Development of Offshore Seaweed Cultivation: food safety, cultivation, ecology and economy

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Contents

1 Introduction

1.1 North Sea Farm

For decades the seaweed industry has primarily been concentrated in Asia. With the Blue Growth ambitions of the European Union, more sustainable use of Europe's oceans is being explored. In this context there is a high potential for offshore seaweed cultivation. Large scale seaweed cultivation can be sustainable and be part of a circular production system. To accelerate this development, North Sea Farm (NSF) was established in 2014. NSF is a driving force in the seaweed industry, committed to develop a strong and healthy seaweed supply chain, in and from the Netherlands. NSF supports businesses and stakeholders in the realization of a strong seaweed sector by creating a platform for knowledge exchange, cross sectoral cooperation and valorisation of available expertise. In addition, NSF is facilitating innovations in the cultivation of seaweed at the Dutch North Sea with their 'North Sea Innovation Lab' (NSIL). NSIL is an independent test site for research, pilots and the upscaling of innovations in the field of seaweed cultivation and co-use of other functions at sea. NSIL is located 12 kilometres off the coast of The Hague – Scheveningen.

1.2 Knowledge and Innovation Program ProSeaweed

In the four-year Knowledge and Innovation Program 'ProSeaweed' (In Dutch *Maatschappelijk Innovatie Programma, MIP*), Wageningen University & Research and NSF are partnering with industry to develop a comprehensive and sustainable seaweed sector. The work involves multifunctional seaweed farms in the North Sea linked to a land-based chain for logistics, processing and sales to the food an feed industry. The objective of the MIP program is to create a sustainable source of healthy food products, additives and feed by means of cultivation in the Dutch waters. Wageningen University & Research and NSF work together with 13 partners in 10 coherent research projects. In these projects, the effect of seaweed as feed supplement is investigated for pigs and pets, health effects for fish, reduction of volatile components (such as methane) in cows, safe use of seaweed by developing norms and a certification standard, and the ecological effects of seaweed cultivation in offshore pilots in the North Sea. The program is sponsored by the Ministry of Economic Affairs and industrial partners. The current report describes a project within MIP program, that focused on the potential for offshore cultivation at the North Sea, in which NSF worked together with Wageningen Plant Research (WPR), RIKILT, Wageningen Economic Research (WEcR), and Wageningen Marine Research (WMR).

1.3 MIP Project: Development of Offshore Seaweed Cultivation (2018)

Since 2014 NSF has developed and executed several offshore seaweed farming pilots. A new pilot commenced in December 2017. For this pilot two Scalable Macro Algae Cultivation (SMAC) modules, with a total of 2000m seaweed production lines, have been installed to cultivate *S. latissima*. The goal of this pilot is to gain more insight on ecological and food safety impact, optimization of cultivation methods and developing scenarios for upscaling and executing new pilots within offshore wind parks. The main questions for the current project are: What is the impact of offshore seaweed farming (*S. latissima*) on ecology and food safety aspects, and what are scenarios to develop large scale sustainable offshore seaweed cultivation in the Dutch North Sea?

The project has been divided into three main themes:

1. Cultivation of kelp in the North Sea: field study investigating the optimal moment of seaweed harvest
2. Ecological effects of seaweed cultivation
3. Economic scenarios for offshore seaweed cultivation in the North Sea

During the project, sensors have been installed at the cultivation module to monitor abiotic parameters (temperature and light). The growing process of the seaweeds has been monitored monthly by NSF using a procedure provided and checked by Wageningen Plant Research. Multiple samples of *S. latissima* from the cultivation site have been analysed on macro- micronutrient and contaminants. Proteins, amino acids, iodine and arsenic are considered focus points. Potential ecological effects of seaweed cultivation on biodiversity were outlined in a factsheet (desk study), and a first screening of fauna associated with seaweed lines at the NSIL were investigated in an additional project (KB SEM 24-18[1]) of which the results will become available early 2019. Co-cultivation of mussel and seaweed in the North Sea may result in a number of interactions, of which the potential benefit of nutrient excretion by mussels for seaweed growth was studied in a land-based experiment. Furthermore, data from earlier research programs and relevant information coming from this pilot is used to develop a scenario based report showcasing the scalability of offshore seaweed cultivation in the North Sea.

The following deliverables resulted from this project, which are synthesized in the current deliverable:

- Van der Werf A & I van der Meer (2018). Productivity and chemical analysis of kelp – season 2018. Internal note
- Van Tuinen S (2018). Fluctuations in contaminants in kelp grown at the North Sea Innovation lab – season 2018. RIKILT report (in prep)
- Tonk L, P van Dalen, HM Jansen (2018). Bepaling van de larvendynamiek en mossel broedval bij de Noordzeeboerderij ten behoeve van optimalisatie oogstmoment zeewier. WMR report number (C097.18)
- Tonk L & HM Jansen (2018). Notitie: Potentiële effecten van duurzame zeewierproductie op de biodiversiteit in de Noordzee. WMR report number C013/19. https://doi.org/10.18174/470707
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- Tonk L & HM Jansen (2018). Co-cultivation of the seaweed *Ulva sp*. and *Mytilus edulis*. WMR report number C011/. https://doi.org/10.18174/470705
- Van den Burg S.W.K,, C Wakenge & P Berkhout (2019). Economic prospects for large-scale seaweed cultivation in the North Sea. WEcR memorandum (2019/12). https://doi.org/10.18174/470257

[1] KB24 18 Biodiversiteitsmonitoring offshore aquacultuur met DNA barcoding en settling technieken

2 Cultivation of kelp in the North Sea: field study investigating the optimal moment of seaweed harvest

2.1 Introduction

Commercial cultivation of seaweeds is still in its infancy in Europe, both in terms of management and in terms of productivity. For further development of the sector, seaweed crops with predictable yields and stable biochemical composition are essential. Yet, literature indicates substantial seasonal variation in both productivity and chemical composition of kelp. The current study investigated the possibilities to cultivate kelps at the NSIL location in the North Sea, and thereby focussed on density, chemical composition and food safety aspects of kelp in May and June. Further insight in seasonal variations are necessary to match requirements of the processing industry (demand) and the farm management (supply), and thereby to define the optimal harvest moment.

Biotic changes in the environment may also interfere with decision to harvest. Spring time is for example the season for bivalve reproduction and mussel spat fall can compete with seaweed for available space on the seaweed lines. Lines that are overgrown are more difficult to harvest and contamination with mussel seed may affect product quality. This study therefore also investigated mussel larvae abundances and spat fall to investigate if fouling can be prevented by early harvest, thereby leading to a better quality seaweed product.

2.2 Approach

By late 2017 a series of seeded *S. latissima* lines were deployed at offshore location NSIL in the North Sea, and subsequently harvested in 2018 at two dates. By the 5th of May 2018, eight vertical ropes of 7m length, each, were harvested, and another batch (nine ropes) by the 6th of June. Each line was divided into three parts of 2.3m each, and fresh weight and dry weight of each part were determined. Chemical analyses were performed on the upper two parts of the ropes for the two harvests: crude protein[2], crude fat, crude dietary fibre, starch, sugars and ash. Essential and non-essential protein amino acids concentrations[3] were also determined on the same material. Also the concentration of contaminants (heavy metals, iodine) in the kelp were determined for these samples, and where applicable/possible compared with the current EU food and feed legislation levels. Additional to the seaweed sampling program, from March to July water samples were collected to determine larvae densities, and collectors were deployed for monitoring of mussel spat fall.

2.3 Results on seasonal variability in densities and chemical composition

Irrespective of harvest moment, standing crop decreased with increasing depth, and increased over time, irrespective of depth (Table 1). However, during deployment of the ropes, mechanical problems were encountered according to NSF, and during the growing season ropes got entangled, which may have caused physical damage of the seaweed thalli. Therefore conclusions with respect to productivity or standing crop over depth and growing season are hard to derive from these data. However, it is

[2] Crude protein was calculated as total nitrogen concentration (DUMAS-method) times 6.25

[3] True protein concentration was determined as sum of all amino acids after correction for H_20 that binds to the individual amino acids during protein hydrolysis.

considered likely that productivity at 5m below sea level will be too low for commercial application. Future tests with seaweed cultivation at depths lower than 5m should verify this.

Crude protein concentrations, measured as total nitrogen, showed little variation with depth. However, at the second harvest (June) crude protein decreased more than 50% (Table 1). Contrary to this observation, *true protein*, calculated as the sum of all protein amino acids concentrations, remained fairly constant both with depth and over time (10-11% of DW). Calculations showed that in May, on average 60% of total nitrogen was not incorporated in proteins and free amino acids, whereas one month later roughly 80% of total N was incorporated in proteins and free amino acids. So, the question now remains in which seaweed compounds this nitrogen is incorporated in? And do these compounds have a commercial value?

Of the major nutritional compounds, crude fat concentration was low and decreased in time (from 1.7 to 0.7), starch was variable over time (between 0.7 and 1.7) and true protein remained fairly constant (11%), whereas crude dietary fibres increased over time from ~ 34% in May to 46 % of DW in June. As mentioned before, total nitrogen decreased from ~ 29% to 14%. This all occurred in only one month time, and may have significant influence on the economic value of the seaweed biomass. It is also important in regard to the desired end-product, whether it is food, feed or building blocks for bio-based products like e.g. plastics. Further research is needed to determine which N-containing compounds accumulated in kelp in the May samples. If this is caused by accumulation of alkaloids or other phytonutrients, interesting (new) health-promoting compounds could be present which make kelps an interesting source for the nutraceuticals- or food supplements market.

Table 1 Variation in Density (g DW), proteins (mg g-1 DW) and contaminants (mg kg^{-1} DW)per month and depth section (surface, mid, lower). Values present average values, including max-min values for density and proteins, and the standard deviation for the contaminants

	May			June		
	surface	mid	lower	surface	mid	lower
Density	94 (290-5)	41 (84-0)	6 (12-3)	214 (504-37)	41 (84-0)	6 (12-3)
Crude protein (N)[1]	278 (283-273)	298 (302-294)	-	137 (139-132)	136 (148-125)	-
True protein[2]	112 (118-102)	102 (110-96)	-	105 (106-104)	101 (104-95)	-
Arsenic	54 ± 7	47 ± 3	-	25 ± 5	24 ± 6	-
Inorganic As	0.23 ± 0.06	0.46 ± 0.02	-	0.21 ± 0.08	0.27 ± 0.12	-
Cadmium	0.22 ± 0.05	0.24 ± 0.01	-	0.15 ± 0.02	0.20 ± 0.03	-
Mercury	0.05 ± 0.01	0.05 ± 0.002	-	0.06 ± 0.01	0.07 ± 0.01	-
Lead	0.39 ± 0.08	0.62 ± 0.06	-	0.41 ± 0.02	0.60 ± 0.08	-
Iodine	2796 ± 501	3320 ± 233	-	1055 ± 463	1252 ± 685	-

2.4 Results on seasonal variability in food safety aspects

Interesting patterns were observed for the analysis regarding food safety parameters. Concentrations of most heavy metals (arsenic, inorganic arsenic and cadmium) and iodine decreased by approximately 50% from May to June (Table 1). The average arsenic concentrations in May exceeded the maximum allowed level of 40 mg/kg (88% DW) for feed application. As a result of the decrease of the average contamination level, concentrations of all elements were below the EU-limits for feed applications in June. For application in food the values reported for May and June were below the European maximum levels.

The observed iodine concentrations still raise concerns (Table 1). Despite the fact that there is only an EU recommendation for the maximal content of iodine in seaweed, these recommended values are exceeded easily in the samples analysed.

The expected seasonal variations in heavy metal concentrations as described in literature (Sharma et al. (2018), Nielsen et al. (2016), Schiener et al. (2015)) are confirmed by the field trial performed at the NSIL. The current study contributes to more insight in potential variability as a result of seasonal/environmental parameters, but since element uptake mechanisms in seaweeds are still largely unknown, it is not yet possible to explain the results observed here. As it is known that variations occur within and between years (inter- and intra-annual), it is advised to repeat the measurements described above to define whether differences show a consistent pattern, or if the observed pattern is a coincidence. Given the large differences between the two sampling moments (Table 1), it is preferred to collect more samples throughout the growing season to understand the dynamics and variations better.

2.5 Results on timing of mussel spat fall

Highest number of mussel larvae were recorded in week 15 (April), and spat was observed in week 23 (June) and week 29 (July) (Tonk et al. in press). However, frequency of sampling (every 3-6 weeks) did not allow for exact identification of the peak in larvae and spat abundance. We also explored correlations with spat fall in the Oosterschelde (OS) and Waddensea (WS) to identify the potential for using existing monitoring as a predictor for spat fall in the North Sea. Total numbers recorded at the offshore NSIL location were not comparable to the OS and WS, which are important production areas for the mussel industry: maximum larvae densities (per 100 L) at NSIL were 176 compared to >15.000 in OS and WS, while number of recorded spat per collector were 32 at NSIL compared to a few hundred at the more inshore locations (Capelle pers comm). Despite low numbers of larvae and spat, dense mussel patches were observed on the seaweed lines during a diving inspection in July. This indicates that either low number of larvae and spat might still result in high mussel densities, or that sampling techniques as applied for OS and WS are not suitable for offshore conditions, e.g. samples are collected at the water surface and water column might be less mixed or mussel spat might move deeper in the water column to avoid high wave action.

It is therefore recommended to include depth stratified sampling as well as high(er) frequency sampling to investigate correlations between the different cultivation areas in more detail. Based on the data from OS and WS spat fall will take place in May and June, and usually starts somewhat earlier in the OS compared to WS. Exact timing however varies between years.

Those results indicate that seaweed harvest might indeed suffer from fouled seaweed lines when harvest is performed later in the season. In May no to little fouling with mussels is expected, while harvesting in June may experience disadvantages caused by mussel spat on the seaweed lines. Taking moment of spat fall into account in management strategies for seaweed harvest can therefore lead to better quality of the seaweed product.

2.6 Conclusions & Reflections on optimal moment of kelp harvest

Large variability in chemical composition of seaweeds was observed between months, with the interesting observation that the N fraction in May contains more other components than proteins. Whether these include for example interesting (new) health-promoting compounds needs to be further elucidated. This indicates that despite lower overall harvestable biomass in May compared to June there might be reasons to harvest earlier in the season. This would also be beneficial from the perspective of mussel settlement on the seaweed structures which might interfere with efficient harvest techniques and product quality.

However, an opposite pattern was found for the contaminants. For most of the critical contaminants and elements the observed concentrations were ~50% lower in June compared to May. This implies that for meeting the EU limits for safe food and feed the moment of harvesting the kelps in the North Sea should be postponed to at least June. The current study could not elucidate if even later harvest would further reduce contaminant concentrations.

3 Ecological effects of seaweed cultivation

Although seaweed farming is often considered as a sustainable way of protein production, upscaling does require an active approach to address potential impacts on nature and marine environments. Cultivation of seaweed leads to a number of ecosystem interactions, which can be positive (ecosystem services), or negative (ecological impacts) to the surrounding marine ecosystems. Examples of ecosystem interactions include extraction of nutrients (from eutrophication from land run-off or in integrated aquaculture), carbon capture, effects on biochemical functioning of sediments, and/or effects on biodiversity.

3.1 Biodiversity

During the current project we focussed on one of the ecosystem interactions, i.e. biodiversity, as this is an important parameter in several marine policies, e.g. in water framework directives. A factsheet was published (Jansen & Tonk 2018, Tonk & Jansen 2018a) describing positive and negative effects of seaweed aquaculture on biodiversity based on a literature study. In this study it was taken into consideration that offshore seaweed cultivation will be developed in combination with wind farms, and therefore cumulative effects were evaluated.

The factsheet highlighted that seaweed (aquaculture) may attract marine biota from several trophic levels by providing habitat, protection, serving as a nursery location, or as a food source. Seaweed longlines form 3D structures in the water that attract all kind of biota, including organisms that naturally only live on the seafloor such as small crabs or bivalves. It was shown that a single kelp leaf could attract up to 40 species and up to 8000 individuals of benthos, demonstrating the effect of seaweed on enhancing biodiversity. Fish generally use the farming structures as a nursery habitat or to seek shelter. Higher trophic levels (birds, mammals) are not necessarily attracted by the seaweed farm as such, but rather by the increased number of prey animals. They may also use farm structures (e.g. buoys) to rest. Low trophic levels (plankton) are mostly affected by seaweed farms through the competition on nutrients. Attraction of multiple marine biota may have a positive effect on biodiversity in and around seaweed farms. However, when non-native species use the seaweed structures as a ‘stepping stone’ for further dispersal, it is considered a negative impact which should be carefully examined. It should be noted though that existing oil rigs, windmills and a number of ship wrecks already form a reef-network in the North Sea and it is the question what the cumulative effects of seaweed farming will be, including an evaluation whether similar types of species will be attracted to different types of hard structures.

Moreover, the factsheet highlighted the need for more empirical data to quantify the effects of seaweed farming (stand-alone activity and in multi-use context) on marine biota, as most studies so far presented theories and anecdotal information rather than evidence based on structured monitoring programs. Efficient policy and management strategies taking biodiversity dynamics into account can only be developed if site specific and quantitative information is available.

Figure 1 Seaweed farms provide shelter for small fish. Photo taken at Dingle Bay Seaweed Ltd in Ventry Harbour (Ireland, © Jose Franco Farinas)

3.2 Co-cultivation of seaweed and mussels

Co-cultivation (also referred to as integrated culture) of seaweed and shellfish is mentioned as a multi-use approach to efficiently use space in offshore wind parks. Amongst the many interactions between these two species is the potential for seaweed to benefit from additional nutrients (in particular ammonium) excreted by mussels. Therefore processes such as growth and nitrogen assimilation were investigated for green seaweed *Ulva spp.* cultivated as mono-culture and in co-cultivation with blue mussels *Mytilus edulis* (see Tonk & Jansen 2018b). Under nitrogen limited conditions, co-cultivation is expected to directly increase growth rates of *Ulva*, under light limited conditions growth or nitrogen uptake might still be enhanced as NH_4 excreted by mussels costs less energy (ATP) to assimilate compared to NO_3, which is naturally more abundant in marine waters.

Surprisingly, no differences in growth were observed after one month. C:N ratios in tissue decreased throughout the experiment indicating the nutrient limitation was less likely limiting *Ulva* growth at start of the experiment, however, no variation between mono- and co-cultivation was observed either. These results were contradictive to our hypothesis of nitrogen enhancement by mussels. At the end of the growth experiment nutrient uptake experiments were performed to quantify nitrogen release by mussels and nitrogen uptake by *Ulva* in the different treatments. Although it was a point measurement, this showed a complete lack of nitrogen enhancement in the mussel tanks, contradictive to pilot measurements where nitrogen release was measured according to rates as published in literature. Several causes might apply, where nitrogen conversion to N_2 gas or nitrogen assimilation by fouling species/bacteria seems the most likely reason, though it is difficult to understand the exact processes based on these data. Exact reasons for lack of nutrients in mussel tanks thus remain unknown, and the possible explanation for the unexpected result likely lies in a combination of several factors. Results of this study are therefore inconclusive with regard to growth or nitrogen enhancement for co-cultivation of mussels and seaweed, as it cannot be elucidated whether results are due lack of nitrogen enhancement by mussels or whether additional nutrients do not affect seaweed growth.

Table 2 Ulva growth and composition in monoculture and co-cultivation with mussels after one month experimental period

	Unit	Monoculture	Co-culture
Productivity	g DW m^{-2} d^{-1}	9.0 ± 1.5	8.0 ± 1.6
SGR	% DW d^{-1}	7.7 ± 0.86	7.8 ± 0.89
C:N ratio	molar	13.2 ± 2.80	10.4 ± 1.29

Although these results do not evidently demonstrate an advantage of seaweed cultivation in combination with mussels they do not rule out potential benefits from combined seaweed-shellfish production. Moreover these results underline the complexity of seaweed-shellfish ecosystem interactions and the importance of environmental factors in combined production.

3.3 Conclusions & Reflections on seaweed-ecosystem interactions

Literature study indicated that ecosystem interactions such as biodiversity can be influenced by seaweed aquaculture, but empirical data is largely lacking. This makes it difficult to evaluate changes in specific fauna groups as a function of seaweed farming (as a stand-alone activity or in combination with wind farming), including changes throughout the production cycle. It is therefore unknown if farm management can be adapted to account for temporality and/or further stimulation of the ecosystem services. For example, seaweed farming provides shelter for juvenile fish, yet this nursery function is temporal and it is unknown if seaweed harvest (removal shelter) takes place before or after the juveniles have migrated to areas outside the farm for further growth. To stimulate or reduce the attraction of marine mammals and birds one could also think of technical adaptations to develop advanced nature inclusive farming systems. Furthermore, the cumulative effects of seaweed farming in relation to the already existing reef-network (incl windparks) in the North Sea should be evaluated in terms of attracting native and invasive sessile (hard substrate) fauna. Site specific information is thus important as interactions between seaweed, potentially mussels, and the ecosystem are complex and environmental factors are important drivers. Effects of large scale seaweed farming are therefore not straight forward and vary from system to system and depending on other marine activities in the area (e.g. in a multi-use setting with wind farming). Development of the seaweed sector should thus go hand in hand with (standardised) monitoring of environmental interactions.

4 Economic scenarios for offshore seaweed cultivation in the North Sea

The costs of producing seaweed in the North Sea are an important determinant for successful upscaling of production. The expected future costs of production were calculated and compared with reported values of seaweed in the global market.

4.1 Model Outcome

The EnAlgae Model (available online[4]) was used to calculate the expected cost of production under different scenarios. In all scenarios, we assume that *S. latissima* is produced offshore, using a system with longlines and V-droppers. The study investigated (i) how upscaling, (ii) changes in cost of plant material and (iii) increases in yield affect the cost of production.[5] Additionally, a scenario was studied in which the yield increased and costs for plant material were lower. The outcome of the scenario studies are presented in table 3 below.

Table 3: Results economic scenarios for offshore seaweed cultivation in the North Sea

Change foreseen	Changes	Cost prices seaweed (€ kg FW)¹	Cost price per ton[6] (€ ton DM)²
Base-case		0.78	5200
Upscaling	1000 to 5000 production units	0.78-0.70	5200 – 4667
Reduce costs plant material	From €5 to €1/m seed line	0.78-0.38	5200 – 2533
Increasing yield	From 10 kg/m to 30 kg/m	0.78-0.29	5200 - 1933
Increase yield and lower cost plant material	From 10 kg/m to 30 kg/m, plant material costs €1/m	0.38-0.16	2533 - 1066

1) FW = Fresh weight; DM = dry matter
2) Assuming 15% dry weight

4.2 Conclusions & Reflections on economic scenario's

Based on the results, we conclude that significant cost reductions are possible, with expected resultant cost prices down to €1200 per ton DM. If all goes well, relatively low-value markets such as the alginates are within reach, with reported values of raw material of US$950 per ton (Nayar and Bott 2014). More realistically, a mix of low- and medium-value markets is needed to cover the costs of seaweed production in the North Sea. Current developments indicate that these markets exist; particularly in the food market where seaweeds are promoted as organic, sustainable and fair trade products (Buschmann et al. 2017).

[4] http://www.enalgae.eu/getfile.php?type=site_documents&id=WP2A7.06%20model%20economics%20macroalgae%20v18.02.15.xlsx

[5] In the full report, some additional scenarios are described with combinations of changes.

[6] Assuming 15% dry weight

5 General conclusions

This project investigated a broad range of aspects regarding offshore seaweed production in the North Sea based on field-, lab-, experimental-, literature- and economic modelling approaches. Interesting and promising results are:

(i) high variability in chemical and contaminant composition of kelps, with only one month between sampling moments, was observed. This demonstrates the potential to harvest at the right moment, to provide the processing industry with desired products. However, it simultaneously shows the challenge to provide products with stable biochemical composition,

(ii) preliminary chemical composition analysis revealing an accumulation of putatively interesting N-containing compounds in the May samples,

(iii) economic analysis indicates that relatively low-value markets such as the alginates are within reach for seaweed production in the North Sea, though for the near future a mix of medium- and low-value markets needs to be targeted

(iv) seaweed cultivation can have significant effect on the surrounding ecosystem, including biodiversity enhancement. But site specific information is required for the North Sea to evaluate how this activity relates to for example requirements by marine framework directives, and if farm management can further stimulate the ecosystem services provided by seaweed cultivation (through timing of harvest and/or technical adaptations to become more nature inclusive).

This all indicates that seaweed farming in marine systems is complex and (harvest) management can be adapted according to highest biomass production, directed towards production of specific components (in certain months), accounting for contaminant concentration, aiming for lowest fouling with mussel seed, or to be most sustainable in terms of stimulating ecosystem services such as biodiversity (e.g. nursey function for juvenile fish). Each scenario will have consequences for economic and ecologic feasibility of offshore seaweed farming.

However, discrepancies between assumptions in the model (10-30 kg FW m^{-1}; based on other production areas) and measured production (max 3.8 kg m^{-1}) were also observed. This indicates that there still is a large potential for (technical) improvements. This includes that better understanding of environmental drivers for seaweed production at this site are required (e.g. light penetration and mixing of water column). Furthermore, it was shown that production costs (€) per unit of biomass produced are strongly determined by seeding costs of the ropes (chapter 4). As low productivities were observed below 5 meters of depth (chapter 2) and the cause for it could not be verified due to lack of useable data, it is recommended to continue research with seaweed cultivation at depths lower than 5m until the data is conclusive.

6 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2021. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

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Justification

Report C012/19
Project Number: 4318100175

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

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Signature:

Date: 19 February 2019

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