measured in tCO₂/kg wet weight, yield in kg wet weight.

The carbon price includes two scenarios: (i) using the median value from Gold Standard carbon credits at €42/tCO₂ and (ii) potential future inclusion in the EU ETS at €78/t CO₂, assuming seaweed cultivation could qualify as an eligible carbon sequestration activity under the scheme.

4.3 Biodiversity enhancement

To value biodiversity enhancement monetarily, there needs to be an understanding of how seaweed supports biodiversity, and what is to be valued. Kelp forest provides shelter, feeding and nursery areas for a high diversity of associated organisms such as other seaweeds, invertebrates, crustaceans, echinoderms and a variety of fish species (Hasselström *et al.*, 2018). The benefits associated with increased 'biodiversity' from kelp forest and to an extent also seaweed aquaculture, can include enhanced species richness, abundance, biomass, and functional diversity and such benefits can also extend to the services that biodiversity supports and enhances, such as fisheries (Bennett *et al.*, 2015; Eger *et al.*, 2021; Krumhansl *et al.*, 2017).

Biodiversity valuation is often done using contingent valuation methods, which assess the willingness to pay of individuals for species protection, enhancement or habitat conservation can be assessed through carefully designed surveys and hypothetical scenarios development (Martin-Lopez *et al.*, 2008; O'Connor *et al.*, 2020). This approach is particularly valuable for biodiversity as it captures both use and non-use values, including existence values (the satisfaction of knowing species exist) and bequest values (the benefit of preserving biodiversity for future generations) that are not reflected in market transactions. Yet, this approach requires careful survey design to avoid bias, can be resource-intensive for a large sample size, and depend on effective communication of complex ecological concepts to survey respondents.

Benefits transfer methods can alternatively provide cost-effective preliminary assessments under time and budget constraint by adapting existing valuations from similar ecosystems. However, its successful implementation depends

on the availability of relevant studies and risk of recycling old values, thus might lead to inaccurate valuation (Bateman *et al.*, 2000; Norton & Hynes, 2018). The benefit transfer method is stated by Liu *et al.* as a "second-best" strategy, since the values are transferred from a study site to another site, but these derived values vary across geographical space and/or time (Liu *et al.*, 2010). The study of Hynes *et al.* (2021), which estimated the willingness to pay for restoring natural kelp forests to enhance species abundance to be €15.92 per person per year for the restoration of natural kelp forests with medium abundance of approximately 75 species. However, species numbers vary significantly based on factors like farm location, season, size, cultivation methods, environmental conditions, and stochastic weather events like storms (Corrigan *et al.*, 2022; Visch *et al.*, 2020). It appears that in discussing the biodiversity benefits of kelp aquaculture is unlikely to replicate the ecological functions of kelp forests or deliver significant biodiversity outcomes from both cultivations and natural forests, a literature review by Forbes *et al.* (2022). This and the species variability, makes a benefit transfer from studies based on kelp forest not suitable.

Another method for valuating biodiversity enhancement refers to supporting services to fisheries activities or of other species that may benefit from the habitat created by seaweed aquaculture. The method from Ncaves and Maia (2022) suggests quantifying productivity changes to estimate the contribution of the stock to catch per unit effort multiplied with the market price. This could be compared to before the seaweed cultivation and during the seaweed cultivation, or to a reference site. Many knowledge gaps remain, and assumptions would have to be made to estimate the economic value of fish stock related to habitat created by cultivated seaweed.

Another approach would be the market price method, which evaluates the market value of species enhancement, referring to additionally commercially interesting fish catches. Challenges arise due to the fact that no quantitative data on fish catches in is available as a status, with no baseline observations before and after the establishment of the seaweed farm.

The results of the MCDA to decide which valuation method is most appropriate to use in relation to biodiversity enhancement are presented in .

Table 4: Review of valuation methods' applicability to biodiversity enhancement.

Method/Criteria	Availability of		
	Time	Budget	Data
Market price	YES	YES	NO
Production function	NO	NO	NO
Replacement cost	YES	YES	NO
Contingent valuation	NO	NO	NO
Choice experiment	NO	NO	NO
Benefit transfers	YES	YES	NO

To assess the monetary values for biodiversity enhancement in this deliverable, the first step is to review the data on species enhancement quantification from D9.3. While data on biodiversity enhancement was collected and assessed for the ORF site in the Faroe Islands, no such data is available for France and Norway. To conclude, due to the lack of data on biodiversity enhancement for seaweed cultivation, neither market value nor benefit transfer methods could be employed in this deliverable. Therefore, the findings will focus solely on biodiversity quantification rather than monetary valuation. Assigning monetary values to biodiversity enhancement from seaweed cultivation could be achieved through methods such as contingent valuation or choice experiments. However, as discussed in the overview of methods, these approaches require significant time and resources for primary data collection, which is not feasible within the scope of this deliverable.

5. APPLYING THE MONETARY VALUATION METHODS

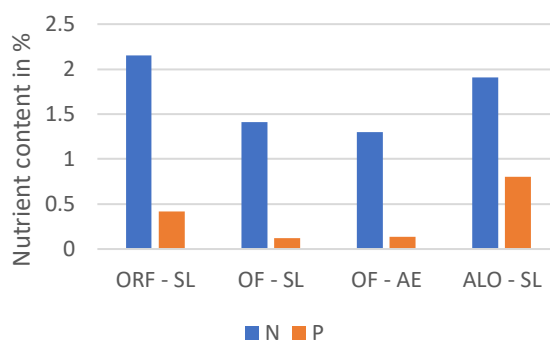
5.1 Nutrient bioextraction

Table 5 shows the nutrient bioextraction quantification results for all three companies. With a varying nutrient content, from 1.41 to 2.15 for N and 0.12 – 0.8 for P in S. Latissima (Figure 3 top), the removal potential also changes (Figure 3 bottom). The total nutrient bioextraction potential for the 2024 harvest was calculated to be 321.2 kg N and 62.74 kg P per total WW harvest for the ORF site in the Faroe Islands, 200 kg N and 19.29 kg P per total WW harvest for the OF site in Norway, and 381.7 kg N and 160.67 kg P per total WW harvest for the ALO site in France, view.

The value for the total nutrient bioextraction per ton WW is €65 for ORF, €62 for ALO, and €27 for OF, with ORF contributing €50 from N and €15 from P, ALG contributing €38 from N and €24 from P, and OF contributing €24 from N and €3 from P, Figure 4 top. The reason for the different values lies in the difference in removal per t WW (Figure 4 top), which is based on the different nutrient content in the seaweed biomass (Figure 3 top). The nutrient content changes over the seasons and site (Bak et al., 2018; Grebe et al., 2021; Racine et al., 2021). The value for the nutrients for the total WW harvest of 2024 is €12.454 for ORF, €8.305 for ALO, and €2.141 for OF. For ORF, the value comprises €7.634 from N removal and €4.820 from P removal. For ALO, the value includes €6.423 from N removal and €1,882 from P removal. For OF, the value is €1.901 from N removal and €241 from P removal (as seen in Figure 4 bottom).

Figure 4: Nutrient bioextraction value per ton (up) and total value (bottom). Bold numbers show totals.

The nutrient content per site and species



Nutrient bioextraction potential

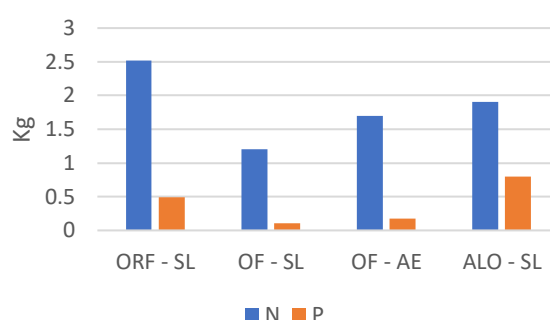
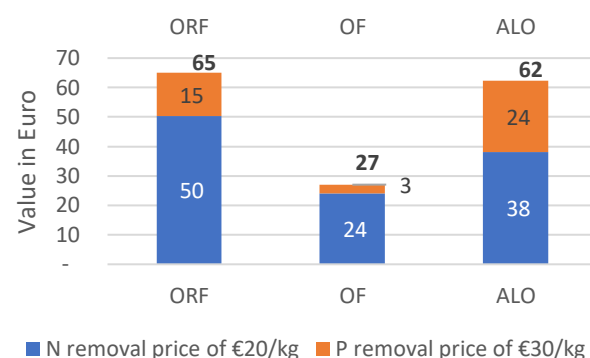


Figure 3: Nutrient content (top) and bioextraction potential (bottom) from the 3 sites in 2024 based on harvested yield.

Nutrient bioextraction value per ton WW



Total nutrient bioextraction value

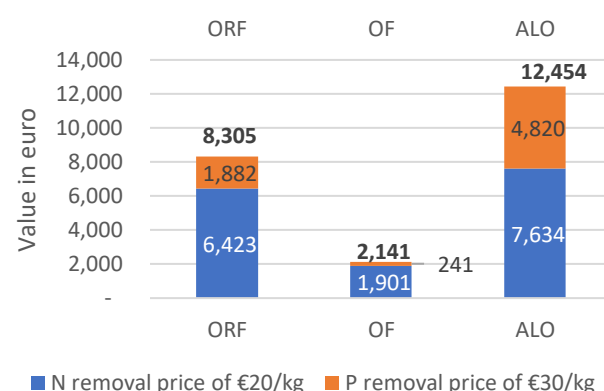


Table 5: Nutrient bioextraction potential for the 3 sites in 2024.

Site	Species	Area (ha)	Harvest (t WW)	Yield (kg m ⁻¹)	Yield (kg m ²)	Content (%)		Removal					
								Kg per total WW harvest		Kg per ton WW		Kg per ha	
						N	P	N	P	N	P	N	P
ORF	SL	17.85	127.7	1.51	0.72	2.15	0.42	321.2	62.74	2.52	0.49	18.0	3.51
OF	SL	N.A.	79.2	4.02	N.A.	1.41	0.119	95.04	8.02	1.2	0.101	N.A.	N.A.
	AE	N.A.	62.1	2.38	N.A.	1.3	0.139	105.6	11.27	1.7	0.18	N.A.	N.A.
ALO	SL	150	200	N.A.	0.13	1.91	0.801	381.7	160.667	1.91	0.801	2.5	1.1

5.2 Potential carbon sequestration and direct uptake

Figure 5 top shows the carbon content of the seaweed per site at the moment of harvest. The total carbon removed from the ecosystem via harvest can thus be calculated, figure 5 bottom. This is not part of the carbon sequestration potential as a potential sequestration depends on the fate of the seaweed and would be included in LCA studies. The carbon uptake can however be linked to a local ocean acidification reduction.

Table 6 and Figure 6 show the results of the quantified potential carbon sequestration potential from the three sites. The sequestration potential depends on a number of factors, the carbon content of the biomass lost being one of them (Figure 5 top). Another factor is a by greater biomass loss observed during winter storms in the Faroe Islands which increased sequestration potential.

An uptake of 27 kg C (99 kg CO₂e) t⁻¹ WW harvested was estimated for ORF in the Faroe Islands, 12 kg C (45 kg CO₂e) t⁻¹ WW harvested for ALO in France, and 18 kg C (66 kg CO₂e) t⁻¹ WW harvested for OF in Norway.

The estimated total values of potential CO₂ sequestration for seaweed cultivations at the three sites are presented in Figure 6. The calculations were based on potential carbon

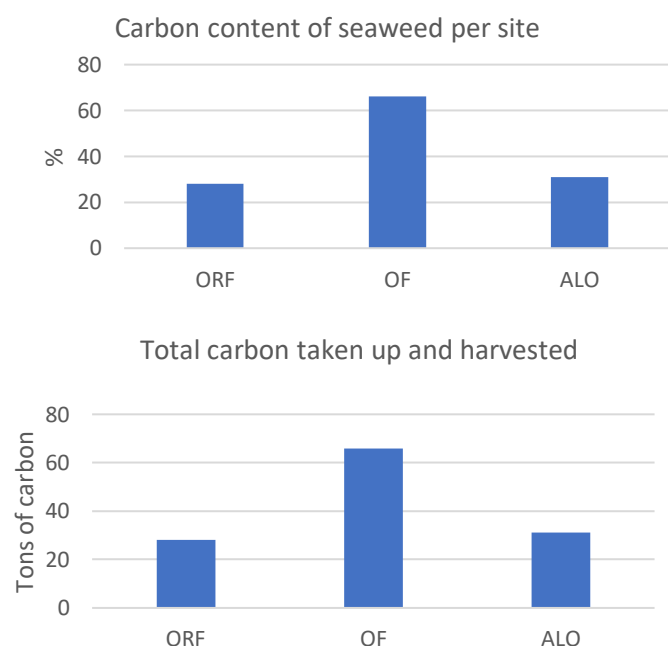


Figure 5: Carbon content in seaweed (top) and carbon removed from ecosystem by harvest (bottom).

kg CO₂e sequestered per t WW

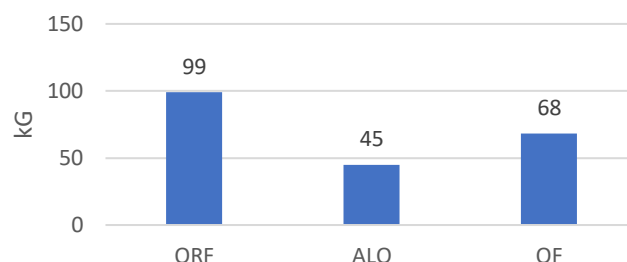


Figure 6: Carbon sequestration potential of the three sites in 2024.

sequestration data for each site and two potential carbon pricing options including Gold Standard carbon credits (€42/t CO₂) and the EU ETS (€78/t CO₂). At ORF, the potential total CO₂e sequestration value is €531 under the Gold Standard and €986 under the EU ETS. At ALO, the total value is €378 under the Gold Standard and €702 under the EU ETS. At OF, the total value is €394 under the Gold Standard and €702 under the EU ETS. At OF, the total value is €394 under the Gold Standard and €732 under the EU ETS.

Figure 8 illustrates the potential CO₂ sequestration value per ton of wet weight harvested for three sites. At ORF, the potential CO₂ sequestration value is €4.1580 per ton WW under the Gold Standard and €7.722 per ton WW under the EU ETS. For ALO, the values are €1.8900 per ton WW (Gold Standard) and €3.51 per ton WW (EU ETS). At OF, the potential CO₂ sequestration value is €2.8560 per ton WW under the Gold Standard and €5.3040 per ton WW under the EU ETS.

The different total values are mainly due to the different yields and overall seeded biomass, and the resulting harvests of each site, Table 6. However, even when looking at per t WW comparison, there is a difference, as seen in Figure 5 for the biomass and Figure 7 for the value. This is due to the different dry weight (DW) matter and carbon content (%) becomes relevant (D9.3). Furthermore, the ORF site has a higher potential sequestration rate, because their seaweed stays partially harvested in the water over the winter and therefore has a higher particulate organic carbon (POC) loss, leading to higher burial rates (D9.3).

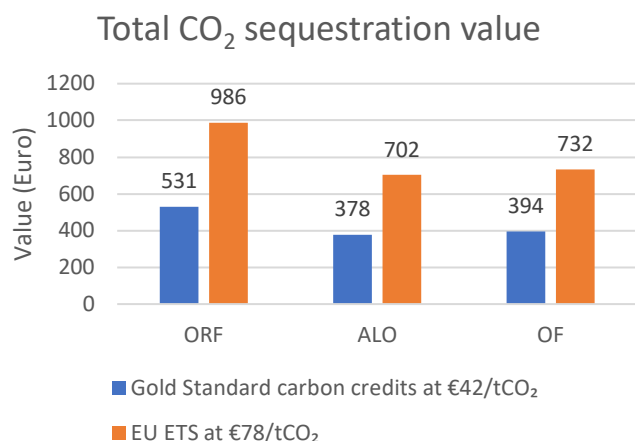


Figure 7: Monetary value of the potential total CO₂e sequestration of wet weight harvested for three sites in 2024.

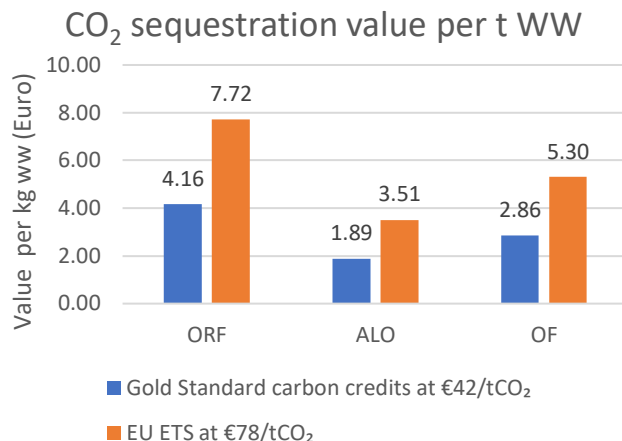


Figure 8: Monetary value of the potential CO₂e sequestration per ton of wet weight harvested for three sites in 2024.

Table 6: Potential carbon sequestration potential of the three sites in 2024.

	ORF in the Faroe Islands		ALO in France		FO in Norway	
Total harvest	127,674 kg WW harvest on 135,696 m growth line		200,000 kg WW harvest on 150 ha		141,400 Kg WW on 36,893 m growth line ¹	
Yield	1.51 kg m ⁻¹ ; 0.715 kg m ⁻²		N.A. m ⁻¹ ; 0.133 kg m ⁻²		3.83 kg m ⁻¹ ; N.A m ⁻²	
C content	21.7%		21.6%		33%	
	Carbon sequestered (kg C yr ⁻¹)	CO ₂ eq sequestered (kg CO ₂ e)	Carbon sequestered (kg C yr ⁻¹)	CO ₂ eq sequestered (kg CO ₂ e)	Carbon sequestered (kg C yr ⁻¹)	CO ₂ eq sequestered (kg CO ₂ e)
Per total harvest	3,446.24	12,636.2	2,456.00	9,005.34	2,560.41	9,388.16
Per t WW	27	99	12	45	19	68
Per kg C harvested	1.06	3.9	0.51	1.86	0.51	1.86
Per m	0.0254	0.09	N.A.	N.A.	0.07	0.25
Per m²	0.0334 ¹	0.12	0.0016	0.0060	N.A.	N.A.

6. DISCUSSION

6.1 Nutrient bioextraction

Cultivated seaweed has significant potential to extract nitrogen (N) and phosphorus (P) from marine environments. Using the replacement cost method, the monetary value of this service was highest at ORF (€65/t WW), followed by ALO (€62/t WW), and lowest at OF (€27/t WW). However, replacement cost method may overestimate true economic value by assuming complete equivalence between natural and engineered solutions which do not always exist for the filtration service of N and P (Dominati *et al.*, 2014). The method can be effectively complemented by production function approaches that quantify the relationship between water quality improvements and resulting economic benefits (Trégarot *et al.*, 2017). Information must be available to describe the change in a natural ecosystem (Barbier, 2007).

The value of nutrient bioextraction is location specific. In areas with high agricultural activity, nutrient run-off or leakage can be problematic. Our three assessed sites represent two

scenarios: The French coast of Brittany having an issue with eutrophication and thus making nutrient bioextraction a relevant ES in this location, while the Faroe Islands and Norway, both present limited local drivers for nutrition markets. This disparity highlights the importance of context-specific monetization for this ES.

6.2 Carbon sequestration and credit markets

The carbon sequestration potential of seaweed cultivation is estimated at €4.16 to €7.72/t WW at ORF, €1.9 to €3.51 /t WW at ALO, and €2.9 to €5.3 /t WW for OF under two pricing scenarios. However, current carbon credit markets do not yet recognize seaweed aquaculture (Van den Burg *et al.*, 2022). There is a growing interest in establishing a seaweed industry in Europe and its potential as a mechanism for carbon dioxide removal, but many uncertainties remain in the marine carbon sequestration calculation from seaweed cultivation (Dolliver & O'Connor, 2022; Hurd *et al.*, 2024; Hurd *et al.*, 2022) and see details in D9.3.

Japan is leading efforts in blue carbon offset crediting and, as of now, hosts the only three blue carbon schemes that include

seagrass meadows, macroalgae farming, and macroalgae beds (Kuwae *et al.*, 2022). In the EU, regulatory and methodological uncertainties, particularly around permanence, additionality, and cross-boundary carbon flows (Dolliver & O'Connor, 2022; Hurd *et al.*, 2024; Hurd *et al.*, 2022), limit immediate monetization through established carbon schemes like EU ETS or voluntary programs.

In the European Union, the proposed EU-wide voluntary framework to reliably certify high-quality carbon removals, 2022/0394 (COD), builds on the Q.U.A.L.I.T.Y criteria to address some of these challenges; quantification, additionality, long-term storage, and overall sustainability. This framework represents a promising step toward enabling seaweed farmers to monetize the potential carbon sequestration services they provide (Hughes *et al.*, 2025). Continued methodological research and pilot certification projects are necessary to solidify seaweed's role in blue carbon frameworks.

As the certification for carbon removal via the marine pathway still holds challenges, credits for land-based carbon storage products, such as biochar or plastic replacement, could also be traded (UNGC, 2021). These different carbon sequestration pathways are discussed in further detail in D9.2, where also more information on different ambitions from the EC regarding carbon sequestration and the seaweed sector are provided.

Market price methods in general offer a straightforward approach to marketed services, but they also have limitations including market volatility, regional variations, availability and access to these markets, and potential overvaluation when market prices fail to reflect true social costs (Dominati *et al.*, 2014; Heal, 2000).

6.3 Biodiversity enhancement

Valuing biodiversity enhancement from seaweed cultivation remains challenging due to data limitations, species attribution uncertainty, and the transient nature of cultivated habitats. While the quantification of biodiversity enhancement for ORF reported diverse taxa and habitat provisioning benefits, quantification of added ecological or economic value (e.g., enhanced fisheries) remains highly unknown. Contingent valuation and productivity-based approaches lack sufficient baseline data to be implemented robustly. Even though studies show that cultivated seaweed creates habitat that supports communities of associated organisms by providing structure, attachment sites, and trophic subsidies (Hasselström *et al.*, 2018; Theuerkauf *et al.*, 2022; Visch *et al.*, 2020), there is still a lack of experimental research and knowledge gaps on the extent that seaweed cultivation can provide biodiversity benefits. Recent studies agree that, to support biodiversity, there are operational factors that cultivated seaweed will need to consider such as harvesting and removal of the farms, which might be in odds with cultivation objectives (Bekkby *et al.*, 2023; Forbes *et al.*, 2022). The quantification of biodiversity found around seaweed

cultivations itself does not yet provide all the necessary data for valuation of the species. It is not possible to verify if the species are additional or just aggregated coming from the surrounding area (Gentry *et al.*, 2020; Theuerkauf *et al.*, 2022). Furthermore, the value of these species changes if they are in an abundant ecosystem or very sparsely populated ecosystem. The surrounding ecosystem would have to be also assessed thoroughly to state what the value of these species are for this specific ecosystem.

Biodiversity value could be recognized through non-market mechanisms, such as eco-certifications or conservation grants. Initiatives like the Plan Vivo Foundation's PV Nature are open to project applications for biodiversity Standard to support biodiversity conservation and restoration (Plan Vivo, 2023) and integrated credits that reward biodiversity as part of broader ecosystem outcomes may offer feasible alternatives. Tedersoo *et al.* (2024) suggested that incorporating biodiversity into carbon crediting schemes could enhance both environmental and social sustainability. Strategic investment in biodiversity monitoring and policy recognition is needed to move from conceptual to actionable valuation.

6.4 Research and Policy needs

Science based accreditation frameworks are key to facilitating investment by climate-conscious investors, helping the seaweed industry to grow (UNGC, 2021). Robust use of methods needs reliable and theoretically consistent evidence following transparent data collection, or evidence (IPBES, 2019).

To value biodiversity, methodologies to quantify an increase of commercially valuable species in and around seaweed cultivations need to be tested and refined to provide a full picture of the actual increase in biodiversity. Lost fishery habitats and decimated fish populations need to be characterized (UNGC, 2021). A monitoring methodology framework needs to be developed and certified, that is capable to differentiate in permanence and different cultivation methods.

Moving forward, prioritizing research on monitoring, reporting and verification (MRV) systems for marine carbon and biodiversity is essential. Policy alignment at the EU level, particularly through the EU taxonomy and carbon removal certifications, will be critical for scaling payment mechanisms. Collaborative efforts across sectors, including aquaculture, climate policy, and conservation, should be fostered to establish actionable, fair, and science-based es markets.

7. CONCLUSION

This deliverable aimed to assess the value of ecosystem services (ES) provided by seaweed cultivation. A multicriteria decision analysis was developed to assess the best suited monetary valuation methodology for nutrient bioextraction, potential carbon sequestration, and biodiversity enhancement.

For nutrient bioextraction the calculated value using the replacement costs method, shows a value of €12,545 for ORF for the total WW harvest, €8,305 for the total WW harvest of ALO and €2,141 for the total WW harvest of OF. This approach highlights the economic value of nutrient removal but risks overestimation without complementary methods that link environmental changes to real economic benefits.

Potential carbon sequestration demonstrated measurable value across all three sites, ranging from €1.89 to €7.72 per ton WW depending on carbon pricing assumptions. However, seaweed aquaculture is not yet included in existing compliance markets, and methodological barriers remain. The EU's emerging Q.U.A.L.I.T.Y framework point to a shifting landscape, but much work remains in refining MRV (monitoring, reporting, and verification) systems and certification processes.

Biodiversity enhancement showed important ecological potential, especially at the ORF site, though valuation remains

hindered by data gaps and lack of standardized methods. While eco-certifications and integrated credits offer promising non-market avenues, advancing from conceptual value to actionable mechanisms will require significant investments in research, monitoring, and policy frameworks.

Our estimates suggest a total value from ES per ton WW of € 69 or 73 for ORF, € 29 – 31 for OF and € 65 – 67 for ALO for 2024, subject to variations every year. Overall, to unlock the full potential of seaweed aquaculture as a provider of ecosystem services, strategic coordination across scientific, regulatory, and commercial spheres is essential. Developing robust, transparent, and theoretically sound valuation methods, alongside EU-level policy alignment and cross-sectoral collaboration, will be critical to scaling sustainable blue economy solutions. This integrated approach can ensure that seaweed cultivation contributes not only to environmental goals but also to meaningful economic and social outcomes.

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DATA SETS

1. Valuation of ES for ORF, OF and ALO.