Final Report:
Pre-feasibility Study on the potential for commercial cultivation of African kelp along South Africa's West Coast

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EXECUTIVE SUMMARY

South Africa has an extremely diverse seaweed flora, with more than 850 recorded species. Kelps are large brown seaweeds, which only occur in cold and warm temperate seas. There are four species of kelp in South Africa including *Ecklonia maxima*, *Ecklonia radiata*, *Macrocystis pyrifera* and *Laminaria pallida.* Large and significant kelp forests in the Benguela upwelling region along the west coast are based on three of these (*E. maxima, M. pyrifera* and *L. pallida*). Economic exploitation of this resource started decades ago with collection of beach-cast material, drying, and exporting for alginate extraction. Since the 1970s, there has been an increase in the use of freshly harvested kelp for abalone feed and production of a plant growth enhancer. This industry is based on the harvesting and collection of kelps from natural kelp beds and is subject to seaweed concessions with limitations on the amounts that can sustainably be harvested on an annual basis.

On a global scale, more than 99% of the world's seaweed production (over 35 million tonnes worth US$ 14.7 billion) is grown through aquaculture, with over 99% of production in East Asia. In recent years, there has been a lot of interest and research into kelp aquaculture in Europe and North America. There has also been significant increase in the current and potential uses of seaweeds including food, food supplements, nutraceuticals, functional foods, fertilizer and plant growth enhancers, textiles, bioplastics, and biofuel. In addition, there is increased interest in the use of seaweeds for climate change mitigation, carbon credits and biorefineries (for conversion of seaweed biomass into numerous different economic products).

The size of the South African kelp industry is about 10 000 tonnes (t) per annum (p.a.), which is 3% of global 'wild harvested' kelp production, and 0.1% of total global kelp production (including 'wild harvested' and aquaculture). Global seaweed production is growing rapidly, and most of this production is kelp in temperate regions. Kelp has never been grown in commercial aquaculture in Southern Africa before, and there is limited information available on many aspects of local kelp growth in aquaculture. Kelps release billions of tiny spores, which produce the microscopic stage of kelps, known as the gametophyte. These and the resulting juvenile kelp plants must be cultivated for a period in land-based climate-controlled hatcheries. After several weeks, strings seeded with spores from the hatchery are placed on rope rafts in the sea. Methods used elsewhere for hatchery growth and rope raft construction can be adapted for South African conditions. The country has a long coastline with significant kelp forests, four indigenous species of kelp, high levels of coastal light and a major upwelling region on the west coast with high, consistent nutrient supply. Significant growth of the kelp industry in South Africa will depend on successful commercial cultivation of the species that are currently utilised, to increase the biomass availability.

The aquaculture sector in South Africa consists of 229 freshwater and marine aquaculture farms with total annual production of more than 6000 t. Most of this production comes from marine aquaculture, led by mussels (more than 2000 t) and abalone (more than 1500 t). In addition, around 2000 t of seaweed (*Ulva*) is cultivated on abalone farms as part of integrated culture systems and fed to the abalone.

The consistent growth of global seaweed aquaculture, increase in current and potential uses of seaweed, increased interest in kelp cultivation in Europe and North America, presence of thriving kelp forests, existing aquaculture industry and environmental conditions with potential for kelp cultivation, is driving increased interest in commercial cultivation of South

African kelp. In terms of environmental sustainability, there is potential for the use of kelp cultivation in Integrated Multi-Trophic Aquaculture (IMTA) in existing aquaculture, climate change mitigation and carbon credits. Due to the limited number of sheltered bays for inshore aquaculture, there is also a need to investigate the potential for offshore kelp cultivation along the coastline.

Over the years, the scientific community, seaweed, and aquaculture industries in South Africa have been independently involved in initiatives to grow seaweed including kelp, and to develop niche products and markets for seaweed. Although *Ulva* is successfully cultivated on abalone farms as feed, no other successful seaweed or kelp cultivation industry has yet been established in the country. Some of the problems experienced with experimental cultivation included low nutrient and low oxygen events. This highlights the need for collaboration between government, industry, and research organisations to combine forces to address the potential development of a kelp aquaculture industry. It will reduce duplication of effort, maximise returns on investment in research and development, enrich efforts through the different areas of expertise, and potentially reduce the timeline from experimental to commercial kelp cultivation.

The bivalve shellfish industry (oyster and mussel) is the only sea-based industry in South Africa and is represented by the Bivalve Shellfish Farmers Association of South Africa (BSASA). It is therefore a natural extension that interest in kelp culture, which uses similar farming practices, can be implemented by this sector. In collaboration with government and research entities, BSASA applied for and received an allocation of Evidence Funding (EF) from the Foreign, Commonwealth & Development Office of the Government of the United Kingdom (FCDO) to set up a South African Kelp Project. This project was a collaborative effort involving the aquaculture industry, government, research institutions and academic institutions. The aim of the collaborative approach was to make the outcomes of the research available to broader stakeholders, existing sector, and all new potential entrants into the sector.

The main aim of the project was to conduct a pre-feasibility study to assess the potential for kelp cultivation in South Africa. This included synthesizing available biological, environmental, and economic information, and setting up facilities for conducting initial experiments on kelp seeding. Additional activities included the following:

1. Investigation of the use of kelp cultivation as an IMTA platform to improve the sustainability of existing aquaculture activities in Saldanha Bay
2. Investigation of the potential for coastal commercial kelp cultivation to provide value chain opportunities to coastal communities along the West Coast.

The FCDO-BSASA Pre-feasibility Study on the potential for commercial cultivation of African kelp along South Africa's West Coast focused on three kelp species occurring along the West Coast (between Cape Agulhas and the mouth of Orange River). These included *E. maxima* (sea bamboo), *M. pyrifera* (bladder kelp) and *L. pallida* (split fan-kelp). The project consisted of the following three components:

1. **Project Component 1:** Understanding the methodology for laboratory production of gametophytes and sporophytes in a laboratory environment:
    a. Kelp seeding and growing experiments in laboratory environments at Viking Aquaculture's abalone farm in Buffeljags, Western Cape, and the Department of Forestry, Fisheries, and the Environment (DFFE) Marine Research Aquarium at Sea Point, Western Cape.

   b. Although trials started in February 2022 and results up to March 2022 are included in the pre-feasibility study, these trials are expected to continue and will be used to support the proposed kelp raft cultivation pilot in Saldanha Bay. This will depend on further funding.
2. **Project Component 2:** Understanding the potential for cultivation of three kelp species, requirements for integration with existing aquaculture activities, and optimum products and markets:
   a. Identification and synthesizing of all available relevant information on biology, genetics, growth rates, environmental tolerances, chemical and nutrient composition
   b. Identification and engagement with aquaculture stakeholders to share scientific findings and establish interest among aquaculture farmers
   c. Assessment of the potential of Saldanha Bay and offshore areas along the West Coast as kelp cultivation sites
   d. Assessment of the potential of developing seaweed markets/product pipelines), including the following activities:
      i. Determine nutritional value of different species of seaweed
      ii. Map the requirements for a seaweed product development chain and market
3. **Project Component 3:** Understanding the most appropriate technologies and business models for sustainable joint ventures between industry and coastal communities. The objective was to use the results from the kelp seeding and growing experiments to enable the establishment of a research platform for government and industry stakeholders to continue to derive learning beyond evidence funding (EF) allocated in the 2021/22 financial year. Activities included the following:
   a. Site selection and set up of pilot kelp cultivation systems (rope rafts) in Saldanha Bay, and to continue beyond March 2022.
   b. Cultivation system design, concluded in March 2022.
   c. Understanding the most appropriate business models, in conjunction with activities related to Project Components 2.b and 3.a and concluded in March 2022.

These project components were conducted by different project teams from industry (Viking Aquaculture), BSASA, DFFE, University of Cape Town (UCT), independent experts and the Council for Scientific and Industrial Research (CSIR). The role of the CSIR was to collate and synthesise the results of all the activities from the FCDO-BSASA Kelp Project as part of a Pre-feasibility Study on the potential for commercial cultivation of African kelp along South Africa's West Coast. The CSIR used its own Pre-feasibility Study process to prepare the study and this report.

A pre-feasibility study is a preliminary study done to determine if it would be worthwhile to proceed to the feasibility study stage. It is used to clearly describe and define a potential opportunity, is qualitative, and is based on high-level information, estimates, and assumptions. In contrast, a feasibility study is used to support a decision to invest in an opportunity, and to check the viability of establishing an enterprise. It is quantitative, and based on detailed market and technical research, and financial modelling. The project collaborators therefore regarded the pre-feasibility study as a necessary pre-cursor to justify further investment in a full feasibility study.

This pre-feasibility study was based on an investigation of the scientific case for commercial kelp production, testing the appetite of the industry and availability of sea space before further investments into more detailed studies. As there is no commercial kelp cultivation in South Africa, and much needs to be done to develop a viable kelp aquaculture industry in the country, this pre-feasibility study was conducted to better understand the needs and de-risk further investment into more detailed research and studies, inform the sequencing of follow-on work and provide the basis for motivation for follow-on funding. The results from various work streams (science, product value chain, GIS, raft infrastructure and business model) were used to inform the recommendations from this study.

The pre-feasibility study identified that there is an existing kelp industry in South Africa based on the harvesting and collection of natural populations of kelp along the West Coast. Expansion of the local market and meaningful access to the global market will depend on successful commercial cultivation of the three kelp species under consideration. The global kelp market was estimated at US$1.7 billion in 2021. If a South African kelp cultivation enterprise could access 1% of this market, this would translate to US$17 million (ZAR 251 million). If 0.1% of the global kelp market is accessible, this would translate to R25 million.

The study also identified that coastal kelp cultivation is possible along the West Coast of South Africa, including ten offshore areas, and inshore areas in the Saldanha Bay ADZ. A kelp cultivation operation set up as an IMTA platform on an existing aquaculture farm (e.g., mussel or oyster farm) in the Saldanha Bay ADZ could meet a local market potential of about 1000 t p.a. and could provide an additional income stream to aquaculture farmers.

As part of the pre-feasibility study, kelp seeding and cultivation experiments were conducted, which indicated that laboratory-based kelp seeding, and cultivation experiments are successful. A rope raft was also designed and constructed. Depending on further funding, this raft will be seeded using the sporophytes produced during laboratory trials and installed in Saldanha Bay for pilot sea-based kelp grow-out experiments. Ongoing trials will provide valuable insights and technical guidelines on 'force cultivation' to reduce kelp outgrowing time until harvest. Offshore kelp cultivation will need more marine engineering inputs, and investment in production system design and testing. Successful commercial cultivation of kelp (in the Saldanha Bay ADZ and offshore areas) could significantly increase the biomass available for further growth of the South African kelp industry.

The study further indicated that a 4-ha kelp farm using longline production system (250 lines of 100 m each), producing 20 kg fresh weight (FW)/m/harvest, with two harvests (1000 t FW per year), could be potentially viable. These assumptions and the technical and economic feasibility of commercial kelp cultivation should be tested through pilot kelp cultivation trials in inshore and offshore locations, testing all three species, and operating for at least one year, but ideally for three years. The pilot should produce enough kelp for development of value-added products that could be tested in the market.

Detailed key insights from the pre-feasibility study can be summarised as follows:

- **Nutrient production and removal model for Saldanha Bay**: The nitrogen removal capacity of cultivated kelp in Saldanha Bay was estimated at between 5 and 17.5 t/ha per year, and the CO_2 removal capacity at between 0.36 and 1.5 t/ha per year. Given nutrient levels in Saldanha Bay, that translates to a potential kelp production of 17 750 t in the Saldanha Bay ADZ (if a maximum of 30% of the 884-ha area will be used for kelp cultivation).
- **Kelp seeding and growing experiments**: The four trials initiated on production of gametophytes (microscopic sexual phase) and sporophytes (macroscopic asexual

phase) of *E. maxima* and *L. pallida* at the Marine Research Aquarium were successful. Gametophyte development of up to two cells could be seen under a microscope. At Viking Aquaculture's abalone farm in Buffeljags, the trial on gametophyte production of *M. pyrifera* was not as successful. The successful trials meant that the sporophytes could be produced and grown out to a stage where they could be transplanted to rope rafts in the sea; this signified the green light for pursuing commercial kelp cultivation.

- **Nutritional values of kelp species**: The proximate (protein, lipid, carbohydrate, moisture, and ash content) and fatty acid composition of samples of *E. maxima, M. pyrifera* and *L. pallida* were analysed by the Cape Town University of Technology. Results of these tests are expected by June 2022.
- **Appropriate technologies for kelp cultivation**: Suitable sites for kelp cultivation were identified in Small Bay and Big Bay (Saldanha Bay) which are part of the shellfish farming areas of West Coast Oyster Growers. A rope raft cultivation system was designed and constructed for the pilot cultivation trials. Preparations of the site where it will be installed, are in progress.
- **Geographical Information System (GIS) study for cultivation areas along the West Coast**: Based on synoptic assessments, ten potentially suitable areas for offshore kelp cultivation were identified for the open West Coast, Saldanha-St Helena area, and the southern study area. The Northern Cape coast, with its extensive Namakwa ADZ, moderate annual wave energy and short distance to suitable water depth, should be suitable to offshore kelp farming, especially in the vicinity of the small towns. There is high potential for kelp farming between Betty's Bay and Hawston, southwest of Gans Bay and between Franskraalstrand and Pearly Beach, given high settlement density, low to moderate wave energy and extensive suitable depth zones. False Bay might be suitable, too, but it is not in a designated ADZ. In Saldanha Bay, the areas within the ADZ were regarded in general as suitable for kelp cultivation, however stratification of the water column in Inner Bay in March may impact negatively on kelp cultivation in Small Bay and Big Bay.
- **Potential production requirements**: Kelp cultivation studies elsewhere in the world were used to estimate potential production requirements for South African kelp species. A production system of 250 longlines of 100 m each, spaced 1.5 m apart, will need about 4 ha space to produce between 200 and 1000 t kelp per year. This will require seeded ropes (produced in a hatchery), two harvests per year and production of between 10 and 20 kg/m cultivation rope. Production equipment includes a work boat and skiff or inflatable boat and harvesting tools. Labour requirements include a skipper and three crew members, and a diving outfit. Farming processes include raft inspections and harvesting. An on-land facility will be required for drying, milling, and processing.
- **Potential financial viability**: Three scenarios based on annual production of 500 t, 750 t and 1000 t fresh kelp were used to assess potential viability. The results indicate that at production of 1000 t p.a., projected sales of R2 037 500 and establishment cost of R7 335 000, a payback period of 3.6 years is achievable and indicates a potentially viable kelp farming operation. These assumptions will need to be tested with inshore and offshore kelp cultivation trials of the three indicated species, lasting at least one year each but ideally three years, to test different densities, harvesting frequency, seasonality, stocking frequency etc., and producing enough biomass to develop products that can be tested in the local and global markets.
- **Summary and recommendation**: The pre-feasibility study results indicate that South African commercial kelp farming industry is viable based on demonstrated successes of laboratory growth, and early findings from GIS studies and raft design opportunities to deploy a pilot production system in the environment. Local and global market potential

has been assessed and further techno-economic studies are required to inform investment need and opportunity.

These insights confirmed the potential feasibility of commercial kelp cultivation along the West Coast of South Africa. A kelp farm producing 1000 t kelp per year could be potentially viable. The authors are of the view that there is enough evidence to suggest progression to a full feasibility study as the next phase. The pre-feasibility study achieved its original intent of assessing whether the opportunity for commercial kelp cultivation is worth investigating further through a feasibility study.

The recommendation from the pre-feasibility study is therefore to proceed with a techno-economic feasibility study of commercial kelp cultivation along the West Coast of South Africa. A full feasibility study should investigate which of the potential demands will best be met through cultivation of kelp e.g., catalysing new start-ups, developing SMMEs in the value chain, reducing the need for abalone farmers to focus on harvests rather than their core business, grow more kelp for carbon mitigation etc.

It is recommended that during the next phase, existing aquaculture farms in the Saldanha Bay ADZ are used to set up pilot kelp cultivation farms, using available farm infrastructure. This will enable the production of kelp as an IMTA platform, reducing costs associated with the kelp farming activities, and producing an additional crop that could increase the sustainability of the existing aquaculture farms. These pilot farms should form part of a broader, comprehensive feasibility study including offshore cultivation pilots, that could generate the technical and economic information required for further investment decisions.

A full techno-economic feasibility study should generate the data and information, including detailed market and technical research and financial modelling, needed to support a decision to invest in a kelp farming opportunity.

Specialist report: potential for kelp aquaculture in South Africa

A Specialist Report on kelp aquaculture prepared by Emeritus Professor John J Bolton was used as the foundation to inform all the activities related to Project Components 1 to 3. The report entitled "The potential for kelp (Laminariales) aquaculture on the west coast of South Africa, including a synthesis of available biological and ecological information" is included in this report as Appendix B.

Market Insights: Summary

In 2019, world seaweed cultivation production was estimated at 34.7 million t, generating US$14.7 billion first-sale value. The major global applications of seaweed and 2020 market volumes and values were as follows:

- Human food such as kombu, nori or wakame, utilised raw or sun-dried (12.7 million tonnes (t), US$ 7.6 billion)
- Raw material for hydrocolloids (polysaccharides) or gums such as alginates, carrageenan, and agars (15.7 million t, US$ 11.6 billion)
- Others such as plant bio stimulants and bioenergy (2.3 million t, US$ 1.4 billion).

In 2019, global aquaculture production of brown seaweeds (including kelp) was estimated at 16.4 million t, with an estimated value of US$ 7.6 billion. World production of kelp (wild harvested and aquaculture) was 12.6 million t in 2019, with 98% (12.3 million t) from aquaculture. Global demand for kelp was estimated at US$1.7 billion in 2021. Kelp is used as food for humans, as animal feed in aquaculture (e.g., as abalone feed), for use in fertilisers and plant growth stimulants, as a source of iodine, potash, and other salts, to produce acetone, kelp char, and seaweed gums/alginates (for use in the drug, food and other industries).

The size of the South African kelp industry is about 10 000 t p.a. (3% of global wild harvested market), with 70% used fresh as abalone feed. This is based on the sustainable harvesting of natural populations or collection of beach-cast biomass by seaweed concessionaires. Each seaweed concession area is subject to maximum sustainable yields (MSYs), set at 10% of the estimated biomass of kelp beds p.a. The total MSY for kelp is about 25 500 t. Most of the unused MSY is in the northern parts of the West Coast where there are few abalone farms and no large industries dependent on kelp. Expansion of this industry is therefore hampered by local restrictions on the removal of biomass from natural kelp beds in the southern parts of the West Coast where most of the demand is, and limited demand in the northern parts.

Based on feedback from industry, the accessible local market for cultivated kelp, that a start-up producer could realistically access, is estimated at 10% of the local kelp market (1000 t valued at R3 million). A conservative estimate of 0.1% of the global kelp cultivation market is 12 000 t with potential value of more than R20 million. However, just 1% of the global kelp cultivation market could translate to more than 120 000 t, with potential value of more than R200 million.

The kelp species considered for this study includes the three species found along the West Coast of South Africa including *E. maxima*, *M. pyrifera* and *L. pallida.* The key kelp products sold in the local market are fresh kelp blades used as abalone feed (average price R1 800/t), whole kelp used for manufacturing of plant growth stimulants (average price R2 700/t) and dried, milled, and graded kelp sold to the export market and locally to niche product manufacturers (average price R20 500/t).

Technical insights: Summary

Kelps are the largest and fastest growing marine algae. The three species growing along the West Coast benefit from the cold, nutrient rich waters of the Benguela Current that runs northwards along the coast. Kelps use dissolved nutrients such as carbon, nitrogen, and phosphorus present in the water to grow. In waters polluted by excess nutrients (e.g., from agricultural fertilizers), seaweed (including kelp) could take up these excess nutrients and thus act as a biofilter. This has given rise to the use of seaweed in IMTA systems where more than one species from different trophic levels are grown together to complement each other.

Although there have been a few local laboratory and sea-based experiments on kelp cultivation, kelp has never been grown on a commercial scale in South Africa before. The FCDO-BSASA project therefore included several technical components aimed at building a foundation of knowledge on which to build a kelp cultivation industry. These components, included the following aspects:

1. Kelp nutrient production and removal model for Saldanha Bay.
2. Kelp seeding and growing in a laboratory environment
3. Study of nutritional values of different species of seaweed
4. Study of the appropriate technologies for kelp cultivation
5. GIS study to assess areas available for commercial cultivation.

The kelp nutrient production and removal model for Saldanha Bay assumes that a maximum of 30% of the Saldanha Bay ADZ could be used for kelp production, and that production levels like those achieved for sugar kelp (10 kg/m or 250 t p.a.) elsewhere in the world could be achieved. If it is further assumed that the minimum farm size is 3.75 ha, with annual production of 250 t each, this would translate to 71 kelp cultivation farms producing 17 680 t kelp p.a. (1768 t dry weight). The nitrogen removal capacity of kelp in 30% of the Saldanha Bay ADZ was estimated at 0.05 t/ha p.a., and the CO_2 removal capacity at 5 t/ha p.a.

The kelp seeding and growing experiments took place at the DFFE Marine Research Aquarium in Sea point, and at Viking Aquaculture's abalone farm in Buffeljags, Gansbaai. At the Marine Research Aquarium, hatchery capacity was developed and the trials on production of gametophytes and sporophytes of *E. maxima* and *L. pallida* were successful. At Buffeljags, the trial on gametophyte production of *M. pyrifera* was not as successful. Follow-on funding would enable the trials to continue. Expected outcomes would be further understanding why some trials were successful, what can be done to make the unsuccessful trial work and understanding the conditions to accelerate the growth of the other two in the laboratory and in the sea.

A study on the nutritional values of the three kelp species was conducted to generate data and information that could be used in development of value-added products using nutritional and functional ingredients from kelp for human consumption and animal feeds. The proximate (protein, lipid, carbohydrate, moisture, and ash content) and fatty acid composition of samples of *E. maxima, M. pyrifera* and *L. pallida* were analysed by the Cape Town University of Technology. Results of these tests are expected by June 2022 and will be shared with the FCDO. It will also be added as an appendix to this report.

A study of the appropriate technologies for kelp cultivation was based on site selection and a cultivation system design for the set-up of pilot cultivation systems. Suitable sites were identified in Small Bay and Big Bay (Saldanha Bay) which are part of the shellfish farming areas of West Coast Oyster Growers. These sites already have water leases, research permits and mooring systems in place, which will reduce the costs and timeline for pilot studies. A rope raft was designed and constructed. Preparations of the site where it will be installed for the pilot cultivation trials, are in progress. Follow-up funding will enable the testing and monitoring if the suitability of these raft systems and enable mitigation or adaptation of the design to optimise future use.

A Geographical Information System (GIS) study was conducted to identify areas along the West Coast (west of Agulhas to the mouth of the Orange River). The report prepared by Dr Melanie Lück-Vogel entitled "Offshore GIS study of available area for commercial kelp cultivation along South Africa's west coast" is included in this report as Appendix C. Based on this study, ten potentially suitable areas for offshore kelp cultivation were identified for the open West Coast, Saldanha-St Helena area, and the southern study area.

A GIS analysis of the Saldanha Bay environment indicated that the inshore areas within the ADZ were regarded in general as suitable for kelp cultivation, however stratification of the water column in Inner Bay in March may restrict kelp production in Small Bay and Big Bay during certain seasons. The higher wave energy associated with Outer Bay North and Outer Bay South may be a positive indicator for kelp cultivation. Due to the limited number of sheltered areas for aquaculture, there is a need for offshore kelp cultivation. Follow-on funding will enable further investigation of the potential implications of offshore kelp cultivation on marine mammals, and mitigation measures that could be taken.

Local context – Indication of fit

Aquaculture activities already take place in an approved ADZ in Saldanha Bay. Abalone farming occurs along the study area. Aquaculture development is supported by government, industry, and other stakeholders. An existing kelp industry has been in existence for decades and is based on harvesting and collection of kelp from natural populations. The growth of this industry is constrained by biomass limitations in the southern parts of the West Coast, and by limited demand in the northern parts. Therefore, a study of this kind, and follow-up funding, will benefit the industry if successful cultivation could lead to increased biomass that could be used to develop more value-added product, enable economies of scale and reduced costs of production, develop the demand and industry in the northern part of the West Coast, and provide access a larger share of the global kelp markets. The coastal towns and villages along the study area have a long history of maritime and fishing industries, and growth of the kelp cultivation industry is likely to contribute to the creation of jobs and access to economic opportunities for people in these communities.

There is support for seaweed cultivation through many local, national, and international initiatives. Kelp cultivation has been successfully practiced in East Asian countries for decades. There is growing interest in kelp cultivation and development of new kelp uses and products elsewhere in the world, including a kelp farm under development in Namibia. This is a positive development, allowing for the exploration and development of regional partnership opportunities and cross-border knowledge and innovation transfer.

The kelp cultivation opportunity therefore fits very well with the national agenda for aquaculture development, and the international agenda for kelp cultivation.

Financial insights and payback time conclusion

The financial insights are based on the assumptions that a 4-ha kelp farming area will be established utilising a longline production system, and that kelp will be sold into the South African market. It also assumes that cultivation will take place in the existing Saldanha Bay ADZ, on one of the aquaculture farms that already have marine aquaculture rights and permits, and a lease for sea water space in place. The results indicate that at production of 1000 t p.a., projected sales of R2 037 500 and establishment cost of R7 335 000, a payback period of 3.6 years is achievable and indicates a potentially viable kelp farming operation.

Summary and conclusion

The recommendation from this study is to proceed with a techno-economic feasibility study to generate the data and information needed to support a decision to invest in a kelp farming opportunity. The feasibility study should include detailed market and technical research, and financial modelling. This will require follow-on funding from the pre-feasibility study phase, and should include the following:

1. Continuation of laboratory-based seeding and cultivation of all three species of kelp
2. Continuation of raft-based kelp cultivation trials in Saldanha Bay
3. Design, manufacture, installation, and operation of a pilot offshore kelp cultivation system in one of the areas identified during the pre-feasibility GIS study
4. Product and market development for kelp and kelp-derived products
5. Testing of kelp products in the market
6. Additional stakeholder engagement
7. Food safety testing/certification
8. In-situ environmental testing.

TABLE OF CONTENTS

GLOSSARY OF TERMS

AASA	-	Aquaculture Association of Southern Africa
AquaSA		Aquaculture Association of South Africa
ADZ	-	Aquaculture Development Zone
ANOVA	-	Analysis of variance
AOAC	-	Association of Official Agricultural Chemists
BSASA	-	Bivalve Shellfish Farmers Association of South Africa
BCLME		Benguela Current Large Marine Ecosystem
CAGR	-	Compound Annual Growth Rate
CPUT	-	Cape Town University of Technology
CSIR	-	Council For Scientific and Industrial Research
DFFE	-	Department of Forestry, Fisheries, and the Environment
DW	-	Dry weight
EF	-	Evidence Funding
FCDO	-	Foreign, Commonwealth & Development Office
FW	-	Fresh weight
GIS	-	Geographic Information System
IMTA	-	Integrated Multi-Trophic Aquaculture
ISO	-	International Organisation for Standardisation
MPA	-	Marine Protected Areas
PVC	-	Polyvinyl chloride
SOP	-	Standard Operating Procedure
SA	-	South Africa
SRCA	-	Seaweed Rights Concession Areas
UCT	-	University of Cape Town
US	-	United States
t	-	Tonne
ASTRAL	-	All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture
ZAR	-	South African Rand

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

More than 99% of the world's seaweed production (including kelp) is grown through aquaculture, with over 99% in East Asia. Kelps are large brown seaweeds, which only occur in cold and warm temperate seas. In recent years, there has been a significant increase in current and potential uses of seaweed (including kelp) e.g., for food and food supplements, nutraceuticals, climate change mitigation, etc. There has also been a lot of interest recently in kelp aquaculture in Europe and North America.

South Africa has a diverse seaweed flora, with more than 850 recorded species. There are four species of kelp in South Africa including *Ecklonia maxima*, *Ecklonia radiata*, *Macrocystis pyrifera* and *Laminaria pallida.* Economic exploitation of this resource started decades ago with collection of beach-cast material, drying, and exporting for alginate extraction, and the use of freshly harvested kelp for abalone feed and production of a plant growth enhancer. This industry is based on the harvesting and collection of kelps from natural kelp beds. These activities are subject to seaweed concessions with limitations on the amounts that can sustainably be harvested on an annual basis. The size of the kelp industry is about 10 000 tonnes (t) per annum (p.a.), and significant expansion will be reliant on successful kelp cultivation on a commercial scale. Although kelp has been grown successfully under experimental conditions (laboratory and sea-based) in South Africa, it has never been grown successfully on a commercial scale in the country. There is thus significant interest in the establishment of commercial kelp aquaculture in South Africa.

The Bivalve Shellfish Farmers Association of South Africa (BSASA) is an independent non-profit organisation which promotes the interests of the bivalve shellfish (mussel and oyster) farming industry. It is the only sea-based industry in South Africa, and is mostly based in Saldanha Bay, Western Cape. There are also other aquaculture activities in the area. It therefore made sense that the interest in kelp aquaculture, which uses similar farming practices, can be implemented by this sector. In collaboration with key government and research entities, the BSASA applied for and received an allocation of Evidence Funding (EF) from the Foreign, Commonwealth & Development Office of the Government of the United Kingdom (FCDO) to set up a South African Kelp Project. This project was a collaborative effort involving the aquaculture industry, government, research institutions and academic institutions. The aim of the collaborative approach was to make the outcomes of the research available to broader stakeholders, existing sector, and all new potential entrants into the sector.

The project focused on three kelp species occurring along the West Coast (between Cape Agulhas and the mouth of Orange River). including *E. maxima* (sea bamboo), *M. pyrifera* (bladder kelp) and *L. pallida* (split fan-kelp)*.* The main aim of the project was to conduct a pre-feasibility study to assess the potential for kelp cultivation in South Africa. This included synthesizing available biological, environmental, and economic information, and setting up facilities for conducting initial experiments on kelp seeding. Additional activities included the following:

1. Investigation of the use of kelp cultivation as an Integrated Multi-Trophic Aquaculture (IMTA) platform to improve the sustainability of existing aquaculture activities in Saldanha Bay
2. Investigation of the potential for coastal commercial kelp cultivation to provide value chain opportunities to coastal communities along the West Coast.

The FCDO-BSASA Pre-feasibility Study on the potential for commercial cultivation of African kelp along South Africa's West Coast consisted of the following three project components:

1. **Project Component 1:** Understanding the methodology for laboratory production of gametophytes and sporophytes in a laboratory environment:
    a. Kelp seeding and growing experiments in laboratory environments at an abalone farm in Buffeljags, Western Cape and the Department of Forestry, Fisheries, and the Environment (DFFE) Marine Research Aquarium at Sea Point, Western Cape.
    b. This study was led by Dr Mark Cyrus and a research team including scientists, research assistants and staff from DFFE, University of Cape Town (UCT), Viking Aquaculture, and other organizations.
    c. Activities commenced in February 2022 and results up to March 2022 were included in this study; the trials are expected to continue beyond March 2022 and will be used to support the proposed kelp raft cultivation pilot in Saldanha Bay, depending on further funding.
2. **Project Component 2:** Understanding the potential for cultivation of three kelp species, requirements for integration with existing aquaculture activities, and optimum products and markets. The following activities commenced in January 2022 and were concluded by 31 March 2022:
    a. Identification and synthesizing of all available relevant information on biology, genetics, growth rates, environmental tolerances, chemical and nutrient composition (conducted by Prof. John Bolton, UCT).
    b. Identification and engagement with aquaculture stakeholders to share scientific findings and establish interest among aquaculture farmers (conducted by DFFE, BSASA, CSIR).
    c. Assessment of the potential of Saldanha Bay and offshore areas as kelp cultivation sites (conducted by the CSIR).
    d. Assessment of the potential of developing seaweed markets/product pipelines), including the following activities:
        i. Determine nutritional value of different species of seaweed (Conducted by DFFE)
        ii. Map the requirements for a seaweed product development chain and market (Conducted by CSIR)
3. **Project Component 3:** Understanding the most appropriate technologies and business models for sustainable joint ventures between industry and coastal communities. The objective was to use the results from the kelp seeding and growing experiments to enable the establishment of a research platform for government and industry stakeholders to continue to derive learning beyond EF allocated in the 2021/22 financial year. Activities were conducted by scientists and staff from University of Cape Town, DFFE, Viking Aquaculture, BSASA, CSIR and other organisations. The following activities commenced in January 2022 and some activities will continue beyond March 2022, depending on further funding:
    a. Site selection and set up of pilot kelp cultivation systems (rope rafts) in Saldanha Bay (conducted by UCT, DFFE, BSASA, Viking Aquaculture), and will continue beyond March 2022.
    b. Cultivation system design (conducted by UCT, DFFE, BSASA, Viking Aquaculture), concluded in March 2022.
    c. Understanding the most appropriate business models, (conducted by CSIR), in conjunction with activities related to Project Components 2.b and 3.a; concluded in March 2022.

This Pre-feasibility Study Report incorporates the results of the tasks performed by all project teams responsible for Project Components 1 to 3, including the activities conducted by the CSIR. The full project team and their details are described in Table 1.

Table 1: Project team details

Title	First Name	Last Name	Organisation	Designation	Email
Dr	Dale C. Z.	Arendse	DFFE	Production Scientist	DArendse@environmentza.onmicrosoft.com
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E/ Prof	John J.	Bolton	UCT	Senior Research Scholar	john.bolton@uct.ac.za
Mrs	Bernadette	Brown-Webb	CSIR	Senior Enterprise Development Specialist	BBrown@csir.co.za
Dr	Mark D.	Cyrus	DFFE	Control Scientific Technician	MCyrus@dffe.gov.za
Ms	Deidre	Du Toit	Viking Aquaculture	Group Technical Manager	deidre@vikingaquaculture.co.za
Dr	Melanie	Lück-Vogel	CSIR	Senior Researcher	Mluckvogel@csir.co.za
Dr	Brett	Macey	DFFE	Specialist Scientist: Aquaculture Research	BMacey@dffe.gov.za
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Ms	Nenekazi	Mtombeni	DFFE	Intern	nenemthombeni@gmail.com
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Mrs	Luanita	Snyman-Van der Walt	CSIR	Senior Environmental Assessment Practitioner	LvDWalt1@csir.co.za
Mr	Barend	Stander	BSASA	Chairperson	Barend@standeraquaculture.com

2 SUMMARY OF SPECIALIST REPORT: KELP AQUACULTURE

Around 10 000 tonnes of kelp are used in South Africa from natural populations every year, mostly for feed in abalone aquaculture, plant growth enhancers, and dried for alginate extraction. Kelps have never been cultivated before in South Africa, except for laboratory experiments and two small trials in the sea. This study provided additional knowledge and experience of laboratory trial of sporulation and cultivation of the three species in South Africa which could be cultivated. Therefore, it was important to understand all aspects of kelps before embarking on the Pre-feasibility Study, and as a precursor to inform the design for a detailed techno-economic study.

A Specialist Report on the potential for kelp aquaculture in the Republic of South Africa was prepared by Emeritus Professor John J Bolton, who has worked with kelps for 40 years. The report mapped out all components of the SA Kelp Cultivation Project, as it identified and synthesised all available relevant information on biology, genetics, growth rates, environmental tolerances, chemical and nutrient composition. The full report is attached as Appendix B. However, an executive summary of the report is presented here to give an understanding of the work done by the different project teams on all aspects of the Project that were used in the preparation of this Pre-feasibility Study Report.

2.1 Executive Summary: Specialist Report on kelp aquaculture

This is a detailed report on the potential for growing large brown laminarian algae (kelps) in South Africa. It includes information on the biology and ecology of South African kelps, their laboratory culture and potential for commercial aquaculture. The potential for growing kelp is discussed in the light of current trends in its use in international aquaculture. Other motivators include the availability of sites for kelp aquaculture on the South African coastline, choice of species, sustainability, and biosecurity considerations.

The Benguela upwelling system on the west coast of South Africa/Namibia is a globally significant region with high levels of available nutrients and sunlight. There are three potential west coast species for kelp aquaculture:

- *E. maxima* - grows predominantly in Southern Africa
- *L. pallida* - grows mainly in Southern Africa, and
- *M. pyrifera* - globally widespread and rare in South Africa.

Around 7 000 -10 000 tonnes of kelp are used in South Africa each year from natural kelp forests, mainly cut fresh for feed in abalone aquaculture and agricultural plant growth stimulant. Only a few tonnes are collected as washup and dried for overseas alginate production. Globally, there is a very long and rapidly growing list of actual and potential uses for kelp, and a move toward the use of the 'biorefinery principle' where seaweed biomass can be converted into different economic products. This includes a mixture of high-value niche products and low value commodities for increased economic efficiency.

Although seaweed represents more than half of world marine aquaculture production (ca. 35 m tonnes, worth US$ 14.7 billion), this is almost all grown in East Asia. There are significant moves currently to expand seaweed production into the Western Hemisphere, and the background to this is explained.

Kelps have never been grown in commercial aquaculture in Southern Africa before, and there is limited information available on many aspects of local kelp growth in aquaculture. Kelps release billions of tiny spores, which produce the microscopic stage of kelps, known as the gametophyte. These and the resulting juvenile kelp plants must be cultivated for a period in land-based climate-controlled hatcheries. After several weeks, strings seeded with spores from the hatchery are placed on rope rafts in the sea. Methods used elsewhere for hatchery growth and rope raft construction are summarised.

Kelp raft cultivation is carried out elsewhere in relatively sheltered bays and inlets, although there is an international move, particularly in the North Atlantic, to grow kelps on larger structures further offshore in the open sea. This will require significant marine engineering input and many countries are mapping the space they have available offshore for these activities.

There have been a few local laboratory experiments on small kelp stages and the entire life history of *E. maxima* and *L. pallida* has been completed (once) in the laboratory and the sea. *Macrocystis* is the only local species which can regenerate from its base (holdfast). A short (three-month) experiment grew *Macrocystis* successfully from holdfasts on a rope raft in Saldanha Bay. The logical place to begin kelp cultivation trials in South Africa is Saldanha Bay, where seaweeds have been cultivated before and aquaculture infrastructure is in place. A protected nearby area in St Helena Bay, where the red seaweed *Gracilaria* has been successfully grown before, is also a possibility.

Two main biosecurity concerns with kelp aquaculture involve the potential for the following:

- spreading kelp diseases and
- affecting the genetics of natural kelp forests if material (usually as cultured gametophytes) is moved between different regions.

Although biosecurity measures can be implemented, all three relevant species grow in or close to Saldanha Bay, so these need not be initial concerns here.

Unlike 'fed' aquaculture (e.g., fish and shrimps) kelp is 'extractive' aquaculture. The major kelp nutrients, especially the potentially polluting macronutrients nitrogen and phosphorus, are present dissolved in the water and are removed by the kelp. This has given rise to the idea of IMTA where seaweeds such as kelp are grown close to, and linked with, other aquaculture facilities, thus removing dissolved waste nitrogen and phosphorus released by other aquaculture activities. Saldanha Bay is a good site to test these ideas locally.

Kelps have regular seasonal growth patterns which are critical in kelp aquaculture. From the limited local literature available it appears that local kelp growth correlates with available sunlight, growing fastest in summer. This is different from kelps grown elsewhere which tend to grow fastest in late winter/early spring, with slow growth in summer. In the North Atlantic, levels of major kelp nutrients in seawater are very low in the summer, whereas in the South African open west coast these nutrient levels are high due to summer upwelling.

In the North Atlantic there is evidence that some kelp species store nitrogen and carbon seasonally for use in later growth. *E. maxima* can store nitrogen in the short-term (at upwelling events) but there is no evidence that local *Ecklonia* or *Laminaria* have a seasonal pattern of nitrogen (and hence, protein) storage.

There are mainly four potential environmental factors that limit kelp growth in aquaculture in South Africa. These are:

- Seawater temperature,
- Water flow/wave action,
- Levels of dissolved nutrients (usually negatively correlated with water temperature), and
- Light (linked to depth).

Local west coast kelps are generally limited in their distributions, not present where monthly mean seawater temperatures are over 20°C. Small hatchery stages of local *E. maxima* and *L. pallida* grow well at 15°C. Unlike those two species, *Macrocystis* does not grow east of the Cape Peninsula, possibly because of its more limited tolerance to high temperatures, and elsewhere a temperature of 12°C is recommended for growth of small stages of this species.

Wave action has both beneficial and negative effects on kelp aquaculture. Kelps require sufficient water flow to enable them to take up the required dissolved nutrients and *E. maxima* thrives in quite considerable water motion. *Macrocystis*, on the other hand, only grows in South Africa in particularly wave-sheltered habitats. Extreme wave action can be very detrimental to kelp raft infrastructure and reliable anchoring of rafts is critical.

In the open sea on the South African west coast, levels of the major macronutrient nitrogen are inversely correlated with seawater temperature and are generally available year-round. This is not the case in the Inner Bay in Saldanha where around March stratification occurs, with a warm, nutrient-poor layer of water floating on top of a cooler nutrient-rich layer (the latter around 6m deep). Previous aquaculture operations growing the red seaweed *Gracilaria* were successful year-round apart from crashes of seaweed biomass in March, which may also affect kelp cultivation in the Bay.

Seawater absorbs light, and turbid seawater absorbs light much faster than clear water. Elsewhere kelps are generally grown shallowly, e.g., from 0.5 to 2m in Japan. The red seaweed *Gracilaria* grew fastest at 0.5m depth in Saldanha Bay. This knowledge was incorporated into the raft design for this study, so that initial kelp aquaculture operations would include angled lines from 0.5 to 4m depth to ascertain comparative growth rates with depth.

Low salinity is only likely to be a problem with kelp aquaculture in South Africa close to river mouths. Low oxygen events (especially 'black tides') and perhaps periodic warm events can damage kelps and must be considered as sporadic risks to kelp aquaculture in certain parts of the South African coastline.

Epiphytes (other seaweeds and marine animals growing on the kelp) tend to become a problem in kelp aquaculture when kelp growth slows down. It is hypothesised that this may occur in later summer/early autumn in South Africa, but no data of this is available so far. Testing of this hypothesis could be included in a follow-up study. In natural and local kelp forests there are few epiphytes except on kelps a few years old, and then they mostly consist of four specific epiphyte seaweed species which grow on particular species of kelp.

The limited available information on the chemical composition of local kelp species is summarised. Kelps generally have a high ash content and are very good dietary sources of micronutrients. They have a relatively low (10-12%) crude protein content. Apart from the alginate content and the occurrence of plant hormones in *E. maxima*, which have been commercially exploited for many years, there are recent studies on the potential for nutraceutical products from this species. There is a move in the North Atlantic to increasingly produce human food and nutrition products from kelps.

Although *Gracilaria* spp. are economically important, the main commercially used kelp in South Africa has always been *E. maxima*, and that species should be a target of cultivation. Due to local kelp supply constraints and consistency of availability, a local abalone farm (Viking aquaculture) recently initiated a trial for the cultivation of *Macrocystis*. This is the only local species which has been cultivated on a large scale elsewhere (particularly in Chile) and appears also to be good feed for the locally farmed abalone. Relatives of local *Laminaria* are the target of cultivation trials elsewhere, and it is recommended that all three species should be tested locally in a collaborative approach with industry, academia and government to pool resources and maximise knowledge generation for broad range of stakeholders.

Potential cultivation of South African kelps is still at a very early stage and there are many unknown elements. The following questions need to be answered:

- Which of the three species grows best in aquaculture conditions?
- How easy are they to propagate on a large scale?
- What are the characteristics and potential commercial benefits of 8-month-old cultivated plants of the different species, and are they different from adult plants from natural kelp forests?
- Can new uses be found for cultivated kelp material?
- Can local kelp cultivation be economically viable at scale?

The pre-feasibility study provided an opportunity to start with laboratory-based growth experiments of the three species under consideration, which will be used on an experimental raft under sea-based aquaculture conditions. The study also provided some indications of new uses for cultivated kelp that could be tested once sufficient material is available, and an indication of potential viability. However, there is much work to do before South Africa has a viable kelp aquaculture industry. A full feasibility study on commercial kelp cultivation will be needed to test the growth conditions of the three species in sea-based conditions for at least one year, but ideally three years, to conduct further tests on the characteristics of the cultivated biomass, develop products based on this biomass, test those products in the market, and do financial modelling to determine the viability of local kelp cultivation at scale.

2.2 Structure and purpose of the Specialist Report

The Specialist Report (Appendix B) addresses the following aspects of kelps:

1. Introduction to kelps
2. Why grow kelp in South Africa?
3. Methods of kelp aquaculture
4. Environmental aspects of South African kelp aquaculture
5. Southern African kelp nutrition, physiology, and chemical composition.

The FCDO-BSASA Kelp project included several technical components aimed at building a foundation of knowledge on which to build a kelp cultivation industry. The Specialist Report provided the theoretical foundation for the research teams to plan and execute these components, which included the following:

1. Kelp seeding and growing in a laboratory environment
2. Study of nutritional values of different species of seaweed
3. Study of the appropriate technologies for kelp cultivation
4. GIS study to assess areas available for commercial cultivation
5. Kelp nutrient production and removal model for Saldanha Bay.

The emerging evidence on some of the above is that kelp can be grown in a laboratory environment, that there is enough information and technical expertise available to design and build a rope raft for sea-based cultivation of kelp in South African waters, that there are about ten offshore areas along the West Coast potentially suitable for offshore cultivation of kelp, and that the potential N and CO_2 removal capacity of kelp in the Saldanha Bay ADZ is between 12 and 47 kg/ha^{-1} and 1.2 to 5 t/ha respectively.

3 PRE-FEASIBILITY STUDY METHODOLOGY AND APPROACH

The Scope of Work specific to the activities falling under the responsibility of the CSIR included the following:

a) Co-ordination and collation of relevant reports, outputs, and monthly progress reports.
b) Focused stakeholder engagement with key specialist and value -chain stakeholders to inform commercial, community and sustainable production. These included:
    i. Continuous engagement of Emeritus Professor John Bolton to provide insights and guidance on different aspects of the study
    ii. Attendance of expert webinars such as Dr Sarah Fawcett's webinar on contrasting nutrient dynamics of the northern and southern Benguela upwelling systems
    iii. Attendance of an EU- integrated multi-trophic aquaculture participatory workshop that forms part of the All Atlantic Ocean Sustainable Profitable and Resilient Aquaculture (ASTRAL) project
    iv. Engagements with government officials for insights on specific aspects such as kelp value chain opportunities in coastal communities
    v. Engagements (email questionnaires) with industry to gather high-level market insights about the kelp industry
    vi. A stakeholder workshop where initial results of the pre-feasibility study were presented, and stakeholder feedback obtained to finalize the Pre-feasibility Study Report.
c) Collaborate with relevant scientists and DFFE staff to assess potential link with other aquaculture activities in the Saldanha Bay (using African kelp as IMTA platform to improve aquaculture sustainability by applying a 'circular' use of waste for more efficient economically and eco-friendly production for aquaculture farmers). This entailed the review and synthesis of existing data and other desk-top research to understand opportunities for sea-based aquaculture, including:
    i. Mapping area available for commercial production in Saldanha Bay (based on environmental conditions and approved lease sites)
    ii. Modelling how much kelp might be produced (based on basic nutrient calculations) and how much nutrients could be removed.
d) Offshore GIS study of the available offshore area for kelp cultivation using existing shapefiles/data available.
e) An enterprise-development desktop study to map the inputs needed for commercial kelp cultivation, constraints, market potential and value chain opportunities. This included mapping the requirements for a seaweed product development value chain.

Based on the above, and its understanding of how these activities fit into the broader FCDO-BSASA SA Kelp Project, the CSIR proposed to conduct the work as part of a Pre-feasibility Study, incorporating the results from the other project components.

A pre-feasibility study is a preliminary study done to determine if it would be worthwhile to proceed to the feasibility study stage. It is used to clearly describe and define a potential opportunity, is qualitative, and is based on high-level information, estimates, and assumptions.

In contrast, a feasibility study is used to support a decision to invest in an opportunity, and to check the viability of establishing an enterprise. It is quantitative, and based on detailed market and technical research, and financial modelling.

For the execution of this project, the CSIR followed a tried and tested Pre-feasibility Study Process as described in Figure 1.

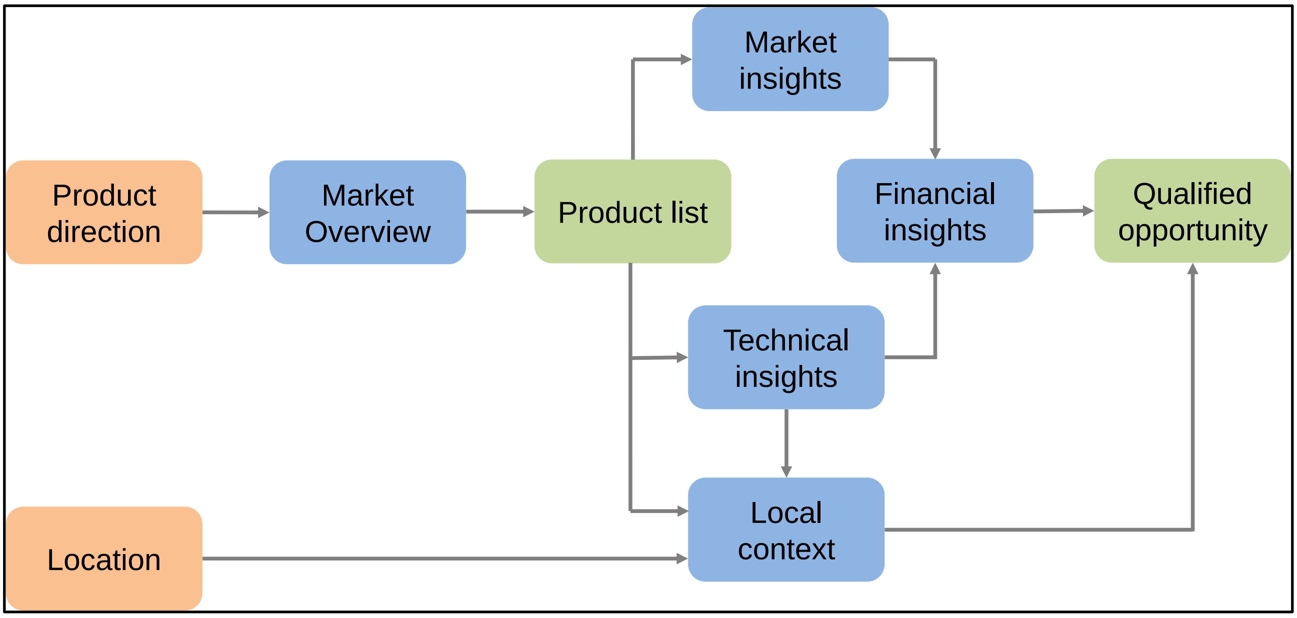


Figure 1: Pre-feasibility study process

4 REFINED OPPORTUNITY DESCRIPTION

4.1 Introduction

The FCDO-BSASA SA Kelp Cultivation Project's strategic objective was to conduct a pre-feasibility study to assess the potential for kelp cultivation in South Africa. This included synthesizing available biological, environmental, and economic information, and setting up facilities for conducting initial experiments on kelp seeding. Further activities included the investigation of kelp cultivation as an IMTA platform to improve sustainability of existing aquaculture farmers, and investigation of value chain opportunities for coastal communities. The study area is presented in Figure 2, and includes the offshore area of the West Coast of South Africa (west of Agulhas to mouth of Orange River), and the inshore area of Saldanha Bay, which is a hub for marine aquaculture with a formalised Aquaculture Development Zone (ADZ).

Kelp forests occur naturally along most of the study area, as do most of the South African abalone farms. The current kelp industry is based on fresh and dried kelp that are harvested from natural populations or collected as beach-cast by seaweed concessionaires. This is a finite resource, indicating that significant growth of the kelp industry depends on successful kelp cultivation. Global kelp production through aquaculture is estimated at 12.3 million t.

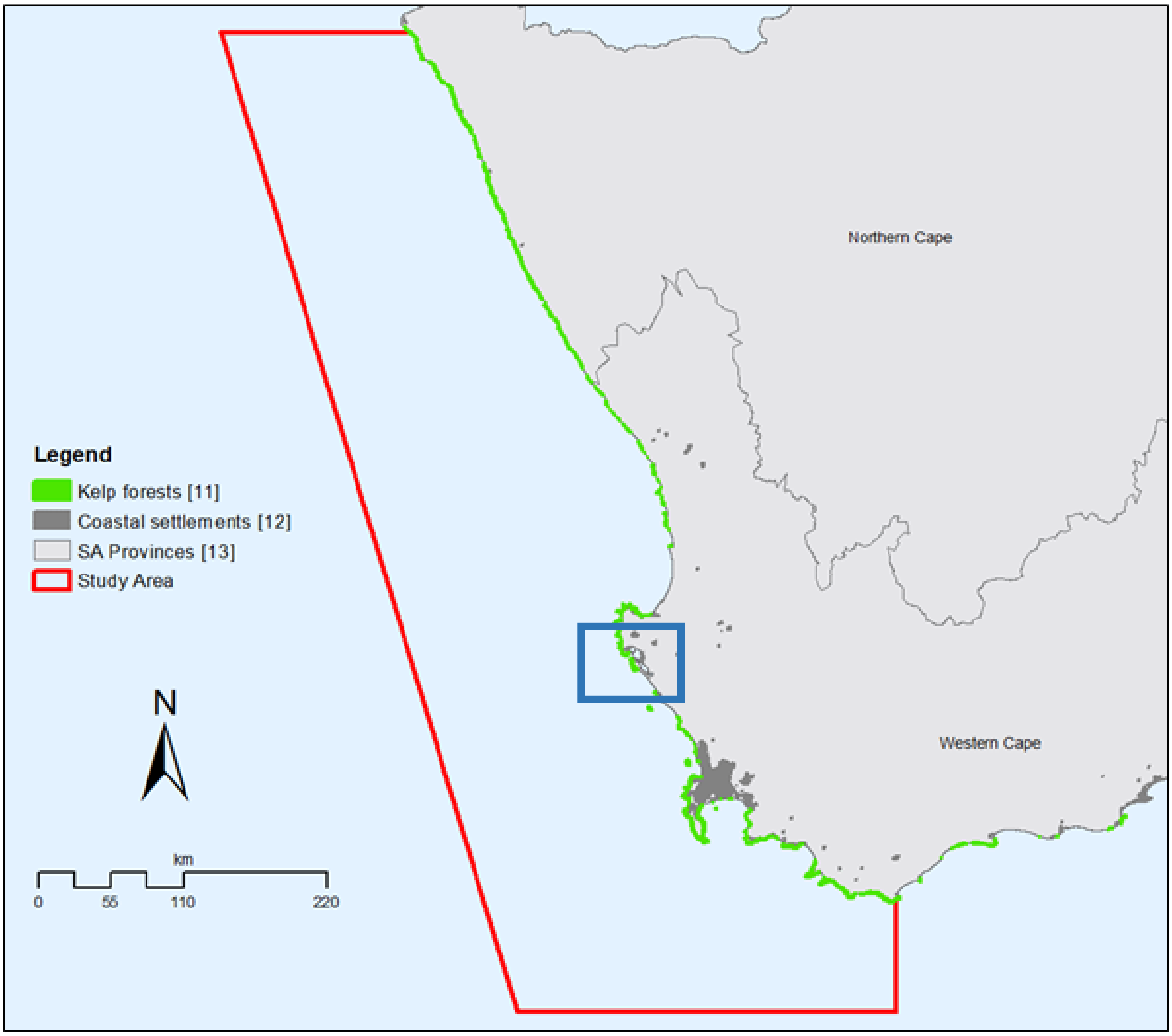


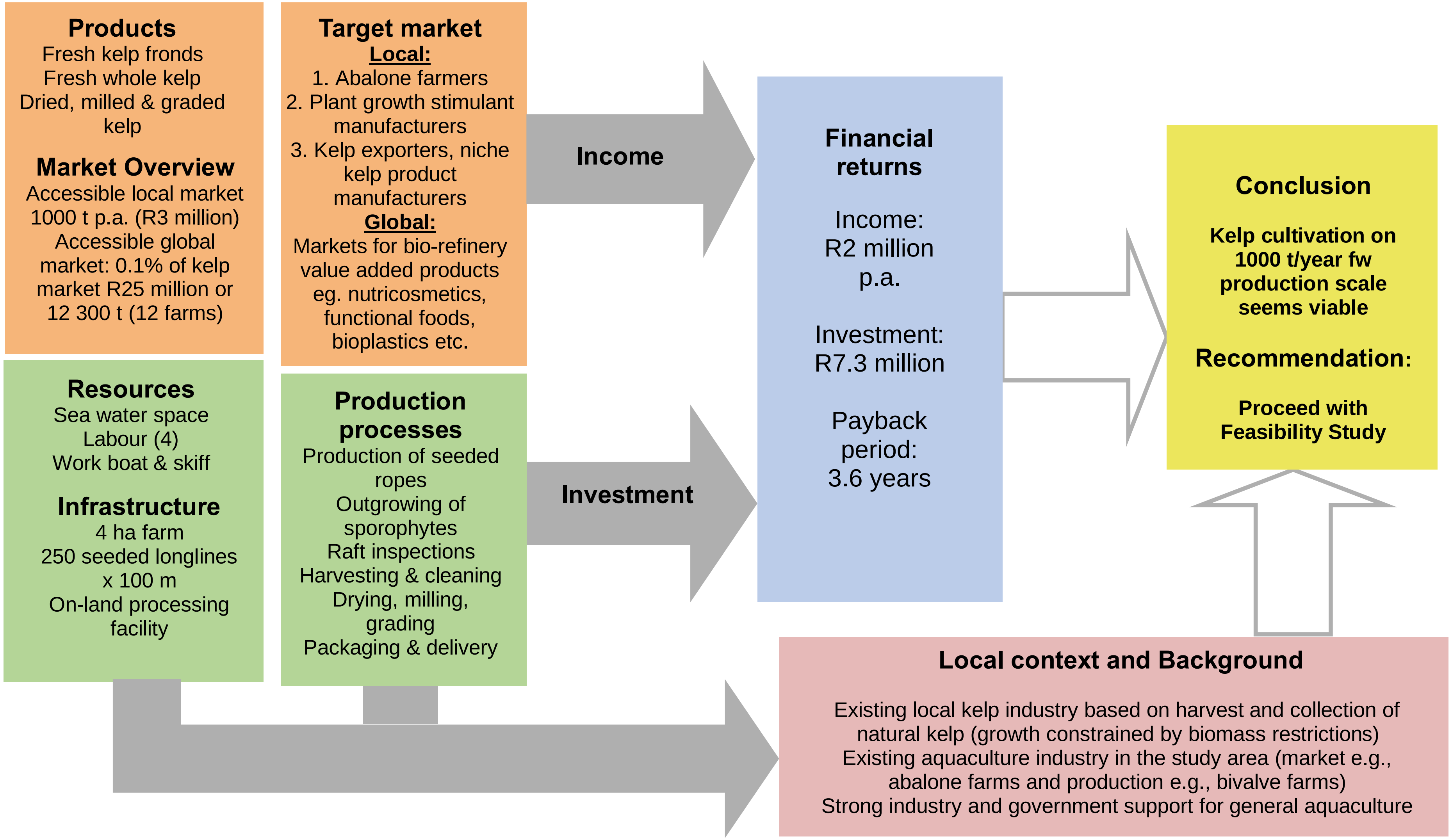
Figure 2: The study area included in the pre-feasibility study

The opportunity is summarised in the diagram below. The following assumptions were made:

- Products from the farm include fresh kelp (blades and stipes), and dried kelp
- Average kelp production is 20 kg fresh weight/m/harvest (double the average obtained for sugar kelp experiments elsewhere in the world), with two harvests per year
- The initial accessible local market is 1000 t p.a., (10 % of the local kelp industry) valued at R3 million
- The potential accessible global market is estimated at 12 300 t (0.1% of global aquaculture kelp market of 12.3 million t); this could translate to about 12 farms
- The local target market is abalone farmers, manufacturers of plant growth stimulants, kelp exporters and niche product manufacturers
- A 4-ha farm with 250 longlines could produce 1000 t kelp per year, with sales income of about R2 million; Given the estimated amount of kelp that could potentially be produced in Saldanha Bay (about 17 750 t), this is not finite but could be grown with market development
- The establishment cost of the farm is R7.3 million
- The estimated payback period is 3.6 years.

At the pre-feasibility study stage, it is not possible to recommend a specific business model. The appropriate corporate form option or business model (e.g., joint ventures, contract farming etc.) will be situation-and area specific. It will be dependent on the nature and size of the opportunity, the role players involved, the objectives of the opportunity and type of funding available.

The conclusion is that an initial 4 ha farm producing 1000 t kelp per year and sales income of about R2 million could be viable, with potential for additional farming with market and value chain development. The recommendation from this pre-feasibility study is therefore to proceed with a feasibility study.


Products
Fresh kelp fronds
Fresh whole kelp
Dried, milled & graded kelp
Market Overview
Accessible local market 1000 t p.a. (R3 million)
Accessible global market: 0.1% of kelp market R25 million or 12 300 t (12 farms)
Target market
Local:
1. Abalone farmers
2. Plant growth stimulant manufacturers
3. Kelp exporters, niche kelp product manufacturers
Global:
Markets for bio-refinery value added products eg. nutricosmetics, functional foods, bioplastics etc.
Income
Financial returns
Income: R2 million p.a.
Investment: R7.3 million
Payback period: 3.6 years
Conclusion
Kelp cultivation on 1000 t/year fw production scale seems viable
Recommendation:
Proceed with Feasibility Study
Resources
Sea water space
Labour (4)
Work boat & skiff
Infrastructure
4 ha farm
250 seeded longlines x 100 m
On-land processing facility
Production processes
Production of seeded ropes
Outgrowing of sporophytes
Raft inspections
Harvesting & cleaning
Drying, milling, grading
Packaging & delivery
Investment
Local context and Background
Existing local kelp industry based on harvest and collection of natural kelp (growth constrained by biomass restrictions)
Existing aquaculture industry in the study area (market e.g., abalone farms and production e.g., bivalve farms)
Strong industry and government support for general aquaculture

5 MARKET INSIGHTS

The focus of this section of the report is to understand the existing and potential markets for seaweed, kelp in general and the kelp species in South Africa, and to get a preliminary indication of unmet demand and the growth opportunity.

Algae or seaweed are simple, non-flowering and typically aquatic plants that include macro-algae (visible to the naked eye) and micro-algae (unicellular forms invisible to the naked eye). They contain chlorophyll but lack true stems, roots, leaves and vascular tissue. Marine algae are found in coastal areas and are typically attached to rocks or other hard substances. Algae species mainly belong to three main groups based on their thallus (plant body) colour (red, brown, or green). Other types include golden-brown, or yellow-green algae.

Brown seaweeds or algae belong to the Class Phaeophyceae in the Phylum Ochrophyta, in which the green chlorophyll pigments are usually masked by a brown pigment called fucoxanthin. Large brown algae or kelps belong to the order Laminariales. Cultivated kelps are eaten by humans and abalone in aquaculture environments. In nature most kelp production is consumed by filter feeders and bacteria.
Brown algae contain alginates, which are extracted and used as thickening agents in food, in pharma and textile printing applications, and as stabilisers in the battery ionisation process. They are also combined with calcium salts to form calcium alginates. These are used in food and other industries or converted into fibres and used to produce surgical dressings (BCC Research, May 2021).

The main commercial sources of kelp are:
- *Saccharina japonica* grown in China
- *Ascophyllum* and *Laminaria* species from Europe,
- *Lessonia* species from South America, and
- *Macrocystis* from Baja California (Mexico) and Chile.

5.1 Product direction

The major applications of seaweed and 2020 market volumes and values include the following (BCC Research, May 2021):
- Human food such as kombu, nori or wakame, utilised raw or sun-dried (12.7 million t, US$ 7.6 billion)
- Raw material for hydrocolloids (polysaccharides) or gums such as alginates, carrageenan, and agars (15.7 million t, US$ 11.6 billion)
- Others such as plant bio stimulants and bio-energy (2.3 million t, US$ 1.4 billion).

Globally there is an increase in current and potential uses of seaweeds for food and food supplements, health benefits and nutraceuticals, animal feed, functional foods, fertiliser and plant growth enhancers, textiles, bioplastics, potential for biofuel, integration in climate change mitigation and carbon credits.

Kelp is used as a source of iodine, potash and other salts, acetone, kelp char, seaweed gums/alginates (for use in the drug, food, and other industries). In 2016, the demand for kelp was expected to increase at a CAGR of 13.6% to reach US$1.7 billion in 2021 (Gobina, 2016).

The three kelp species that predominantly occur along the West Coast, including *E. maxima, M. pyrifera, and L. pallida.* There is a unique species, *E. maxima,* that is mainly found on the Southern Atlantic coast of Africa and particularly the south-west coast of South Africa. It is the main kelp species collected, and used to produce alginate, animal feed, fertilisers, and plant bio stimulants. In the 1970s, Kelp Products Ltd. started using a patented cold-pressure process to extract a liquid fertiliser from this species, which is used to enhance crop yields. Another South African company, Afrikelp (Pty) Ltd, also started producing a similar product.

M. pyrifera (Laminariales), widely known as 'giant kelp', is recorded in South Africa and limited information is available on its distribution and ecology. It is confined to sheltered sites inside forests of the dominant kelp (typically *E. maxima*), along only ca. 200 km of coastline on the cool temperate southern west coast (Fleischman, et al., 2020). The species is used for alginate extraction, for applications in the food and pharmaceuticals industry. It is also used as fresh feed in the abalone aquaculture industry, for dietary supplements and as an ingredient in animal and fish feed. The properties associated with the polysaccharides and proteins from this species have resulted in increased interest in them, enabling their use as functional foods. Improvements and optimisations in aquaculture methods and bioproduct extractions are essential to realise the commercial potential of these seaweeds (Broch, et al., 2019).

Laminaria was used in a commercial trial in the Namibian seaweed industry, to produce 'Kombu', however the product was deemed unsuitable by consumers (Molloy, 1998). *L. pallida* and *Gracilariopsis funicularis* was also used in a recent study on the potential of Namibian beach-cast seaweed biochar as a potential nutrient source in organic agriculture (Katakula, et al., 2020). In South Africa, both *L. pallida* and *E. maxima* are harvested for commercial purposes. However, *L. pallida* makes up a smaller portion of the harvest because *E. maxima* is surface-reaching and therefore easier to harvest from boats (Rothman, et al., 2020). *E. maxima* would therefore be a good focal species for near term future work. A full feasibility study should make provision for testing of the three kelp species under investigation for at least one, but ideally for three years, in the study area.

Kelp is currently used in South Africa as abalone feed (about 70% of the market), plant growth enhancers (about 25%), an export commodity for alginate extraction, and locally as an animal feed additive (collectively about 5%). It is also used as an ingredient in compost tea and a moisture retainer for agriculture and horticulture purposes. The kelp industry is based on kelp that are harvested or collected as beach-cast by seaweed concessionaires. These concessions are subject to Maximum Sustainable Yields (based on 6-10% of estimated standing seaweed biomass) (Troell, et al., 2006). Future expansion of the South African kelp market would require kelp cultivation to increase biomass availability.

Potential future uses of cultivated kelp in South Africa include the extraction of other kelp-derived ingredients, nutraceuticals, functional foods, textiles, bioplastics, biofuel, and integration in climate change mitigation and carbon credits. The Saldanha Bay Industrial Development Zone (SBIDZ) caters to the energy and maritime industries. Synergies for cooperation in areas such as renewable energy, additional uses of *L. pallida* e.g., for biochar, and climate change mitigation should be explored during a follow-up phase of this project.

5.2 Market overview

5.2.1 General overview of the sector

In South Africa, the total market for kelp is about 7 000 to 10 000 t p.a. As summarised in Table 2, the total yield in 2020 was 5 056 t (wet and dry weight) (Dr M Rothman, personal communication).

Table 2: Local seaweed yield in 2020

Seaweed yields 2020	Tonnage produced (t)	Percentage of total yield
Kelp harvested for abalone feed (FW)	3 560	70%
Kelp harvested for growth enhancer (FW)	1 250	25%
Beach-cast kelp for export and local products (DW)	246	5%

The biggest market for kelp is currently for abalone feed. As illustrated in Figure 3, fresh beach-cast and harvested kelp (used as abalone feed) rose to 7 000 t by 2011 but dropped since then (Rothman, et al., 2020). This market is primarily limited to the Western Cape and due to the need for fresh kelp within proximity of the abalone farms, local demand can exceed supply in some areas (A. Bernatzeder, personal communication). Production of kelp use for plant growth enhancers is the second biggest market and has shown steady growth over several years to over 3 000 t p.a. by 2017. The demand for dry beach-cast kelp used for drying, export and local sales has drastically reduced from around 5 000 t in the 1970's to 482 t in 2017 (Rothman, et al., 2020). The export and local markets for dried kelp are also influenced by global market fluctuations and prices, and by limitations on allowable harvest.

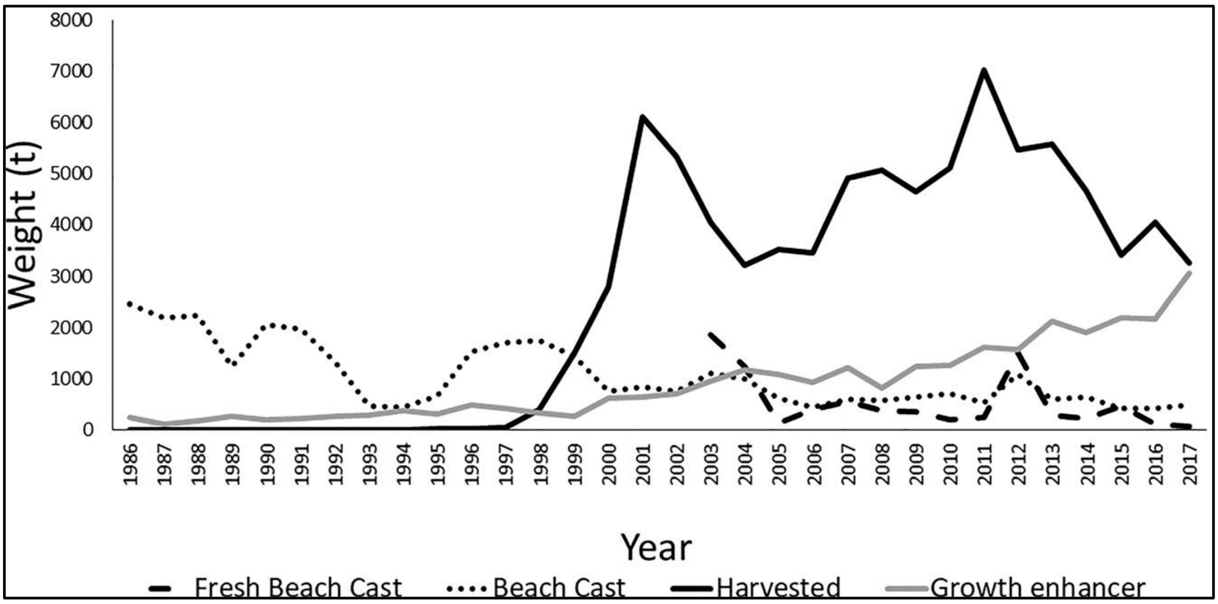


Figure 3: Kelp yields in South Africa from 1986 to 2018

Source: (Rothman, et al., 2020)

5.2.2 Specific conditions and factors that prevail

There seems to be substantial evidence of a growing cottage industry driven by food businesses and restaurants that seeks fresh from the sea ingredients for preparation in various meals and drinks. There are several small start-up companies experimenting with seaweed products for cosmetics and nutritional products (FAO, 2018). Follow-up work could include assessing such opportunities to increase local demand and catalyse more start-up SMMEs.

5.2.3 Any activity in the proposed location

Most of the South African abalone farms occur in the study area. The aquaculture industry invests millions of rands in research, technology, and development (RT&D) for farmed seaweed to use as natural feed stock, such as the cultivation of *Ulva* in integrated systems with abalone (Amosu, et al., 2013). Some abalone farmers (specifically Viking Aquaculture) have also been experimenting with laboratory growth of kelp (*M. pyrifera*). Some of the companies involved in the kelp, bivalve shellfish and abalone industries have expressed keen interest in becoming involved in kelp cultivation pilots in any way, including farming kelp as an IMTA crop, kelp seeding and cultivation trials, product development and other activities required for development of the value chain.

Follow on research should therefore include the involvement of industry in kelp cultivation pilots, testing kelp as an IMTA species, kelp seeding and cultivation trials, product development and market development.

5.2.4 Industry bodies and support organisations

The most relevant industry bodies and support organisations for kelp cultivation in South Africa are described in Table 3.. Abalone farmers have long been involved in research and development of different seaweed species as abalone feed and as an IMTA platform. Follow on research as part of a full feasibility study would better support these efforts, avoid duplication of efforts, and amplify the potential for innovation if role players combine their different perspectives and experiences.

Table 3: Industry bodies and support organisations

Industry role players	Description
Bivalve Shellfish Farmers Association of South Africa (BSASA)	The Bivalve Shellfish Farmers Association of South Africa (BSASA) represents and promotes the interests of the bivalve shellfish farming industry. Its current members are companies holding permits to farm mussels and oysters.
Department of Forestry, Fisheries, and the Environment (DFFE)	Managing of Seaweed rights/concession areas, EIAs, coastal zoning, climate change, and aquaculture research
Aquaculture Association of South Africa (AquaSA)	Represents the interest of the aquaculture industry in Southern Africa, including marine species such as oysters, mussels, seaweed, abalone, and prawns; freshwater species such as trout, catfish, tilapia, ornamental fishes; as well as service providers such as feed companies, equipment suppliers and veterinary services.
Abalone Farmers Association of South Africa (AFASA)	Represents the interests of the abalone farmers in South Africa

5.3 Current producers and value chain

The potential value chain for South African kelp, including cultivation, is summarised in Figure 4. Although about 5% (246 t in 2020) of kelp is exported or sold locally in dry weight form, it is currently not known what percentage is exported. For current harvesting and collection activities, the inputs required include Seaweed Concessions. As set out in Figure 5, there are currently 23 Seaweed Rights Concession areas of which 18 (areas 5-9, 11-16 and 18-19) have kelp rights (Rothman, et al., 2020). Kelp is either harvested (blades or whole plants) or collected as fresh or dry beach-cast material.

In terms of quality assurance, follow on work in the near to medium term should also consider the regulations and certification requirements for local, regional, and global markets.

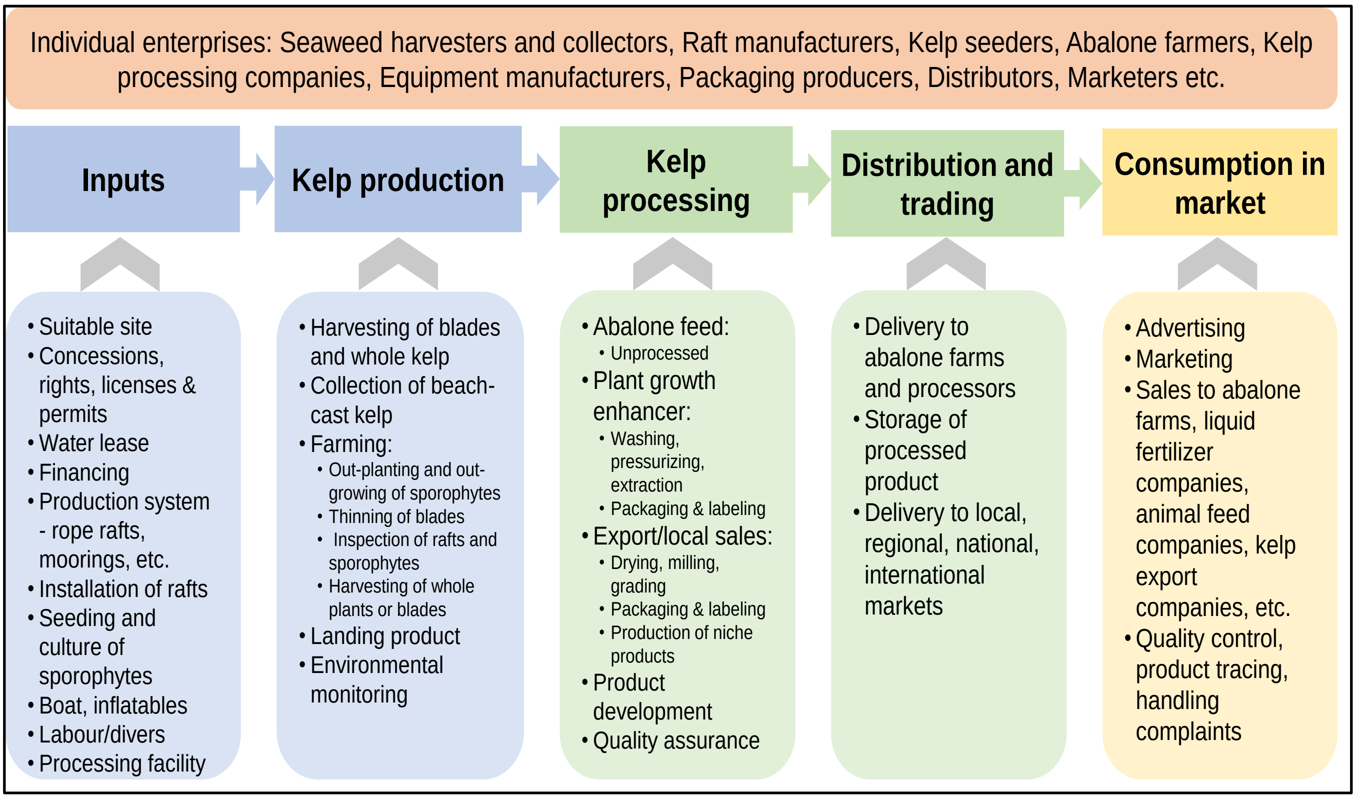


Figure 4: Potential kelp value chain including cultivation

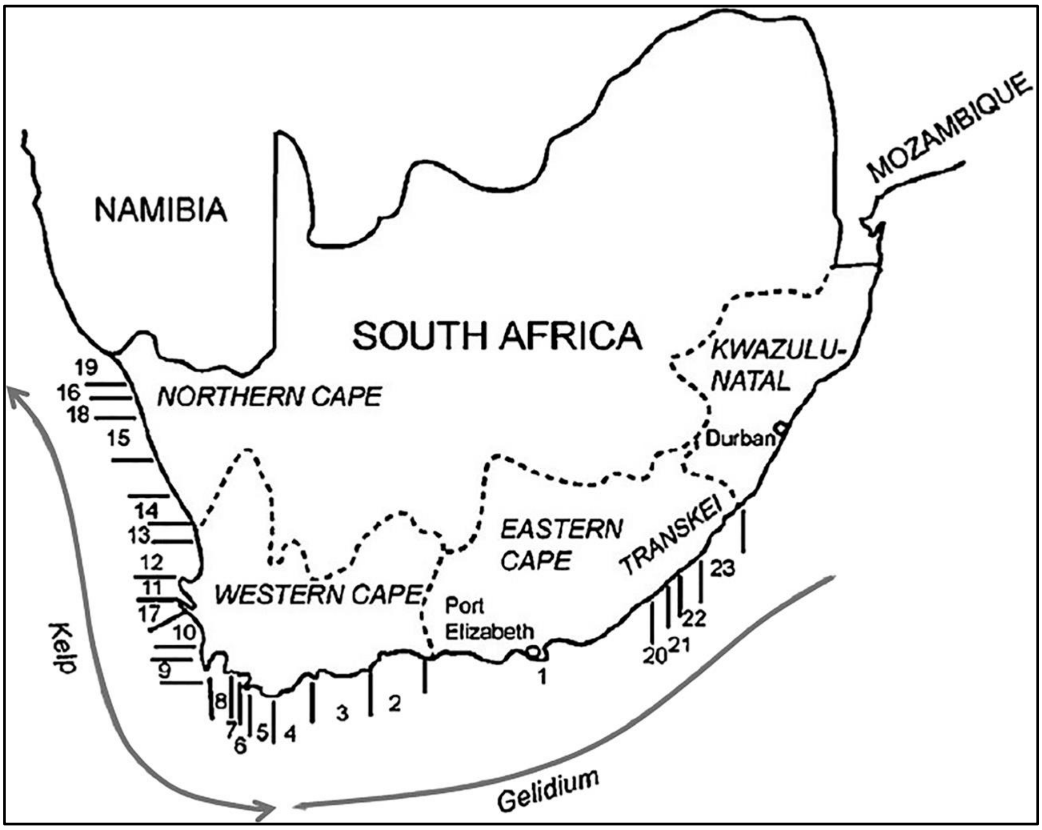


Figure 5: Map of South African Seaweed Rights Concession Areas
Source: **(Rothman, et al., 2020)**

Companies or enterprises currently operating in the market include seaweed harvesters and collectors (e.g., Taurus Cape Kelp), kelp users such as abalone farmers, kelp processors for liquid enhancers (e.g., Kelpak®, Afrikelp® and Rawkelp), manufacturers of organic fertilisers and dried kelp for supplements to animal feed, and manufacturers of nutraceutical and cosmetic products such as Afrakari.

There are about 19 operational abalone farms in South Africa (DEFF, 2019). Most of them occur in the area between Cape Agulhas and Cape Point and north of Saldanha Bay. There were two abalone farms in the Eastern Cape (Troell, et al., 2006), however, one closed in the interim. The abalone farms could benefit from expanded kelp farming activities through availability of more fresh kelp fronds as abalone feed. The quantification of this potential resource could form part of follow-on work during a full feasibility study.

Potential competitors to commercial kelp farmers on the West Coast could include seaweed concessionaires who are currently involved in the harvesting, collection, value adding and sale of kelp and kelp-derived products, and other kelp farmers in the region (e.g., Kelp Blue proposed aquaculture farm in Lüderitz, Namibia). However, these parties could also be regarded as potential collaborators in the development of a commercial kelp aquaculture industry, and potential customers for kelp products. Follow on work as part of a feasibility study could include investigation of the need or scope to further catalyse development opportunities based on existing uses, and the potential for other benefits of commercial kelp growing such as climate change mitigation, IMTA, carbon credits etc.

Abalone farmers, and companies currently involved in the kelp industry, could potentially benefit from the increased production of kelp biomass if kelp aquaculture proves to be commercially successful. Other aquaculture farmers could benefit from the cultivation of kelp as an IMTA platform, to increase the sustainability of their existing operations.

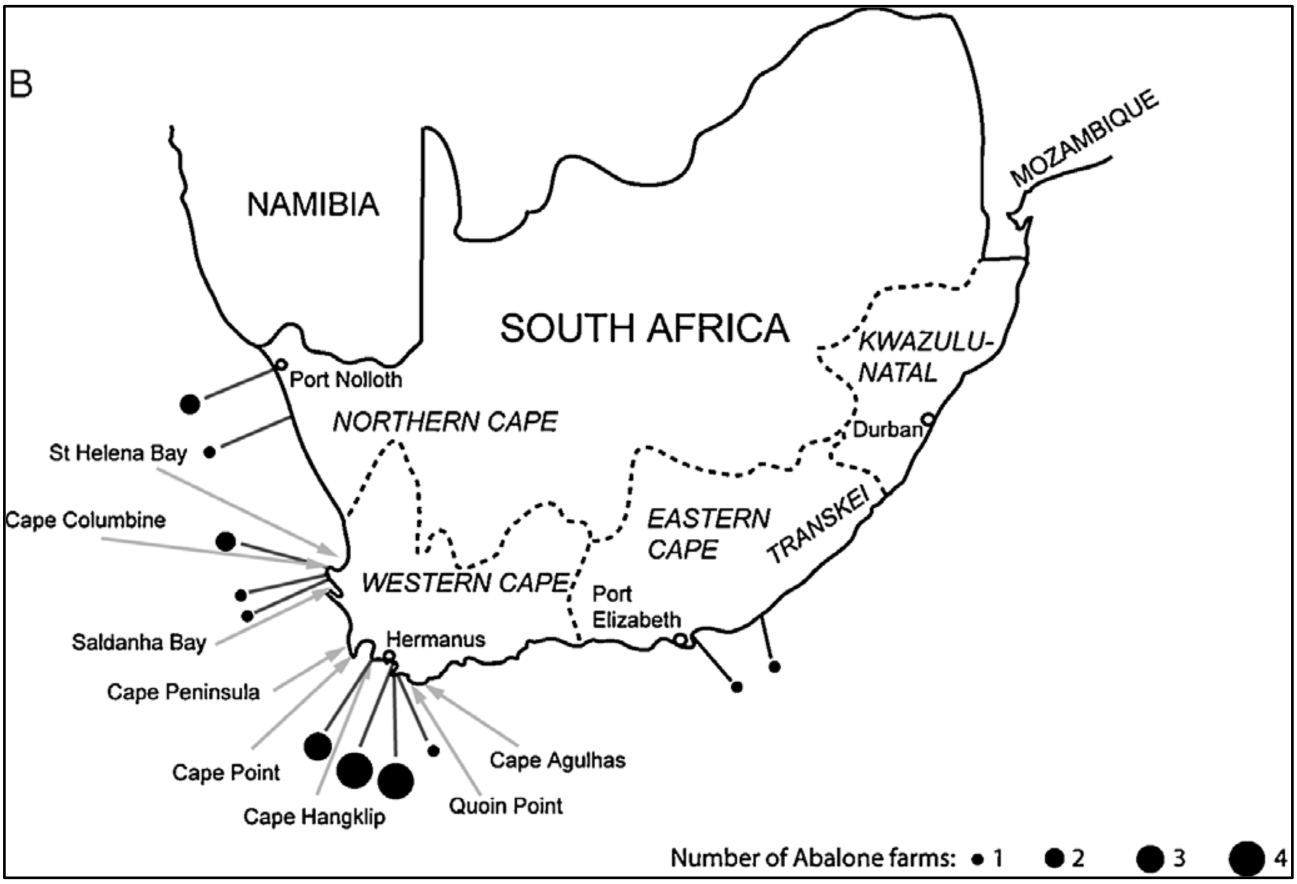


Figure 6: Abalone farms in South Africa
Source: **(Troell, et al., 2006)**

As part of the market overview, thirteen companies in the kelp value chain (including harvesters, abalone farmers and feed producers) were approached to obtain high-level market insights. Three companies responded. They mostly use *E. maxima* in their products and/or operations. Some indicated that they also make use of *Ulva lactuca* in current products. Feed producers mostly obtain dried kelp while abalone farmers make use of raw kelp. The harvesters typically obtain kelp in all available forms, including fresh kelp fronds for abalone farmers, and whole kelp plants for extracting kelp liquid. Beach cast kelp is also collected for drying and milling. The harvesters harvest their own kelp that is mostly supplied to abalone farmers, feed producers and producers of liquid kelp.

The increase in fuel prices, load shedding and electricity prices were listed as major issues for consideration in future kelp farming. In addition, work is labour intensive, and labourers must have the right training and resources to do the work required.

The main barriers to entry into the seaweed sector, include regulatory compliance (seaweed concessions, environmental authorisations, marine/aquaculture rights, licenses and permits), and ISO 9001 certification for seaweed harvesters and manufacturers of raw kelp. Other barriers include access to funding for aquaculture infrastructure and operations, and the technical complexities around aquaculture and production of value-added products.

5.4 Popular products

5.4.1 Products encountered in broad product direction

Existing use of kelp in South Africa is for abalone feed, plant growth enhancers, export for alginate extraction and locally as additive in animal feed, compost tea, moisture retainer for agriculture and horticulture, and cosmetic products. A selection of some kelp-derived products for sale to end consumers, is illustrated in Figure 7. These include liquid and dried plant growth stimulants, and nutraceutical products.

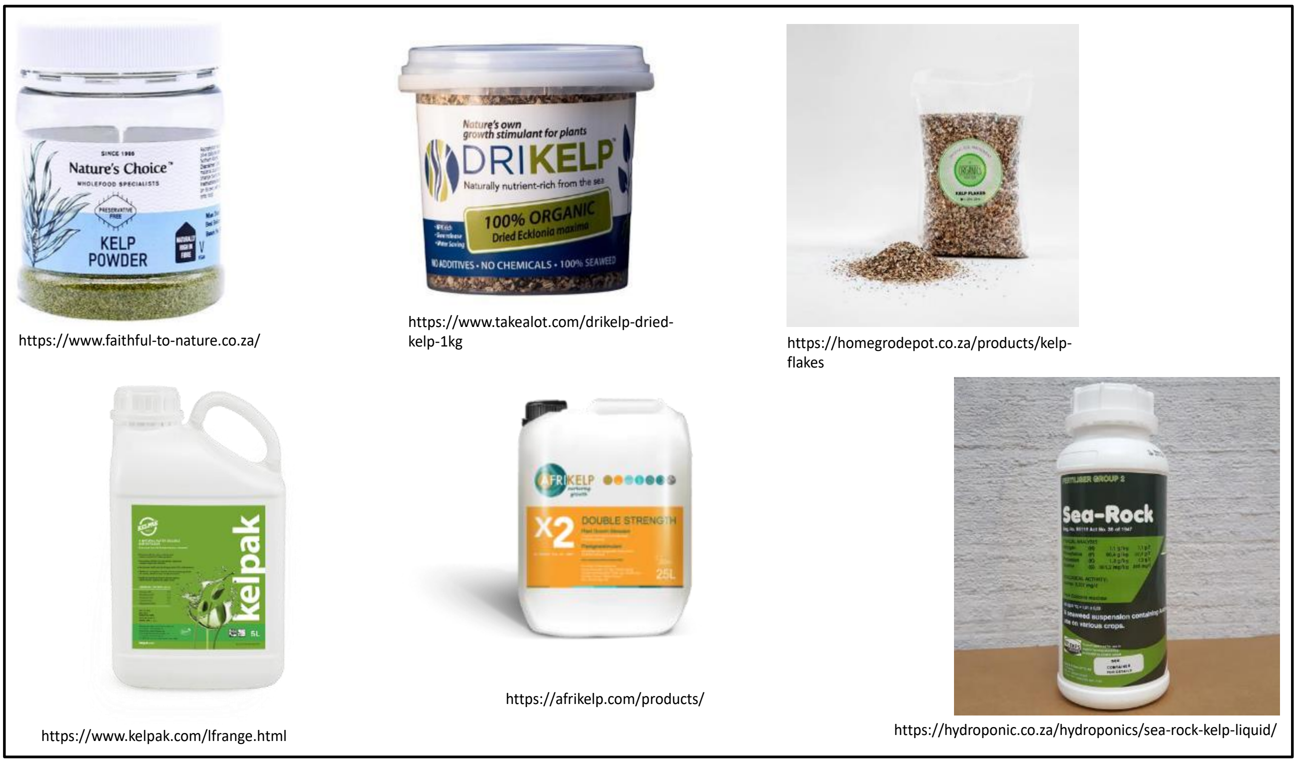


Figure 7: Selection of products manufactured from South African kelp

Currently there is limited commercial use of *L. pallida* and *M. pyrifera* and there is potential in optimising for further use and processing. The potential future applications of these two species include bio-refinery processing to produce ingredients for nutricosmetics, functional foods, cosmeceuticals, and bioplastics (Purcell-Meyerink, et al., 2021).

The future of the South African seaweed industry lies in finding new uses for seaweed and developing value-added products for niche markets and industries. Future expansion of the SA kelp market requires kelp cultivation to increase biomass availability. A 2004 study on potential new applications for the Southern African kelps found that possible uses include bio sorbents in heavy-metal wastewater remediation, potential medicinal value, and seaweed alcohol as consumptive alcohol and its use in brewing and distilling alcoholic beverages (Stirk & van Staden, 2004). The FCDO-BSASA kelp project added to this body of knowledge by identifying current potential uses of kelp such as an IMTA platform, climate change mitigation, carbon credits etc.

The product list used for the investigation of this opportunity include the following:

- Kelp blades for abalone feed (*E. maxima*, *L. pallida and M. pyrifera*), fresh weight (FW)
- Whole kelp (stipe and fronds) for extraction of plant growth enhancer (*E. maxima),* fresh weight (FW)
- Dried and milled kelp for alginate extraction (export market) and local markets (*E. maxima*, *L. pallida and M. pyrifera),* dry weight (DW).

Table 4 shows the market related prices of kelp in relation to the product list. This shows that the different types of kelp use have different price variants. The average selling price for dried, milled, and graded kelp sold locally is estimated at R20 500/ton. The price for dried kelp for export is mainly influenced by international price fluctuations. The price obtained in the local market depends on the size of milled kelp that is sold.

Table 4: Kelp product price indications

Product List	Price Indication (ZAR/t)
Kelp blades for abalone feed (FW)	1 800
Whole kelp (blades and stipes) for plant growth enhancer (FW)	2 700
Dried, milled, graded kelp for export and local markets (DW)	20 500

5.4.2 Preliminary indication

Figure 3 indicated that, although abalone farmers are currently the biggest user of fresh kelp, this market has declined since 2011 (more than 6 000 t in 2011, with a market value of over R8 million, down to a plateau of 4 000-5 000 t p.a.) (Anderson, et al., 2020). The kelp is mostly harvested (by boat) for land-based farms. Expansion of the market is constrained by limitations on allowable harvest by seaweed concessionaires.

The use of fresh kelp for plant growth enhancers has shown steady growth over several years to over 3 000 t by 2017 (Rothman, et al., 2020). However, expansion of this market is also constrained by limitations on allowable harvest.

The use of dried and milled kelp for the export and local markets has drastically reduced in recent years to very small amounts. The expansion of this market is constrained by global market fluctuations and prices, and high operational expenses because of high fuel use and labour costs. Although *E. maxima* is the dominant species harvested, *L. pallida* constitutes a substantial part of the harvest, particularly of beach-cast material. The scope for local alginate extraction could be investigated in the next phase of this project.

The global demand for seaweed is growing and expanding to a diversity of products and industries. Market growth is expected to be driven by the rise in seaweed farming practices which is driven by global demand for production. The increase in industrial, agricultural, and feed-related applications and the rise in the market for seaweed snack product is projected to drive the demand. The rising consumer adoption for plant-based products, consumption of seaweed-based products as source of high nutrients & minerals, and growing government initiatives is expected to further increase the demand for seaweed cultivation. The growing demand for biofuels and technological advancements are expected to create rewarding opportunities for manufacturers in the market (Research and Markets, 2021).

A follow-on feasibility study should investigate which of the potential demands will best be met through cultivation of kelp e.g., catalysing new start-ups, developing SMMEs in the value chain, reducing the need for abalone farmers to focus on harvests rather than their core business, grow more kelp for carbon mitigation etc.

The seaweed cultivation market is projected to reach US$ 30.2 billion by 2025, growing with a compound annual growth rate (CAGR) of 12.6%, from the 2020 value of US$ 16.7 billion (Markets and Markets, 2020). The dry form segment is estimated to direct the largest share of market to fulfil the growing demand for seaweed powder from the food and cosmetics industries. Moreover, its benefits such as comparatively high shelf-life and ease of transport and storage are further expected to support the growth of this market (Research and Markets, 2021).

The market for human consumption (food and beverage) is the largest and fastest growing section of the seaweed market. Kelp products such as kombu (*Saccharina*)form a large part of this application. This growth is attributed to the growing demand for organic food products, increase in consumption of plant proteins and vegan products. Moreover, rapid growth in population, increasing awareness towards health benefits, changes in lifestyle patterns and taste preferences among consumers, healthy eating habits, and rising disposable income are further expected to support the growth of this market (Research and Markets, 2021).

5.5 Summary

There have been significant changes in kelp use over the last 15 years, with a major change from the export of dry beach-cast kelp for alginate extraction, to the use of fresh harvested kelp for abalone feed and plant growth enhancers. Although kelp harvested for abalone feed dominates the market, the annual kelp use for plant growth enhancers has had steady growth.

There are several small start-up companies experimenting with seaweed products for cosmetics and nutritional products. The extraction and manufacturing of kelp and seaweed end-products are technologically complicated, expensive, and influenced by international market pressures. Despite this, the local market is showing growth potential. There are local production companies with an international footprint. Market growth potential assumes that kelp cultivation can supply a growing demand in the market, with development of value-added products aimed at niche markets and different industries.

South Africa is ideally situated to provide raw material, with a long coastline with nutrient-rich and relatively unpolluted sea water. The country has a warm climate for open-air drying of seaweed, available labour force and development of technical skills for mariculture in recent years.

5.5.1 Accessible market

The estimation of an accessible local market assumes that the local kelp market size is 10 000 t p.a., and that current supply does not meet the demand. It also assumes that the market will grow due to the growth in demand for abalone feed, plant growth enhancers and niche products. The volume, price indications and estimated market value for the three market segments is summarised in Table 5. If it is further assumed that a kelp cultivation enterprise could access 10% this market, the accessible local market is estimated as follows:

- Volume: 1000 t
- Value: R3 million.

The above assumptions do not include potential market growth due to increased cultivated biomass. It also assumes that current producers of kelp to the local market are constrained by the limitations on natural biomass harvesting and collection and will not be able to meet growing demand.

Table 5: Estimate of local kelp market size

Product list	Volume (t)	% of total volume	Price indication (R/t)	Estimated market value (R)
Kelp blades for abalone feed (FW)	**7 041**	70%	1 800	12 674 051
Whole kelp (blades and stipes) for plant growth enhancer (FW)	**2 472**	25%	2 700	6 675 237
Dried, milled, graded kelp for export and local markets (DW)	**487**	5%	20 500	9 974 288
Total	10 000			29 323 576

The global kelp market was estimated at US$1.7 billion in 2021. If a South African kelp cultivation enterprise could access 1% of this market, it could potentially access US$17 million (ZAR 251 million if using the average ZAR:US$ exchange rate of 0.0677 US$ for 2021). If 0.1% of the global kelp market is accessible, this would translate to R25 million.

5.5.2 Market opportunity

There is a market opportunity for cultivated South African kelp products based on sales of fresh kelp blades to abalone farmers, whole fresh kelp to manufacturers of plant growth enhancers, and dried, milled, and graded kelp to export companies and local manufacturers of niche products.

The abalone farmers are located along the West Coast with most concentrated in the area between Agulhas and Cape Point, some just north of Saldanha Bay and some in the Kleinzee/Port Nolloth area in Northern Cape. The plant growth enhancer manufacturers, niche product manufacturers and export companies are in Cape Town in the Western Cape, with national and international footprints.

The projected sales volume for a kelp cultivation farm is 1000 t p.a., with projected sales income based on local sales, as set out in Table 6. This does not consider access to the potential global market, which could be realised if sufficient economies of scale can be achieved, especially through successful commercial aquaculture.

Table 6: Projected sales volume and income

Product list	Volume (t)	Price indication (ZAR/t)	Sales income value (ZAR)
Fresh kelp blades for abalone feed (FW)	700	1 800	1 260 000
Fresh whole kelp (blades and stipes) for plant growth enhancer (FW)	250	2 700	675 000
Dried, milled, and graded kelp for export and local products (DW)	50	20 500	1 025 000
Total	1000		2 960 000

6 TECHNICAL INSIGHTS

Brown seaweeds growing in cold waters normally contain higher quality hydrocolloids (alginates) than those growing in tropical waters. Brown seaweeds (such as *Ascophyllum*, *Laminaria* and *Alaria*) can also be used for seaweed meals in animal feed, or for soil enrichment and liquid fertilisers. In South Africa, there are companies that sell seaweed-based liquid fertilisers. Alginates can also be used as an ingredient in cosmetics (BCC Research, May 2021).

Kelps are the largest and fastest growing marine algae. There are four species of kelp (brown seaweeds) in South Africa including *E. maxima*, *E. radiata*, *M. pyrifera* and *L. pallida. E. radiata* is the only kelp species not found along the West Coast of South Africa.

The product direction is based on the potential for cultivation of *E. maxima, L. pallida,* and *M. pyrifera.* The existing uses of kelp in South Africa is as follows:

a) Unprocessed (fresh) kelp used as abalone feed
b) Production of liquid fertilisers/growth enhancers from fresh kelp
c) Dried kelp exported for alginate extraction and sold locally to manufacturers of animal feed additives, soil conditioners, nutraceuticals, and cosmetics.

There is potential to use cultivated kelp in Saldanha Bay and the West Coast for abalone feed, extraction of chemical components, nutrient removal, carbon sequestration, etc. The proposed location of the opportunity is along the West Coast of South Africa, west of Agulhas and up to the mouth of the Orange River, and in Saldanha Bay.

The Benguela Current Large Marine Ecosystem (BCLME) is a major transboundary coastal upwelling ecosystem that extends from east of the Cape of Good Hope, northwards along the west coasts of South Africa, Namibia, and Cabinda Province in Angola. The Benguela biome is one of four global biomes found along the eastern boundaries of the major ocean basins. It is an important centre of marine biodiversity and marine food production. The large productivity of the BCLME is because surface waters are continually fertilised by the upwelling of nutrient-rich deep water. Upwelling is the phenomenon occurring when equatorward and offshore-directed winds blow across the sea surface, causing surface waters to move away from the coast and being replaced by cool, nutrient-rich waters from below (https://www.benguelacc.org).

The productivity of the BCLME supports large populations of marine plant and animal plankton (small and microscopic organisms drifting or floating in the water), which in turn support populations of primary consumers like small fish, shellfish, and crustaceans. Primary consumers are in turn eaten by bigger marine animals such as fish or whales. The BCLME has high levels of available nutrients and sunlight, which is important for kelp growth and support large kelp forests along the west coast.

Although there have been a few local laboratory and sea-based experiments on kelp cultivation, there is currently no established commercial seaweed or kelp cultivation in SA. Sporophytes of *E. maxima* and *L. pallida* were successfully produced on ropes in a laboratory environment testing different conditions of irradiance and grown out in the sea for 8 months during 2014-2015. *L. pallida* grew faster than *E. maxima* in the sea, especially in low-light conditions (Rothman, 2015). A short-term (three-month) pilot cultivation experiment of *M. pyrifera* 'angustifolia)' by holdfast fragmentation on a rope-raft system, was carried out in 2020. Whole sections of the kelp holdfasts were collected, broken in fragments, and fixed to growth ropes. The study provided baseline information on vegetative propagation of this species on a rope-raft system, under different treatment regimes, and showed that vegetative propagation under specific conditions were possible (Fleischman, et al., 2021).

Because of the lack of information about cultivation of South African kelp species, the FCDO-BSASA Kelp project included several technical components aimed at building a foundation of knowledge on which to build a kelp cultivation industry. These components, as summarised in the sections below, included the following:

1. Kelp nutrient production and removal model for Saldanha Bay.
2. Kelp seeding and growing in a laboratory environment
3. Study of nutritional values of different species of seaweed
4. Study of the appropriate technologies for kelp cultivation
5. GIS study to assess coastal (inshore and offshore) areas available for commercial cultivation.

6.1 Potential of kelp in Integrated Multi-Trophic Aquaculture (IMTA)

Kelp plants are 'extractive' because they take up nutrients such as dissolved nitrogen and phosphorus that are present in the water column. Although these nutrients support the growth of algae, an overabundance in the marine environment (e.g., because of human activities such as agricultural fertilizer run-off, fish factory effluent or sewage discharge) could cause excessive growth of algae and phytoplankton (eutrophication), blocking of sunlight into the bottom layer of water, death of algae and prevention of oxygen uptake by organism beneath the blooms. When these dense algal blooms die, the decomposition of organic matter by oxygen-utilising bacteria could lead to partial (hypoxic) or total (anoxic) oxygen depletion in the water body. These conditions could cause a lack of oxygen and death of organisms depending on oxygen. Filter feeders such as shellfish could also absorb microbes associated with algal blooms, many of which are toxic to people.

The links between water quality and eutrophication and the occurrence of harmful algal blooms (HABs) are set out in a synopsis of a "roundtable discussion" sponsored by the US Environmental Protection Agency in 2003. Seven statements regarding these links were adopted by attendees. Some of the statements relevant to this study relates to the link between degraded water quality from increased nutrient pollution and development of HABs, and the importance of management of nutrient inputs to the watershed in reducing HABs (Heisler, et al., 2008).

Non-extractive (or fed) aquaculture such as finfish or abalone farming could also contribute to the nutrient load (especially nitrogen and phosphorus) in the surrounding waters, through un-utilised feed and faeces. The use of seaweed such as kelp to remove dissolved waste nitrogen and phosphorus generated by other aquaculture activities in IMTA systems is gaining interest. IMTA is the integrated aquaculture of more than one species, taking advantage of ecological interaction between the species. It requires the integration of several organisms from different trophic levels to complement each other. One example is the cultivation of seaweed with fish, where the seaweed acts as a biofilter and assimilates excess nutrient from the fish to convert into biomass (Roleda & Hurd, 2019).

This is already practiced in some abalone farms in South Africa, where *Ulva lacinulata* is grown in the effluent water from abalone activities to take up ammonia excreted by the abalone, and then used as feed for the abalone (Bolton, et al., 2009) (Neveux, et al., 2018).

6.2 Kelp nutrient production and removal model for Saldanha Bay

The study area includes Saldanha Bay, where existing aquaculture activities such as mussel and oyster farming take place in an approved Aquaculture Development Zone (ADZ). These activities, and human activities such as effluent discharge, contribute to the nutrient load in the Bay. The Scope of Work for the Pre-Feasibility Study included the development of a model of how much kelp might be produced (based on nutrient calculations) and how much nutrients could be removed (in Saldanha Bay).

Seaweeds require mainly inorganic carbon (C), nitrogen (N) and phosphorus (P) for photosynthesis and growth. In areas with intensive fish farming, decomposition of fish feeds and excretion from animals could increase dissolved nutrients, especially nitrogen, into the water. This could lead to harmful algal blooms and deterioration of the coastal environment.

Nitrogen most commonly limits seaweed growth in natural systems and is available in inorganic forms (nitrate [NO_3^-] and ammonium [NH_4^+]) and in the organic form urea. Nitrate is externally supplied, for example from upwelling, while ammonia and urea are internally generated in a system by invertebrates and fish. Dissolved inorganic carbon in the form of carbon dioxide (CO_2) or bicarbonate (HCO_3^-) is normally not a limiting nutrient in sea water. Organic phosphorus can be utilised using the enzyme alkaline phosphatase, which breaks down organic matter on the seaweed's surface into phosphate (PO_4^{3-}) (Roleda & Hurd, 2019).

Environmental factors affecting seaweed nutrient uptake and metabolism include water motion, light, temperature, carbon dioxide, salinity, and desiccation. Water motion drives nutrient uptake which may be reduced in slow water velocity, and light drives photosynthesis and growth. Temperature affects seaweed physiology through regulation of enzyme activity, chemical reactions, and the rate of diffusion of nutrients. Higher carbon dioxide concentration may increase nitrogen uptake, and lower salinity may increase nitrogen uptake in certain seaweeds. Desiccation of intertidal seaweeds may increase nitrogen uptake rates when they are re-submerged. Environmental conditions and the concentrations of different nutrients in the water column therefore have inter-related effects on photosynthesis and growth of seaweeds. In addition, biological factors such as life stages and age class of seaweeds also affect nutrient uptake (Roleda & Hurd, 2019).

During a project to develop the sugar kelp (*Saccharina latissima*) aquaculture industry in Southern New England, the nutrient content of cultivated kelp from four sites was analysed to determine levels of C, N and P. The average tissue C content varied between 28% and 33%, and average tissue N content varied between 0.7% to 1.6%, respectively. The low N content indicated that nitrogen was limiting during the harvest period, which was thought to be caused by a prolonged phytoplankton bloom in the area. The C and N removal rate was multiplied by the kelp biomass per meter of culture line to calculate the total amount of N and C sequestered by sugar kelp in this location. The estimated CO_2 and N removal at a 1 ha hypothetical kelp farm with spacing of 1.5 m or 6 m between longlines were then calculated. At 1.5 m spacing, CO_2 and N removal was estimated at averages of 5 tonnes (t) and 48 kg, respectively. At 6 m spacing, the average CO_2 and N removal rates were 1.2 t and 12 kg respectively (Yarish, et al., 2017).

As part of the same project, the inorganic nitrogen and phosphorus content of the sea water was analysed. At two of the farms, the total inorganic nitrogen concentration was highest during the winter months and decreased as temperatures increased. However, the concentrations were low throughout the growing season (0.1 to 1.9 µMol per litre) and this was regarded as nutrient limited. At other farms, the total nitrogen concentrations were as high as 7-13 µMol per litre in winter. Phosphorus concentration at one site was low throughout the growing season (0.3-0.6 µMol per litre), but at three other sites showed a similar seasonal pattern as the inorganic nitrogen concentration (Yarish, et al., 2017).

In Saldanha Bay, nutrients in the water column are normally not a problem due to upwelling events from the cold Benguela Current, and the presence of aquaculture activities (e.g., mussel and oyster culture) and activities such as fish factories and effluent discharge, that introduce nutrients into the water column. However, stratification of the water column occurs in March, when warmer, nutrient-poor water floats on top of colder, nutrient-rich bottom water. This could cause nutrient deficiency and die-offs of algae growing in the top layer.

Using N physical flux for entrainment in the Bay (7.94 mmol N m^{-2} d^{-1}) as an indicator, the nutrient load in Saldanha Bay (including Small Bay, Big Bay, and Outer Bay) was estimated at 0.03335 kg/N/m^2/yr assuming a 300-day upwelling year (CapMarine, 2017). This equates to 333.5 kg/N/ha/yr. The total area set aside for aquaculture in the Saldanha Bay Aquaculture Zone (ADZ) is 884 ha spread between Small Bay, Big Bay North, Outer Bay North, and Outer Bay South. The recommended species for farming include bivalve shellfish, abalone, clams, finfish, and seaweed (SRK Consulting, 2017). Considering the nutrient load as estimated above, the nutrient load associated with the whole ADZ is estimated at 295 t N/yr.

As set out in Table 7, calculation of the potential kelp production in the Saldanha Bay ADZ assumes that similar production figures as for *S. latissima* will be achieved (Yarish, et al., 2017). Assuming an average yield of 10 kg/m/harvest FW, 25 000 m of longlines (250 x 100 m), and spacing of 1.5 m between longlines, the minimum farm size is **3.75 ha**, with annual production of **250 t** each. If 100% of the ADZ is used for kelp production, a total of 236 kelp farms producing 59 000 t kelp p.a. (FW) could be established. If only 30% of the ADZ was dedicated to kelp production, this would translate to **71** farms producing **17 680** t kelp p.a. (FW). Using a wet to dry conversion factor of 10:1, potential dry weight production in the ADZ could be **1 768 t** of kelp p.a.

Assuming that similar nutrient removal rates can be achieved in the Saldanha Bay ADZ as for sugar kelp (5 t/ha CO_2 removal and 48 kg/ha N removal) (Yarish, et al., 2017), the potential CO_2 removal capacity of cultivated kelp in 30% of the ADZ is 1326 t (5 t/ha). The potential N removal capacity of cultivated kelp in 30% of the ADZ is 13 t (0.05 t/ha).

Table 7: Potential kelp production and nutrient removal rates in ADZ

Description	Value
Average kelp yield (kg/m/harvest)	10
Longlines (250 x 100)	25 000
Spacing (m)	1.5
Minimum farm size (ha)	3.75
Production per farm p.a. (t)	250
Number of farms in 30% of 884 ha ADZ	71
Potential kelp production in 30% of ADZ (t) p.a. FW	17 680
CO2 removal/ha at 1.5 m spacing (t)	5
CO2 removal per 3.75 ha farm (t)	19
CO2 removal for 30% of ADZ (t)	1 326
N removal/ha at 1.5 m spacing (t)	0.048
N removal per 3.75 ha farm (t)	0.18
N removal for 30% of ADZ (t)	13

6.3 Kelp seeding and growing in a laboratory environment

The first phases of commercial kelp cultivation are conducted in controlled nursery conditions (temperature, light, etc.). A South African kelp seeding, and growing study was conducted by Dr Mark Digby Cyrus and his team at the DFFE Marine Research Aquarium in Sea Point, and by Viking Aquaculture at their Buffeljags abalone farm close to Gansbaai (Western Cape). The objective of the study was to produce baseline data to inform future commercial cultivation of African kelp in South Africa. Although trials started in February 2022 and results up to March 2022 are included in the pre-feasibility study, these trials are expected to continue and be used to support the kelp raft cultivation pilot in Saldanha Bay. This will depend on further funding.

The activities undertaken during the pre-feasibility study included the following:

- Preparation of nursery/lab space
- Assignation of research team
- Finalisation of permits and ethics clearance requirements where appropriate
- Collection and isolation of Seed stock
- Development of protocols/guidelines for storage and maintenance of (gametophyte) cultures
- Finalisation of monitoring schedule and progress/observation reporting and dissemination
- Initiation of test site discussions to secure test farm site and arrangements for outplacement of young sporophytes.

A summary of the results of this study is based on an unpublished report collated by the research team (Meyer, 2022). The kelp trials were based on methods adapted from known best practice guidelines, such as the New England Seaweed Culture Handbook (Redmond, et al., 2014). As illustrated in Figure 9, the nursery for this part of the study was set up in a temperature-controlled laboratory at the DFFE Marine Research Aquarium. Current growth trials at the Marine Aquarium are focused on *E. maxima* and *L. pallida*. The trials were started at the end of February 2022. Kelp reproductive material was collected from the ocean, sporulation induced, and spores allowed to settle on nylon ropes that are wound around PVC spools, as illustrated in Figure 8. The settled spores developed into gametophytes.

To date, four trials are on-going at the Marine Research Aquarium. Three of the trials include only *E. maxima*, and one include *E. maxima* and *L. pallida.* The grow out period for these species in the nursery before being moved to the ocean is at least one month. Results have shown that spore settlement has been a success and gametophyte development up to two cells is evident, as seen in Figure 9 (A). Further monitoring and testing are required to establish the success of kelp growth in this nursery.

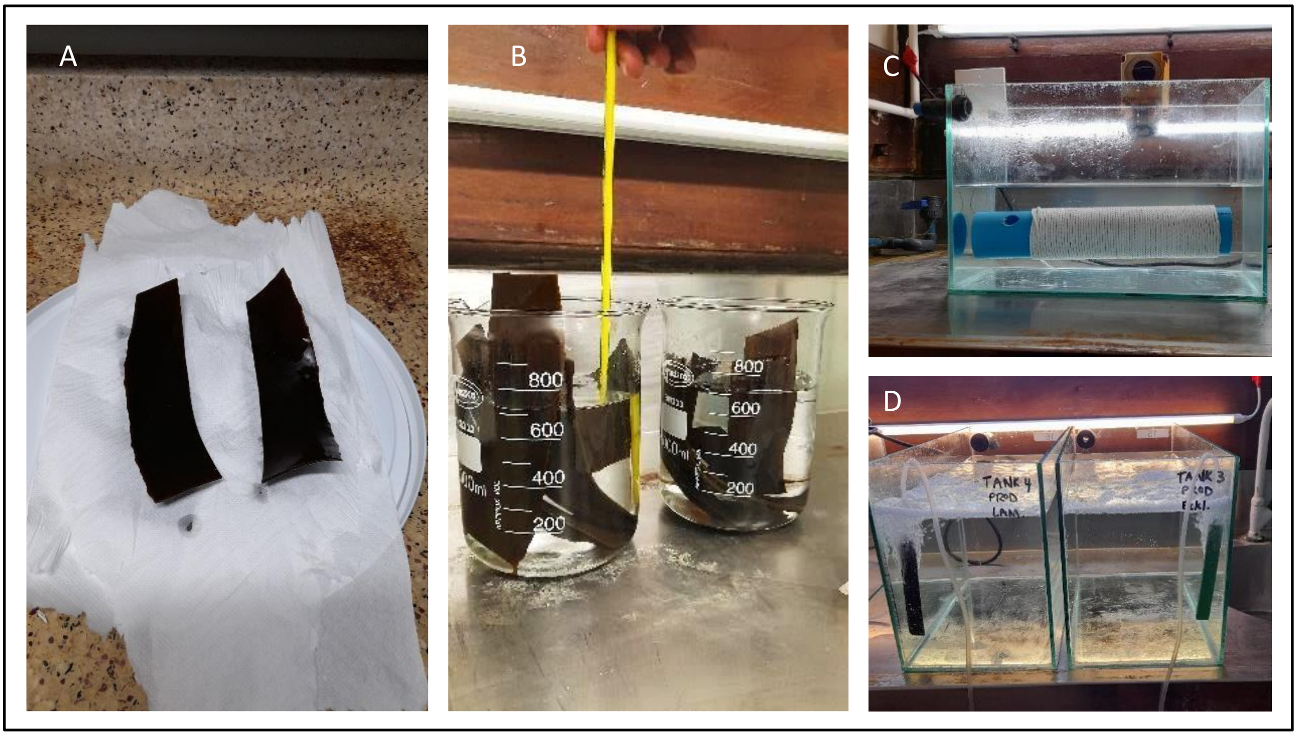


Figure 8: Collection of reproductive material and inducing of sporulation

Figure 9: Kelp seeding and growth trials

Eight weeks after the start of trials, the development of *E. maxima* from gametophytes to sporophytes could be seen. Figure 10 shows the development of gametophytes seven days after inoculation, and sporophytes on the spools after 16 days.

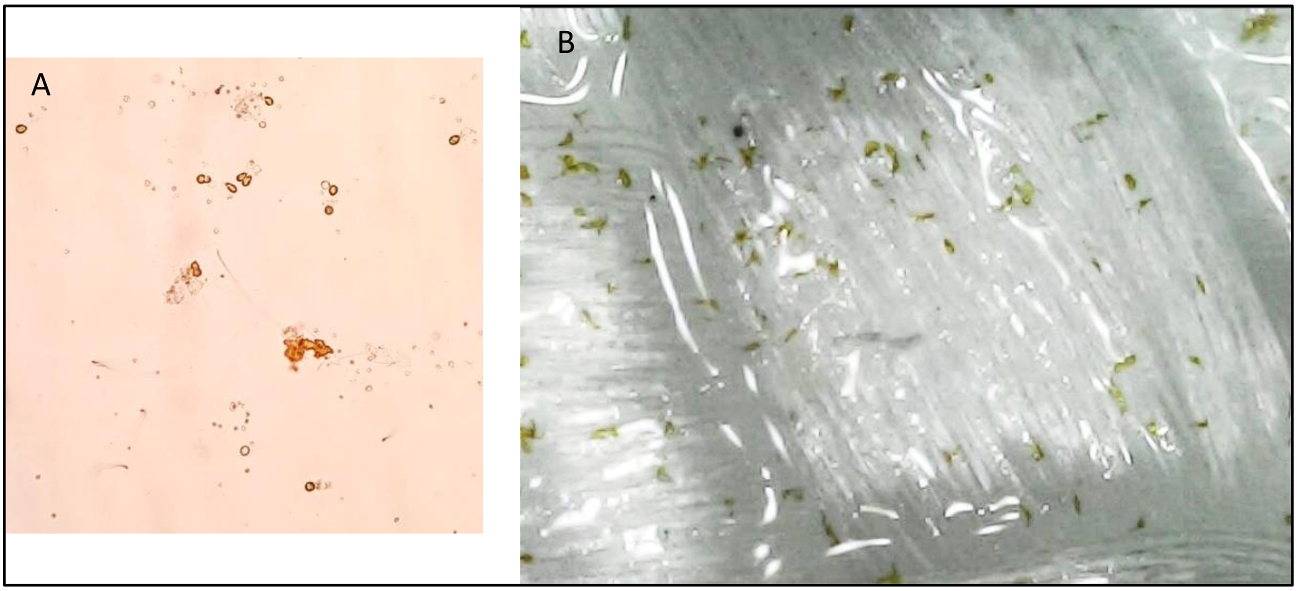


Figure 10: Development from gametophyte (A- 7 days after inoculation) to sporophyte (B- 16 days)

Sporulation and seeding experiments for *M. pyrifera* were conducted by Michelle Loubser at Viking Aquaculture's Buffeljags abalone farm, as this species was shown to be optimal for abalone feed in the farm hatchery. Sporulation was induced using similar methods as those used for the *E. maxima* and *L. pallida* trials. Gametophyte development did take place but seemed to be underdeveloped. A new trial is set to start soon using different nutrients.

The research team developed a standard operating procedure (SOP) for the kelp nursery system to ensure proper maintenance of the kelp production system(s) and welfare of kelps. This will be useful in the set-up of nursery systems in other locations in future.

6.4 Study of nutritional values of different species of seaweed

This study was conducted by Dr Brett Macey (DFFE). The objective was to determine the nutritional value of different species of seaweed (drawing on ongoing work at the CPUT and other partner organisations). The projected deadline for the study was end of March 2022. However, due to the time constraints related to completion of analyses, the full set of results from this study will only be available by June 2022. These results will be attached as an addendum to this report as soon as they become available.

6.4.1 Background

Seaweeds are a typical food item in Asian countries and more recently their consumption in Western countries has increased due to their good nutritional values (Enchave, et al., 2022). Seaweeds are a rich source of essential macronutrients, micronutrients and bioactive molecules, including bio-available vitamins, minerals, pigments, proteins, bioactive peptides, dietary fibre, lipids and phytochemicals, which play an important role in human nutrition, health and wellness (Hicks, et al., 2019), (Hua, et al., 2019), (Marques, et al., 2021).

Seaweed farms also have the potential to provide sufficient biomass and protein for a growing population and their cultivation can have a positive impact on ecosystems, providing shelter to marine species, improving local biodiversity, as well as providing several other ecosystem services (Bizzaro, et al., 2022). One of these services is the extraction of dissolved nutrients, such as nitrogen and phosphorus, which has led to increased cultivation of seaweeds with other aquaculture species, such as fish, molluscs, and crustaceans, in what is known as IMTA.

Integration of seaweed(s) with other cultured species in Saldanha Bay could promote better use of the allocated aquaculture space and improve both the environmental and economic sustainability of farms in the bay. However, the nutritional value of the candidate aquaculture seaweeds needs to be characterised to determine their beneficial value for human consumption and for animal feeds, and hence their economic potential.

Therefore, the objective of this portion of the study was to characterise the nutritional value of the three candidate kelp species, *E. maxima, M. pyrifera* and *L. pallida* to identify nutritional and functional ingredients for human consumption as well as for animal feeds.

6.4.2 Methods and work plan

E. maxima, M. pyrifera and *L. pallida* were collected from Kommetjie near Cape Town where all three species co-exist. Three composite samples of each seaweed (0.5 – 1kg each) were collected from the sampling area and placed in sealable (Ziploc) bags clearly labelled with species name, date, composite sample number and sample location, and placed in a cooler box for transportation. Samples were immediately transported to the Department of Biotechnology and Consumer Science, Functional Foods Research Unit, at the Cape Town University of Technology (CPUT) where they were immediately homogenised and freeze dried and stored at – 20 °C until further analysis.

Proximate (protein, lipid, carbohydrate, moisture, and ash content) and fatty acid composition of all samples were analysed at CPUT. The protein content was determined using the Dumas combustion AOAC official method 992.15 (1992), using a Leco protein analyser. The moisture content of all samples was determined using the vacuum oven AOAC official method 934.01 (2002). The ash content was determined using the muffle furnace method according to AOAC 942.05 (2002). Total crude fat content was isolated using the Folch et al. (1956) method. The total crude fat content and fatty acid composition was determined on a GC-FID using the AOAC official method 996.06 (2005). Carbohydrates were calculated by difference.

Specific minerals (iron, copper, selenium, zinc) and vitamins (A, B12, D) were analysed by an external provider, Microchem Lab Services (Pty) Ltd (http://www.microchem.co.za). All analyses were performed in triplicate.

The analysed nutritional values of the seaweeds will be statistically compared by One-way ANOVA ($p < 0.05$). The post-hoc Holm−Sidak method for pairwise comparisons will be used to discriminate the significant differences.

6.4.3 Progress and preliminary results

All seaweed samples were homogenised and freeze dried and aliquots of samples were submitted to respective laboratories for analysis. Mineral analysis of samples has been completed (see Table 8). Analysis of vitamins is underway, with results expected in June 2022, whereas the results on fatty acid content are expected in March 2022. Proximate (protein, lipid, carbohydrate, moisture, and ash content) analysis is underway. Moisture and ash analysis has been completed, with a mean (±SD) moisture content of 82.30±2.07, 80.94±1.04 and 85.66±2.69 and an ash content of 4.10±0.59, 4.28±0.11 and 3.88±0.38 recorded for *E. maxima*, *L. pallida* and *M. pyrifera*, respectively. Protein, lipid, and carbohydrate results are only expected in April 2022.

A comprehensive statistical analysis of data and how results compare with available data on these species in the literature (if data exists) will be conducted once all nutritional analysis has been completed.

The results of this portion of the study will provide essential baseline information for these kelp species in South Africa and the potential for their use as nutritional and functional ingredients for human consumption and for animal feeds.

Table 8: Mineral content of *Ecklonia maxima, Macrocystis pyrifera* and *Laminaria pallida* collected from Kommetjie near Cape Town

	Al	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Cd	Sb	Hg	Pb	Ca	K	Mg	Na	P
	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	ug/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
LOD	121.25	0.64	11.51	8.98	67.04	0.57	8.07	22.43	28.48	4.39	6.25	1.71	0.55	8.77	1.22	10.00	10.00	10.00	10.00	10.00
% Accuracy on internal QC	113.9	112.0	111.8	110.8	112.5	109.6	107.5	111.2	112.0	116.4	122.4	110.7	102.2	113.0	109.3	104.7	102.9	100.7	99.6	117.8
% Recovery on Certified reference Material Tort-3	NA	104.9	107.5	101.3	99.8	107.9	102.1	96.0	101.5	103.6	96.0	101.4	NA	97.9	100.2	NA	NA	NA	NA	NA
Ecklonia maxima	7360.11	558.22	1947.59	4669.92	83024.39	436.54	718.94	2558.91	18092.49	49546.00	25.00	1364.65	29.19	17.91	90.59	9521.18	66248.84	7773.64	40050.21	2396.20
Laminaria pallida	5931.03	495.11	517.43	3571.33	33462.98	450.50	661.03	1881.41	33155.00	58468.57	28.23	867.36	24.51	18.93	76.23	9371.03	69567.41	7570.40	37118.28	3602.79
Macrocystis pyrifera	67711.88	2443.15	606.03	4926.96	39915.37	193.73	678.86	1630.28	17830.82	85825.94	31.42	4369.43	32.57	18.43	117.15	9382.97	86756.35	7636.91	40929.27	4253.71

6.5 Study of the appropriate technologies for kelp cultivation

Dr Mark Rothman (DFFE/University of Cape Town) and Mr Barend Stander (BSASA) conducted a study of the most appropriate technologies for sustainable joint ventures for kelp cultivation. The objectives were to select suitable sites for the set-up of pilot kelp cultivation systems and complete a cultivation system design. The timeline for the site selection and system design was end of March. Depending on further funding, the pilot systems will be set up and operated after March 2022.

6.5.1 Site selection and pilot set-up

This included site selection and setting up of pilot kelp cultivation systems (rope rafts) in both the inner and outer bays of Saldanha Bay. The objective was to use the results from the kelp seeding and growing experiments to enable the establishment of a research platform for government and industry stakeholders to continue to derive learning beyond evidence funding (EF) allocated in the 2021/22 financial year.

The sites selected for the pilot cultivation systems are located within the West Coast Oyster Growers aquaculture farming areas in Saldanha Bay (Figure 11). West Coast Oyster Growers consists of two 15 ha longline bivalve farms (mussels, [*Mytilus galloprovincialis]*, and oysters, [*Crassostrea gigas]*), within the Aquaculture Development Zone (ADZ) in the Small Bay and Big Bay areas of the Saldanha Bay harbour. These sites have current research permits, which is one of the regulatory requirements for the implementation of the pilot kelp rafts. The rafts would be standalone structures, using current moorings to secure them.

The Small Bay farm (Figure 12) use single dropper mussel longline culture method, as well as basket oyster culture. This site is much older and is currently undergoing a realignment, as well as a shift to more oyster production. Line numbers 1-26 was traditionally the mussel farming operation that is now discontinued, line 1-7 have been converted to oyster lines, the area of line 7 - 10 would be the site area for the kelp rope raft (Figure 13). The site has an average water depth of 7 m, with a sandy substrate. Because kelp need water flow to obtain nutrients, there are concerns about the water flow at the Small Bay site. However, the mussel lines will be disconnected on installation of the kelp raft, and therefore are not expected to obstruct water flow.

The coordinates for the proposed Small Bay Site are as follows:

- RR NW 33° 0.262'S 17° 57.802'E
- RR NE 33° 0.262'S 17° 57.834'E
- RR SE 33° 0.289'S 17° 57.835'E
- RR SW 33° 0.289'S 17° 57.802'E.

The Big Bay farm (Figure 14) use continuous mussel long line culture and are restricted in number of lines for cultivation of mussels by the ADZ. The vacant area closer to shore (Figure 15) can be used for the kelp rope raft. The site has an average water depth of 9 m, with a sandy substrate.

The coordinates for the proposed Big Bay Site are as follows:

- B RR NW 33° 1.724'S 18° 1.316'E

- B RR NE 33° 1.738'S 18° 1.344'E
- B RR SE 33° 1.762'S 18° 1.331'E
- B RR SW 33° 1.749'S 18° 1.303'E.

Figure 11: Location of West Coast Oyster Growers Mussel and Oyster Farms within the ADZ of Saldanha Bay

Figure 12: Location of West Coast Oyster Growers Mussel Farm within the ADZ, Small Bay (yellow polygons – A to F)

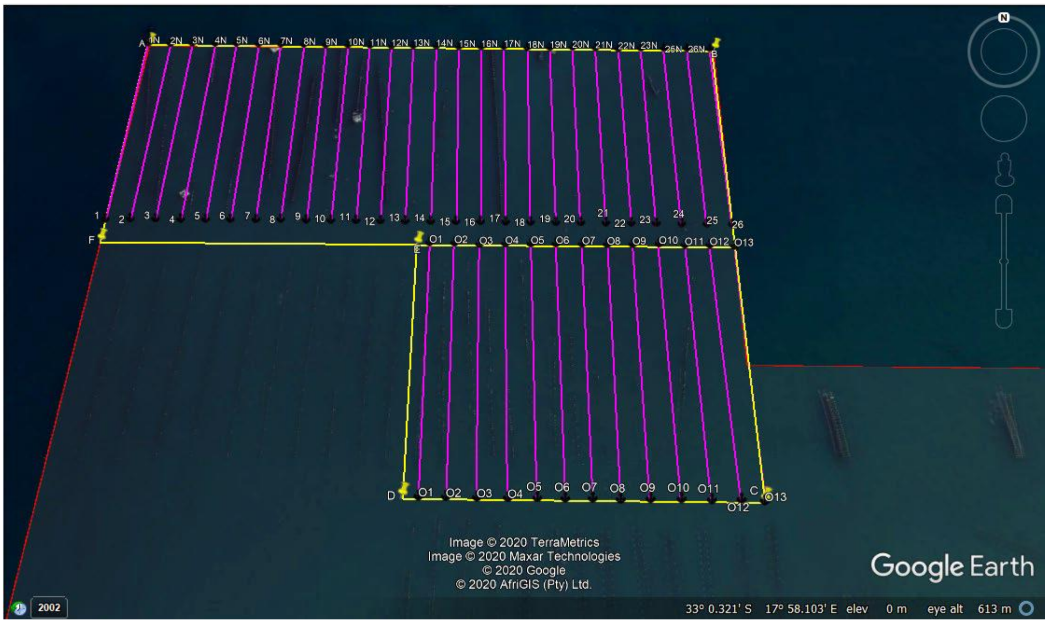


Figure 13: West Coast Oyster Growers 1-26 Mussel and Oyster line with mooring block numbers and West Coast Oyster Growers O1-O13 Oyster line with mooring block numbers

Figure 14: Location of West Coast Oyster Growers Mussel Farm within the ADZ, Big Bay (yellow polygons – B101, B102, B103 and B103)

Figure 15: West Coast Oyster Growers 1-11 with mooring block numbers

6.5.2 Cultivation system design

The cultivation system design included an assessment and review of available systems and recommendations for fit within the proposed environments, and recommendations for systems (including seeding and harvesting technical requirements and any regulatory issues) suitable for Saldanha Bay (inner and outer bay) and offshore environments.

The proposed pilot kelp rope raft is outlined in Figure 16. The raft can be used to grow any of the three kelp species considered for this study. The raft dimensions are 20 x 64 m (1 280sqm). It will have the following components:

- Main frame:
  - Mooring blocks, shackles, and anchor warp
  - Main frame grid and corner floats
- Raft:
  - Raft outer frame and cultivation ropes
  - Raft floats, weights, and bridle ropes.

The estimate cost for one pilot kelp raft (including main frame and raft) is about R114 000, including material transport cost, assembling and installation cost, vessel and diver cost, inspection trip cost, seeding trip cost and spare/service components. For two rafts the costs will be R228 000. Considering that the main frames for both rafts include infrastructure such as mooring blocks a are already in place, the total costs for the manufacturing and installation of the pilot rafts are expected to be less.

The pilot raft has been designed to be angled so that culture ropes hang 1 m below the water surface on one side, and 4 m below the surface on the other side. This will allow observations of the effects of different light and other environmental conditions over the depth gradient on kelp growth. Each pilot raft will have 13 culture ropes of 20 m each. Based on current understanding of pilot and commercial kelp farming in other parts of the world, expected yield could be about 10 kg/m. It is also expected that kelp grow-out time will be reduced through force cultivation (using seeding and growing under controlled condition in a kelp hatchery/nursery).

The rope raft was constructed using the design in Figure 16, and preparation of the site where it will be installed, are in progress. The kelp pilots in Saldanha Bay will be used to test assumptions such as the number of harvests per year and yield per m of culture rope. It will also be used to gather critical technical and economic information to be incorporated in a kelp cultivation feasibility study. It will therefore be critical to apply for follow-on funding to continue with these pilots.

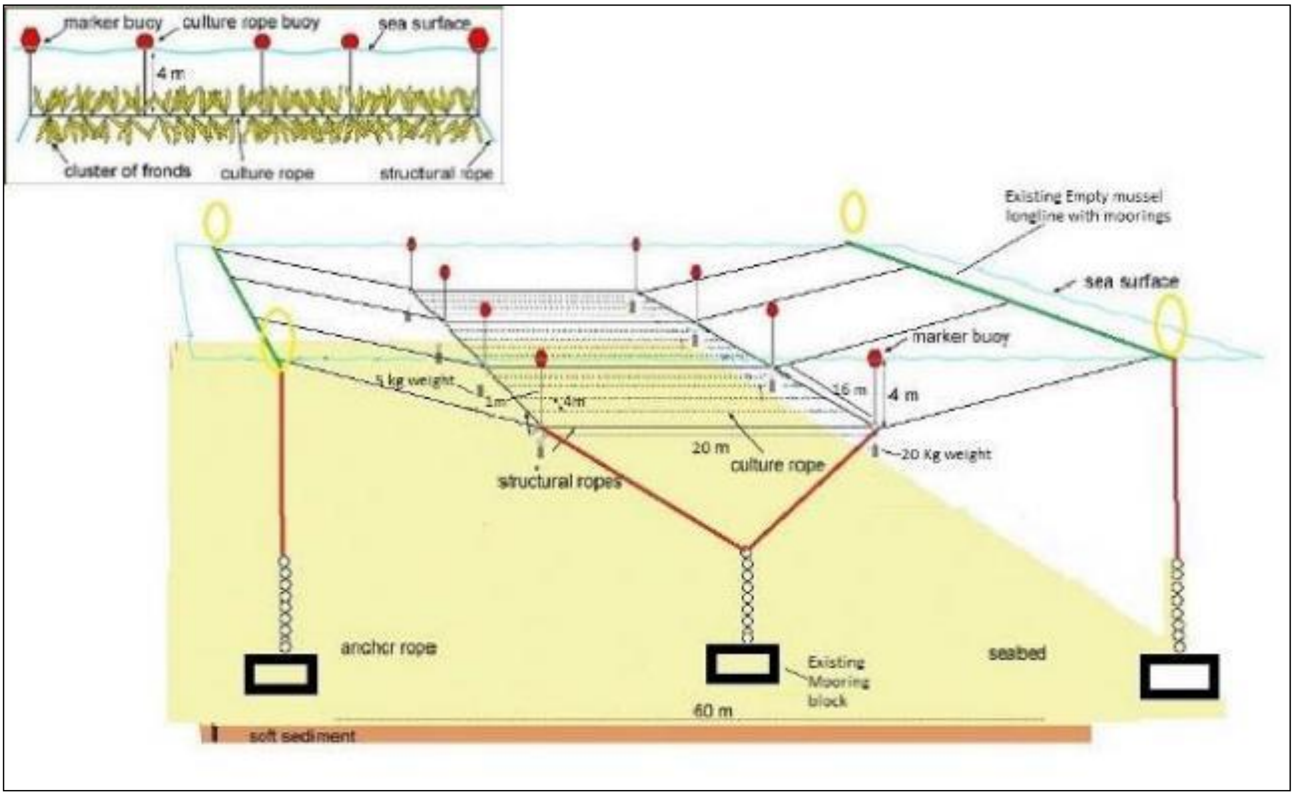


Figure 16: Kelp rope raft design

6.6 GIS study to assess coastal areas available for commercial kelp cultivation along the West Coast

Based on the ecological requirements for optimal kelp growth, areas suitable for commercial kelp cultivation in South Africa were investigated through a GIS study and mapping of areas along on SA's West Coast. This included a GIS analysis of the offshore environment, and of the Saldanha Bay environment.

This study was led by Dr Melanie Lück-Vogel (CSIR Smart Places) and her team from the CSIR Smart Places Cluster and CSIR Enterprise Creation for Development.

6.6.1 GIS analysis of offshore environment

The Final Report: "Offshore GIS study of available area for commercial kelp cultivation along South Africa's West Coast" is attached as Appendix C. The final outputs from the report are summarised in this section.

The work included the following activities:

- Identification of key environmental requirements for kelp growth, together with kelp ecology expert within the project (Prof John Bolton); the three species that were investigated include *E. maxima*, *L. pallida* and *M. pyrifera*.
- Identification of "hotspots" where kelp farming is feasible based on the mapping of the identified thresholds of the respective environment parameters.
- Identification of environmental conditions required for offshore kelp farming, together with the wider project team, and translation of existing geospatial information thereof into a Geographic Information System (GIS).
- Identification and sourcing of existing information on non-ecological requirements for seaweed farming, and translation thereof into a GIS.
- Source existing information on conflicting use areas, such as (marine) protected areas, vessel traffic areas etc. and translation thereof into a GIS.

Based on the collated information the following results were produced:

- Delineation of "hotspots" where kelp farming is biologically feasible
- Delineation of "cold spots" where non-biological factors inhibit or hinder kelp farming.

The study area was the West Coast of South Africa, west of Agulhas to the mouth of the Orange River. The key environmental requirements for kelp growth are listed in Table 9. For these key parameters, GIS datasets were sourced, where accessible. The optimal and tolerated parameter ranges (or range gradients, where no optimal and tolerated ranges could be defined) were displayed.

No analysis was conducted for the coast type, i.e., rocky shores versus sandy shores because it is well established that kelp naturally requires a solid, i.e., rocky substrate to grow on. Secondly, for the offshore farming, there is no dependence on natural substrate, as the plants will be tied to ropes on rafts.

Table 9: Optimal and tolerated ranges of physical and chemical key parameters for kelp growth

	Key Parameter[1]	optimal range	tolerated range	Comments
Physical	Depth [1]	0-20m	< 150m (farms)	
	Wave energy [2]			
	Current strength [3]			No GIS data available for this project phase, for next phase, investigate: https://www.ncei.noaa.gov/access/data/global-ocean-currents-database/category.html
	Sea Surface Temperature (SST) annual mean [4]	8 - 15°C	0-20°C	
	SST monthly max [5]	10-15°C	Monthly max 20°C	No SST monthly max data available for this project phase.
	Turbidity [6]	The less the better		
Chemical	Mean dissolved Oxygen [7]	The more the better		
	Mean Nitrate [8]	The more the better	minimum: 1-2 µmol L-1	
	Mean Phosphate [9]	The more the better		
	Salinity [10]	35ppt	32-38ppt	

Some key land use parameters were analysed to assess if there are potential conflicts with raft-based kelp farming activities to be expected. The analysed parameters include the presence of aquaculture development zones and protected areas, areas licensed for mineral mining and vessel traffic and oil spill risk. Table 10 briefly summarises the expected impact of each of these parameters.

Table 10: Expected impact of key land use parameters on kelp farming activities

Land use parameter	Impact on kelp growth & farming
Aquaculture development zones	Kelp farming may be prioritised
Existing marine aquaculture	Potential market for kelp and existing infrastructure
Conservation/protected areas/MPAs	Exclusive. No farming possible.
Mineral mining	Access restrictions and physical disturbance of rafts
Vessel traffic	Physical disturbance and damage to rafts; pollution

Synoptic assessments of relevant aspects were conducted for the Northern Cape coast (Table 11), the Saldanha- St Helena Bay area (Table 12), and the Southern study area (Table 13).

[1] *Numbers in brackets refer to the source of the related GIS layer provided in the Appendix of the Final Report*

Table 11: Synoptic assessment for the Northern Cape Coast

Aspect	Comments
Water depth & distance to coast	The coast is relatively steep, leading to the 20 km bathy contour being about 2 km away from the shore and the 50 m bathy contour about 5km away, which is very close. From the perspective of access by boat, this is beneficial.
Wave energy	Low to moderate (up to 40 kW/m) between Alexander Bay and Kleinzee. Moderate south of Kleinzee (20-60 kW/m)
Vessel traffic	High around and north of Port Nolloth, low south of Port Nolloth
ADZs and MPAs	No conflict between protected and designated ADZ areas
Settlements	Some small settlements present (Port Nolloth, Kleinzee and Hondeklipbaai) with fishing and aquaculture facilities (and workforce) present. However, long distance to potential markets.
Conclusion	**The Northern Cape coast, with its extensive Namakwa ADZ, moderate annual wave energy and short distance to suitable water depth, should be suitable to offshore kelp farming, especially in the vicinity of the small towns.**

Table 12: Synoptic assessment for the Saldanha- St Helena Bay area

Aspect	Comments
Water depth & distance to coast	In the West Coast ADZ and the open coast of the Saldanha ADZ, the coast is relatively steep, leading to the 20 km bathy contour being between 1-2 km away from the shore and the 50 m bathy contour about 5 km away, which is very close. From the perspective of access by boat, this is beneficial. In the area of St Helena Bay the coast is very shallow, and the 20 m contour is between 3-5 km offshore, and the 50 m contour between 13-20 km. However, the extensive areas shallower than 20 m provide ample space for kelp rafts as well.
Wave energy	The maximum annual wave energy in the area of the West coast ADZ is low to moderate (up to 40 kW/m), in St. Helena Bay it is very low (up to 20 kW/m), on the open coast of the peninsula north of Saldanha, wave energy ranges between low and high (20-60 kW/m), depending on the location of the highly diverse coast.
Vessel traffic	Very low in the West Coast ADZ, very high in the sheltered 20-50m depth zone in St. Helena Bay NE of St Helena, high at the entrance of Saldanha Bay and in Big and Small Bay Low around the Peninsula north of Saldanha Bay
ADZs and MPAs	No conflict. Extensive ADZ area in this region
Settlements	Regional service town (Saldanha) and other settlements present, with good infrastructure, work force and fishing/boating facilities. Good access to large markets (Cape Town).
Conclusion	**Best kelp farming potential in the shallow sheltered southwest area of St. Helena Bay, in waters to 20m depth, St Helena port enables easy boat launch and harvest collection.** **West Coast ADZ might be feasible too, but wave energy here is somewhat higher. The exposed shore of the Saldanha ADZ might be less suitable, due to stronger waves and longer access routes from Saldanha or St Helena Bay. (The inner Saldanha Bay area was**

Aspect	Comments
	assessed separately.)

Table 13: Synoptic assessment for the southern study area

Aspect	Comments
Water depth & distance to coast	Extensive shallow areas in False Bay, with the 20 m contour about 3-4 km offshore and the 50 m contour about 15 km For the open shore southeast of False Bay, 20 m contour between 0.5 and 4 km offshore, the 50 m contour about 3 – 15 km offshore. The extensive areas less than 20 m deep at Bettys Bay and between Franskraalstrand and Struisbaai do perhaps allow kelp farming in those areas too.
Wave energy	Very low to low in False Bay (mostly <20 kW/h) low to moderate between Betty's Bay and Gans Bay Low to moderate between Franskraalstrand and Pearly Beach (no data further east). However, high to very high wave energy around land tips between Pringle Bay and Bettys Bay at Danger Point and Cape Point
Vessel traffic	Very low in the potential kelp farming area on the open coast somewhat high in False Bay, however, the type of vessels here (touristic small vessels?) needs to be established
ADZs and MPAs	The whole of the Cape peninsula and west of False Bay is MPA Entire Walker Bay is MPA Large Agulhas ADZ would enable kelp farming from Bettys Bay eastward False Bay not part of ADZ
Settlements	Simonstown and GordonsBay provide fishing infrastructure in False Bay, several well-established fishing and aquaculture facilities and towns between Pringle Bay and Pearly Beach to facilitate farming activities and provide market opportunities
Conclusion	**High potential for kelp farming between Betty's Bay and Hawston, southwest of Gans Bay and between Franskraalstrand and Pearly Beach, given high settlement density, low to moderate wave energy and extensive suitable depth zones.** **False Bay might be suitable, too, but is not designated ADZ.**

Based on these synoptic assessments, potentially suitable sites for offshore kelp cultivation have been identified. The locations of ten potentially suitable areas in the study area are presented in Figure 17. Potentially suitable areas are also presented for the open West Coast (Figure 18), Saldanha-St Helena area (Figure 19) and southern study area (Figure 20.

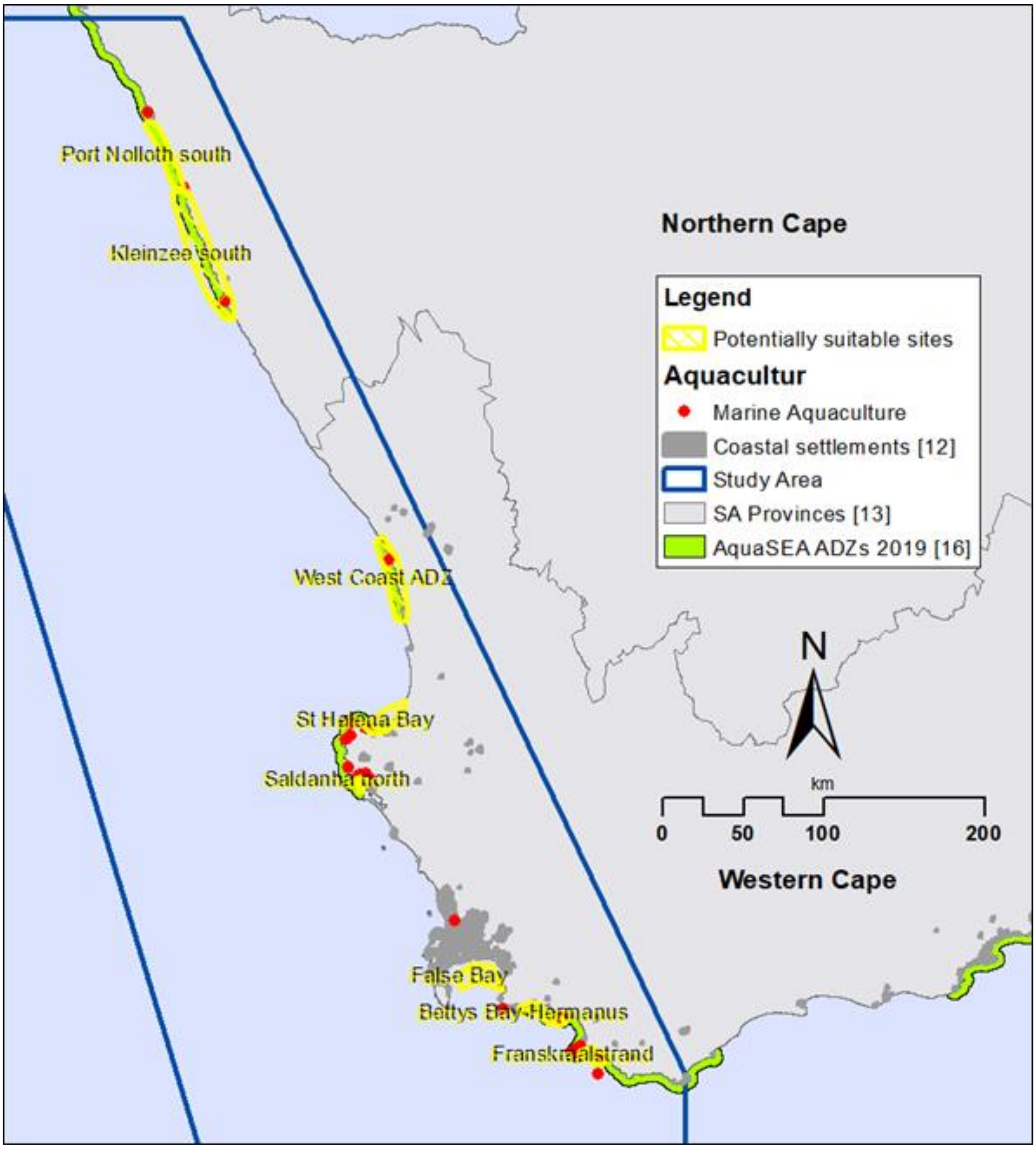


Figure 17: Location of potentially suitable kelp farming areas in the study area

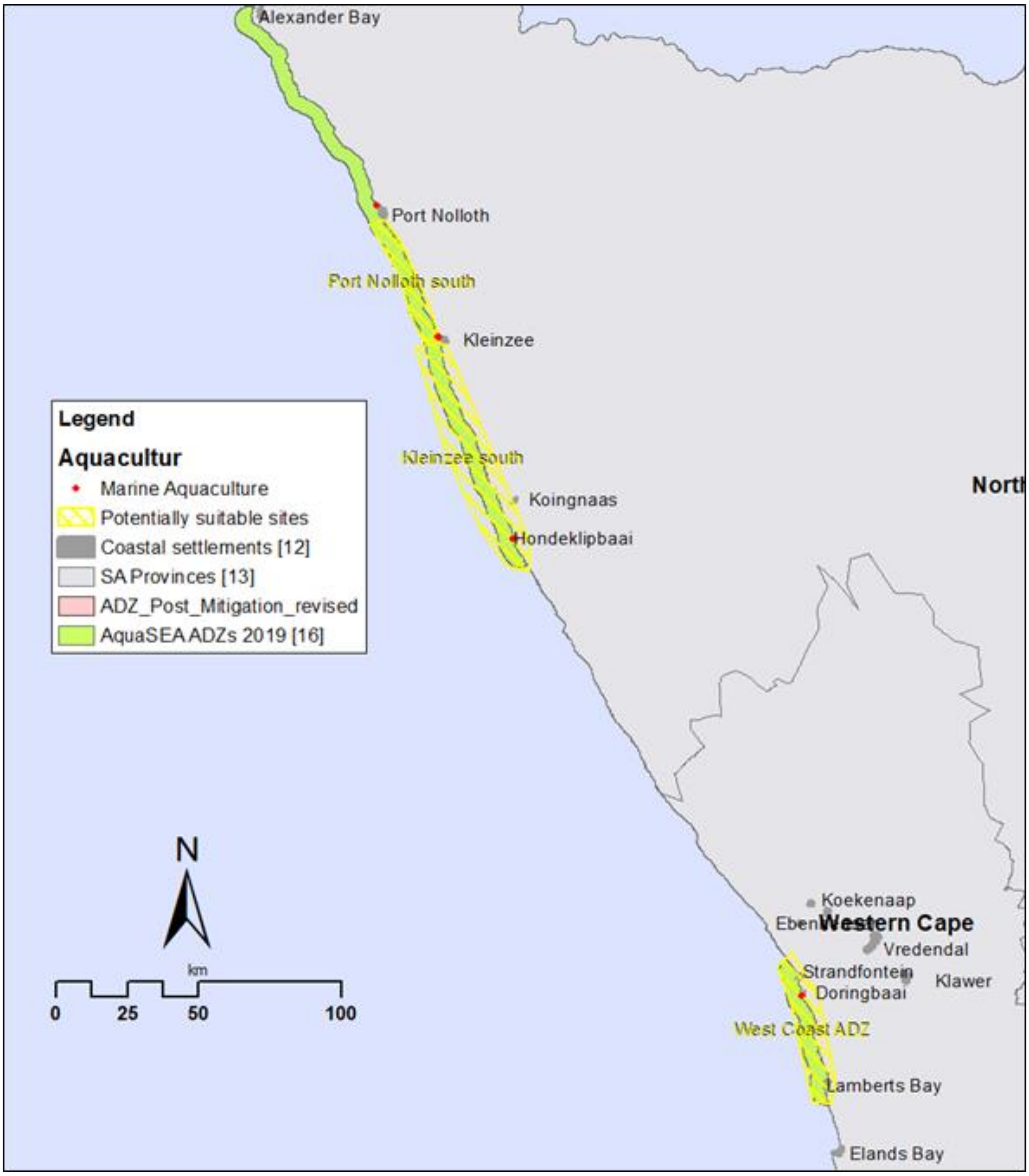


Figure 18: Location of potentially suitable kelp farming areas on the open West Coast

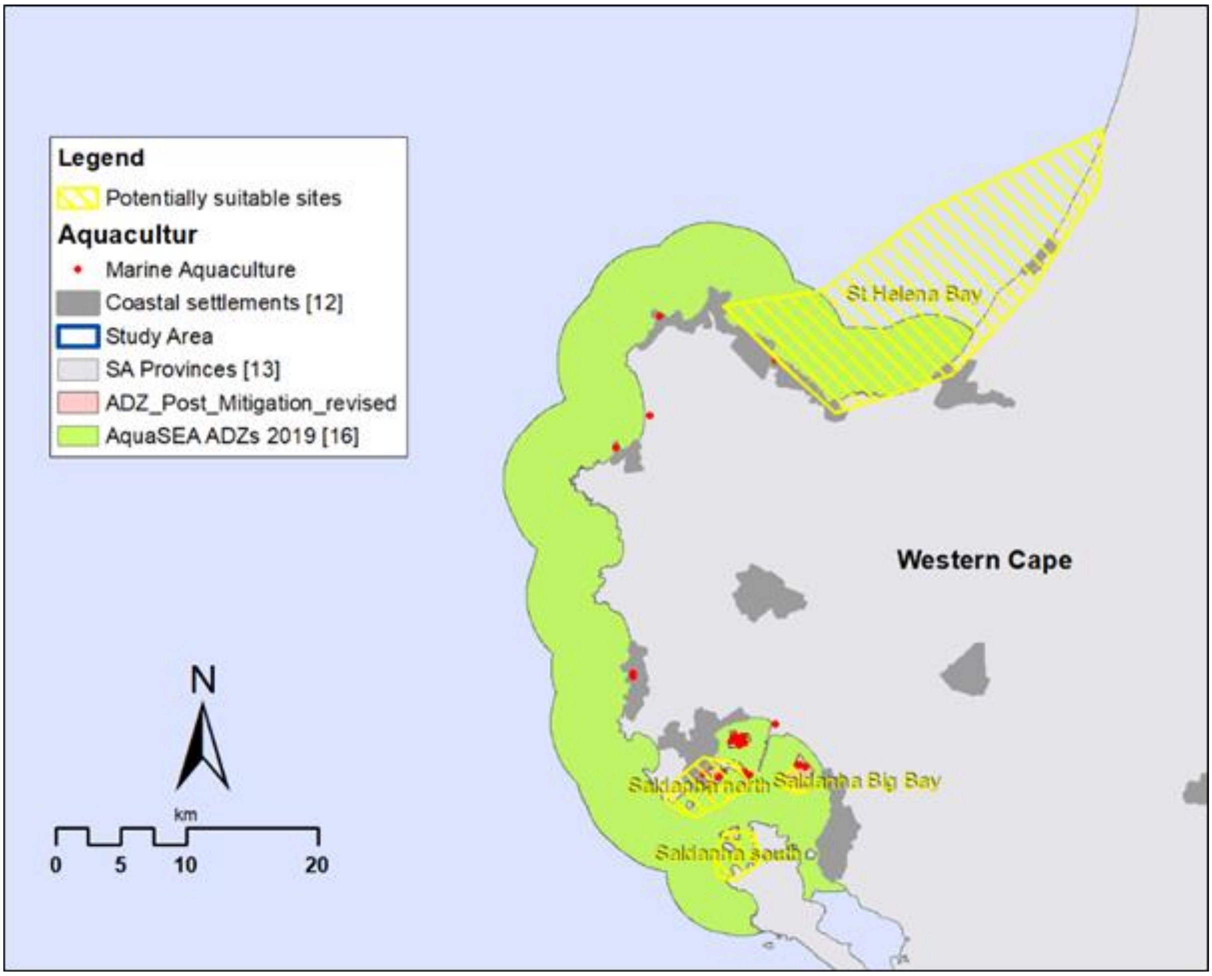


Figure 19: Location of potentially suitable kelp farming areas in the Saldanha-St Helena area

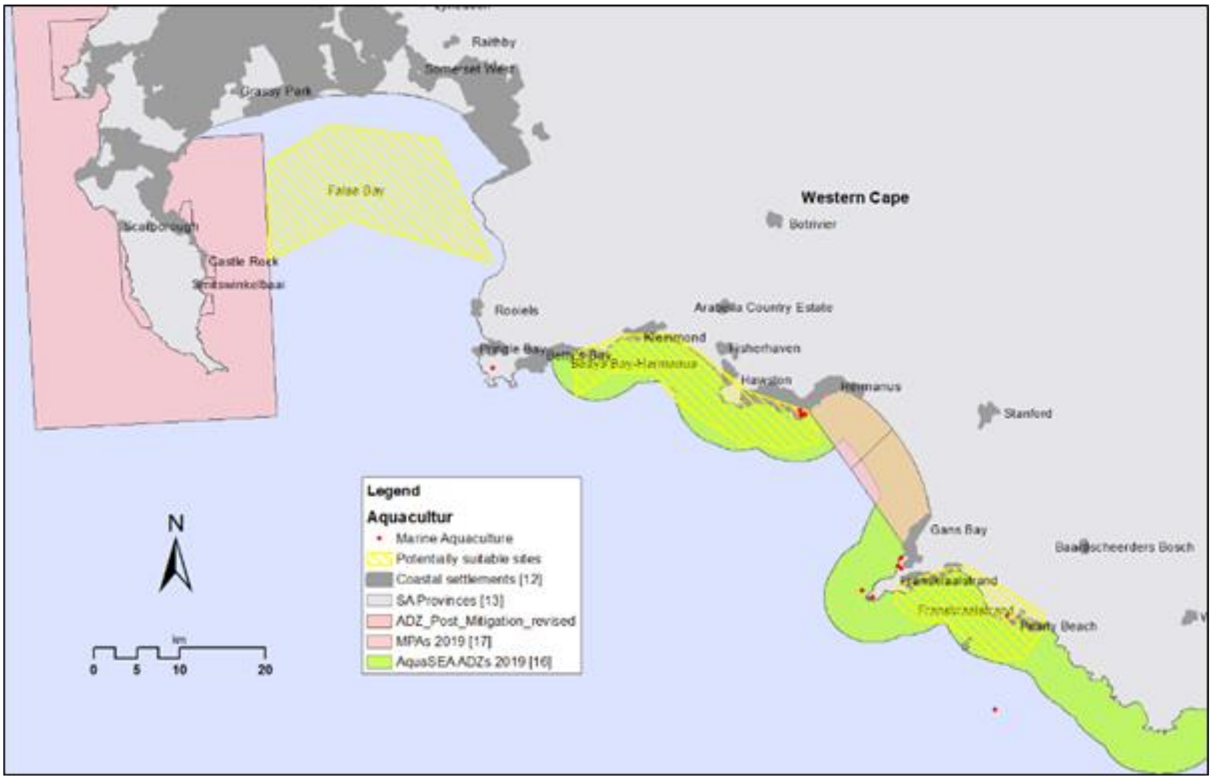


Figure 20: Location of potentially suitable kelp farming areas in the southern study area

Due to the limited time frame of the Pre-feasibility Study, it was not possible to obtain data sets for all the parameters deemed important for assessment of suitable areas. One of the parameters that need to be investigated in the next phase of the project, is the patterns of marine mammal movement in the study area. This will be critical in assessing the potential for entanglement of these animals in offshore kelp cultivation areas. It is therefore important to include this investigation in an application for funding for a full feasibility study.

6.6.2 GIS analysis of Saldanha Bay environment

The objective of this part of the study was to map the area available for commercial production in Saldanha Bay (based on environmental conditions and approved lease sites).

The same environmental conditions (optimal and tolerated ranges of physical and chemical key parameters for kelp growth) for the offshore GIS study (Table 9) were assumed to be relevant to Saldanha Bay.

The average wave energy for winter, as measured along the 7 m and 15 m bathy contours, are illustrated in Figure 21. The ADZ zones are located mostly in areas with average wave energy of less than 35 kW. The wave energy should not be a problem, as kelp need wave energy for sufficient water flow and nutrient uptake. Reduced wave energy therefore may be a problem for kelp nutrient uptake in Small and Big Bay.

In the open sea, nitrogen is generally available year-round. This is not the case in Saldanha Bay, where it is known that stratification of the water column occurs in Inner Bay around March. This is when warm, nutrient poor water floats on top of cooler, deeper (around 6 m deep) nutrient rich water (Anderson, et al., 1996), (Anderson, et al., 1999). This phenomenon caused crashes of *Gracilaria* in previous cultivation operations and may also cause die-offs of cultivated kelp. This may require a farming regime where kelp is harvested before autumn.

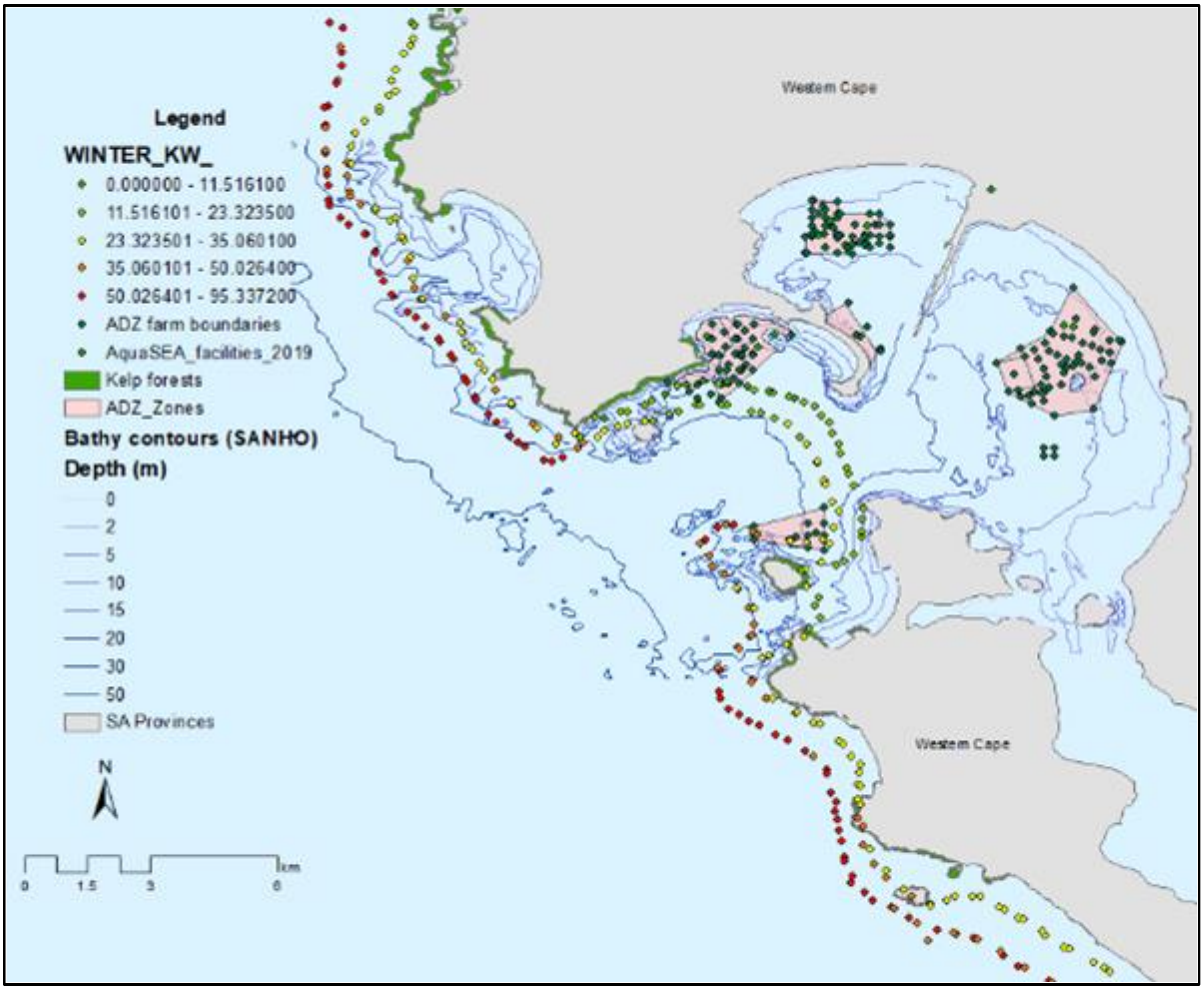


Figure 21: Wave energy patterns in winter in relation to Saldanha Bay ADZ areas

Table 14 summarises the expected impacts of key land use parameters analysed to assess potential conflicts with raft-based kelp farming activities. These parameters include the presence of aquaculture development zones, and ship vessel traffic. Aquaculture development zones are not expected to have a negative impact, as seaweed aquaculture will be allowed in those zones. Passenger, leisure, and oil and gas ship vessel traffic is expected to have low impact on these ADZs. However, fishing vessel traffic is expected to have high potential impact on the ADZ zones (as illustrated in Figure 22). Cargo vessel traffic is expected to have very high potential impact on the ADZ (Figure 23). The implications of these traffic volumes on kelp cultivation in the ADZ, and potential measures for regulation or control, should be investigated as follow-on research during a full feasibility study.

Table 14: Expected impact of key land use parameters on kelp farming in Saldanha Bay

Land use parameter	Impact on kelp growth and farming
Aquaculture development zones	Seaweed farming allowed in areas allocated for Saldanha Bay ADZ
Ship vessel traffic: Passenger, Leisure, Oil & Gas	Expected low impact in Saldanha Bay ADZ zones
Ship vessel traffic: Fishing	High potential impact in Saldanha Bay ADZ zones
Ship vessel traffic: Commercial Cargo	Very high with potential impact in Saldanha Bay ADZ zones

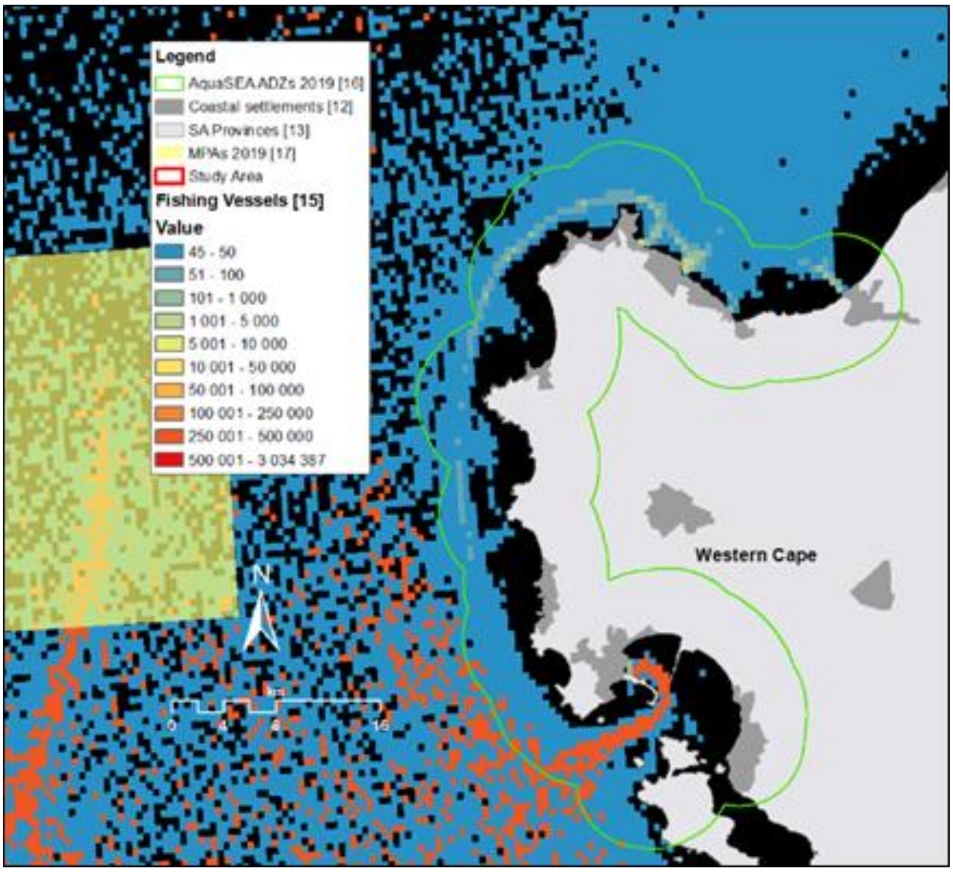


Figure 22: Fishing vessel traffic in Saldanha Bay

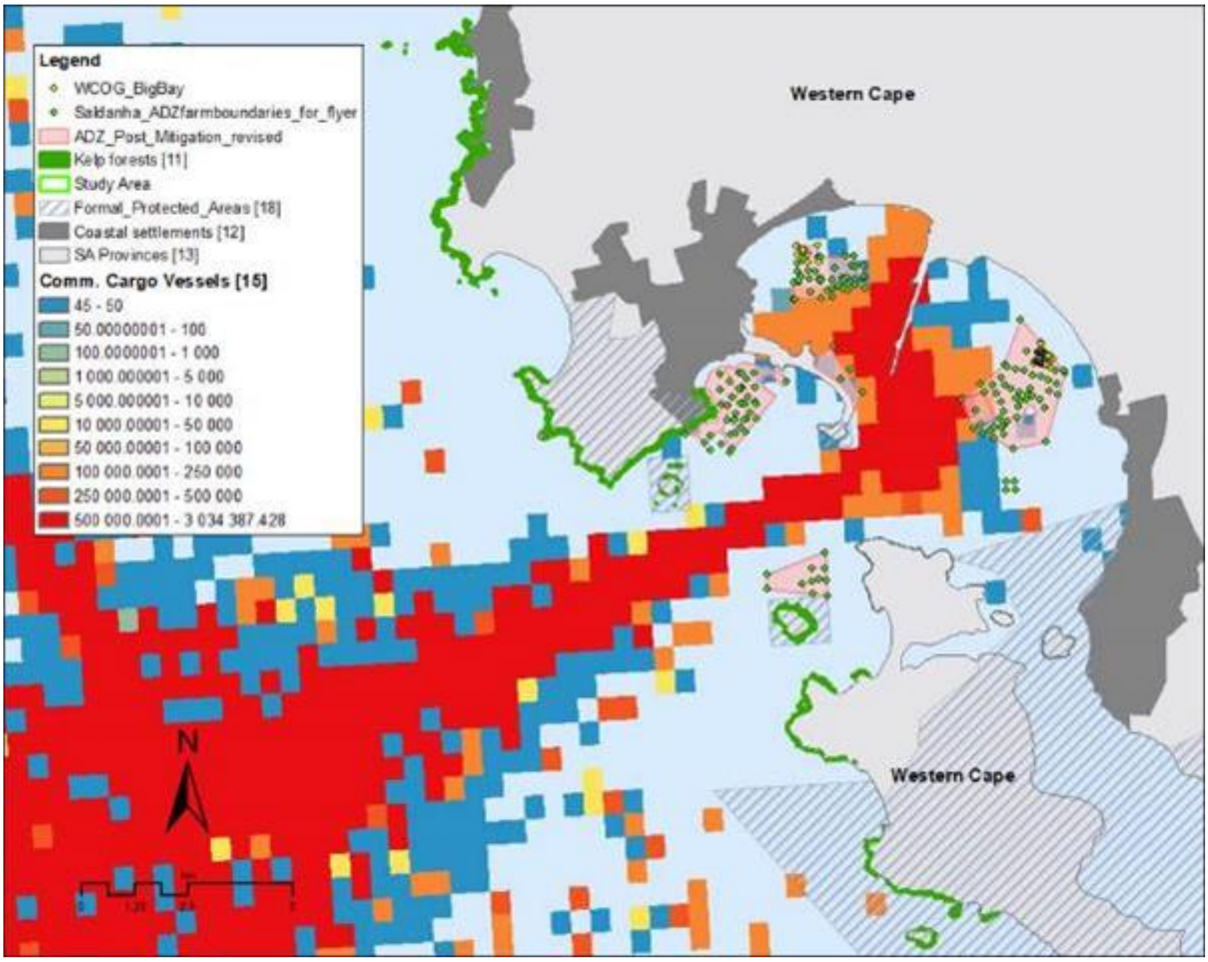


Figure 23: Potential impact of cargo vessel traffic on Saldanha Bay ADZ areas

The Saldanha Bay ADZ includes four areas that have been formally approved and have environmental authorisation for aquaculture activities including seaweed cultivation. Therefore, most limiting factors have been assessed for general aquaculture activities. For kelp cultivation, the limiting factors that could be identified during this phase of the Pre-feasibility Study phase, include potentially limiting nutrient levels in Inner Bay (Small and Big Bay) in March, fishing vessel traffic and cargo vessel traffic. The better areas for kelp cultivation may be Outer Bay North and South, where wave energy is relatively high in comparison to Inner Bay (Small Bay and Big Bay). However, this assumption will need to be tested during cultivation trials. It will therefore be important to include such investigation as follow-on research in funding applications for a full feasibility study.

6.7 Technical requirements for South African kelp cultivation

Due to the limited information available for kelp cultivation in South Africa, assumptions about the technical requirements and estimated costs related to cultivation of South African kelp are based on cultivation trials and commercial cultivation elsewhere in the world.

Because most seaweed aquaculture takes place in East Asia, some lessons can be learnt from East Asian seaweed farmers such as the Japanese kelp (Kombu) growers. Their growth cycle can be halved from 2 years (natural cycle) to 1 year by 'force cultivation' in kelp hatcheries. Seedling production and culture of gametophyte phases take place in facilities with seeding and culture tanks and equipment to control seawater temperature, light, nutrients, and other conditions. Seeded strings/ropes are then hung onto cultivation rafts (see Figure 24) for acclimatisation. After 7-10 days the seeded strings are cut into lengths of 5 mm and inserted into the main cultivation ropes for regular cultivation. Blade wet weight of 1.25 kg could be achieved at harvest time (Kawashima, 1997).

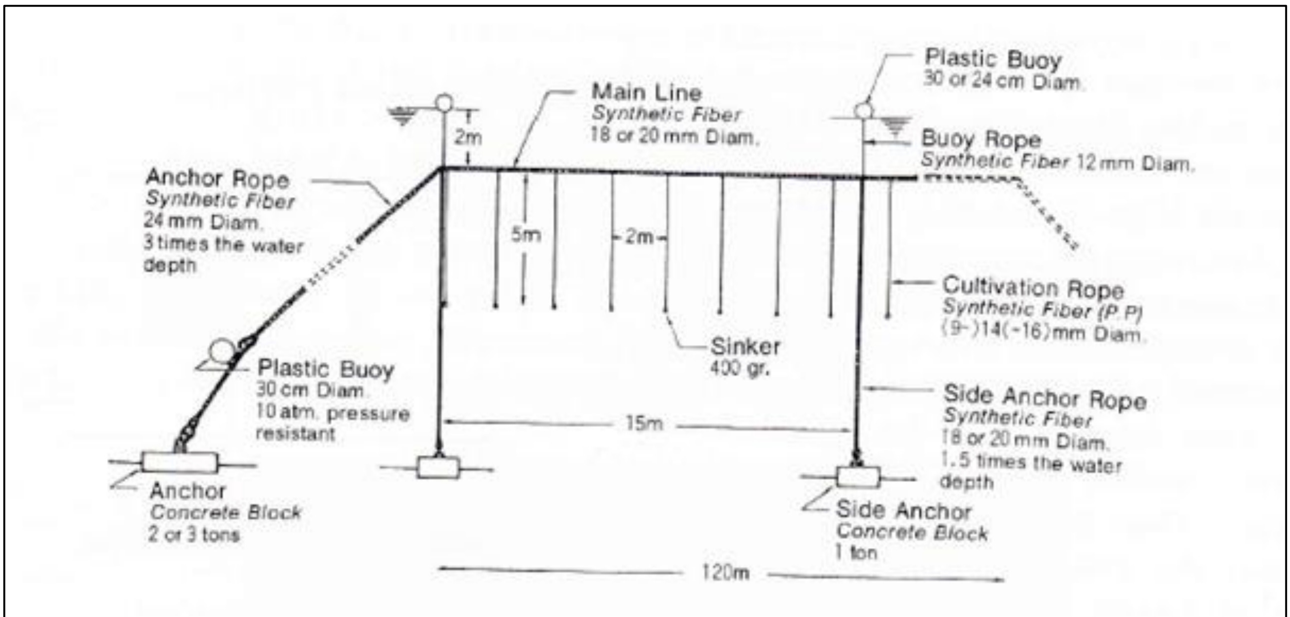


Figure 24: Japanese kelp (Kombu) cultivation raft
Source: **(Kawashima, 1997)**

The results and economic assumptions of three trials on different kelp species are summarised in Table 15. The cultivation of *Saccharina latissima* was tested on an offshore Macroalgae Cultivation Rig (MACR) with 250 vertical growth lines of 10 m each in the Faroe Islands (1ha sea space), at a water depth of >50 m. From four harvests over two years, an average yield of 0.32 kg/m/harvest dry weight (DW), equivalent to 6.4 kg/m/year wet weight FW), was obtained. The total cost per kg dry weight ranged from €36.73 to €9.27 depending on the number of harvests without re-seeding, and the yield per m of cultivation rope. Productivity was estimated at 1437.5 kg/ha/year DW if two harvests without re-seeding were assumed (Bak et al 2018). For purposes of comparison, the cost per kg was converted to US$ cost per kg wet weight. For this trial, the farm gate cost per kg FW was therefore estimated at US$ 2.45/kg. The study did not include estimates of profitable scale or farm gate price.

A study on the cultivation of *S. latissima* in New England using 100 m longline cultivation method indicated an average yield of 10 kg/m/year FW, profitable scale of 250 longlines producing 250 t/year FW, farm gate production cost of US$1.16/kg FW and profitable farm gate price indication of US$2.20/kg. Delivered cost of consumer product FW was US$5.8/kg (ZAR85.09/kg), cost of delivered consumer product DW was US$8.29/kg (ZAR121.61/kg) and price indication for high-end food market product was US$15/kg (ZAR220.05/kg). This indicated a profitable operation at the 250 longline scale (Yarish, et al., 2017). If longlines are placed 1.5 m apart, a minimum farm size of 3.75 ha is required. At 6 m longline intervals, a farm size of 15 ha will be needed.

A trial on the production of *M. pyrifera* for abalone feed in Chile using 80 m longlines with 134 vertical growth lines indicated average yield of 41 kg/m/year FW, a minimum profitable farm scale of 30 ha, and profitable farm gate price of US$0.078/kg, and return on investment after one year (Correa, et al., 2016). Figure 25 illustrates an experimental harvest of sugar kelp in Scotland.

Figure 25: Experimental harvest of sugar kelp in Oban (Scotland)
Source: John Bolton

The above examples highlight the difficulties in comparing the results of trials on different species, in different locations and using different technologies. They also highlight the importance of conducting species-specific trials in different locations (relatively sheltered and offshore), to test for optimal production systems, environmental conditions, nursery production of sporophytes, harvesting regimes, spacing of lines, and other factors influencing growth and production.

Table 15: Comparison of kelp production trials and assumptions for economic viability

Source	Species and location	Production method	Average yield FW (kg /m/year	Profitable scale	Farm gate production cost US$/kg FW	Profitable farm gate price US$/kg	Comments
(Bak, et al., 2018)	*Saccharina latissima*, Faroe Islands	Macroalgal Cultivation Rig (MACR) – 250 x 10 m vertical growth lines	6.4	Not estimated	2.45	Not estimated	Total cost/kg decrease if # harvests/year without re-seeding increase; profitability influenced by biofouling associated with sheltered locations preventing multiple partial harvesting
(Yarish, et al., 2017)	*Saccharina latissima*, New England	250 x 100 m longlines	10	250 t FW/year	1.16	2.20	Economic model assumes 250 longlines of 100 m length, yield of 10 kg/m, annual production of 250 t FW, integrated farm and processing operation
(Correa, et al., 2016)	*Macrocystis pyrifera,* Chile	80 m longlines with 134 vertical growth lines	41	30 ha	Not estimated	0.078	Kelp produced for abalone feed; animal food grade plants with 9% protein content harvested; 30-50 ha cultivation producing 41 FW kg/m/year, market value US$78/ton can give return on investment after 1 year

In South Africa, a few attempts were made at growing kelps in the laboratory and in the sea. This included an experimental trial of South African *L. pallida* and *E. maxima* cultivation in the sea at Oudekraal (Rothman, 2015) which yielded biomass of 1 kg per plant after about a year (Mark Rothman, personal communication). During a three-month experiment on *M. pyrifera* in Saldanha Bay (Figure 26) the plants doubled in size during the trial and grew at about 1% per day (Fleischman, et al., 2021). The trial did not run long enough to determine seasonal variation and commercial viability.

Figure 26: Experimental growth and harvest of *M. pyrifera* in Saldanha Bay
Source: John Bolton

The production and infrastructure requirements for a South African kelp farm are based on the model developed for a vertically integrated commercial scale sugar kelp farm off the coast of New England. The vertically integrated operation included seed string production (nursery), the open water grow-out operation (farm) a processing facility, and marketing and distribution activities (Yarish, et al., 2017).

It is assumed that the South African kelp farm will produce the three species *E. maxima, L. pallida* and *M. pyrifera,* with the following products for sale:

- Fresh kelp fronds as abalone feed
- Fresh whole kelp plants for extraction of plant growth stimulants
- Dried, milled, and graded kelp for export (alginate extraction) and local sales to companies manufacturing niche products such as nutraceuticals and cosmetics.

Potential production estimates for this hypothetical farm assume that the same production system will be used as for *S. latissima* in New England, and similar productivity rates will be achieved (Yarish, et al., 2017). The production system is based on 250 longlines of 100 each, spaced 1.5 m apart. This will require a minimum farm space of 3.75 ha. Three scenarios are presented, based on different assumptions for average kelp production (10, 15 and 20 kg/m/harvest FW), and two harvests per year. The potential production ranges between 500 and 1000 t per farm per year (Table 16).

Table 16: Assumptions used to estimate South African kelp farm size and production

Assumptions	Scenario 1	Scenario 2	Scenario 3
Average kelp production (kg FW/m/harvest)	10	15	20
Number of harvests per year	2	2	2
Length of longline for minimum size farm	100	100	100
Number of longlines for minimum size farm	250	250	250
Total m of longlines	25000	25000	25000
Space between longlines m	1.5	1.5	1.5
Width of farm needed (m)	375	375	375
Length of farm needed (m)	100	100	100
Size of farm needed (m^2)	37500	37500	37500
Minimum size of farm (ha) at 1.5 m spacing	**3.75**	**3.75**	**3.75**
Potential production for minimum size farm (t)/harvest	250	375	500
Potential production with 2 harvests/year (t/year)	**500**	**750**	**1000**

The farming operation assumes employment of three employees during an eight-month grow-out and harvest cycle, 250 m longlines of 100 m each, and yield of 10 kg/m. The cost for the production system was estimated at US$ 2000 per m of longline, for 25 000 m of longlines with a working life of five years (Yarish, et al., 2017). At the current US$: ZAR exchange rate (1:14.47), the cost of a longline kelp production system for a 250 seeded longline, 3.75 ha farm is estimated at R7 335 000.

A kelp nursery will require an industrial on-land facility with environmental controls to manipulate light intensity, photoperiod, water temperature, water filtration, water chemistry etc. for the preparation of kelp seedstock (Yarish, et al., 2017). It should also have the capacity to produce enough seed string to supply the farms it services (e.g., 25 000 m per farm). This will require access to natural kelp forests for collection of seed material.

An on-land processing facility will be required to process and store kelp. This will require access to water, energy, and sanitation services. The farm will also require access to boat launching and mooring facilities.

Farm equipment should include a work boat such as those illustrated in Figure 27, with a capacity to carry 4 crew members, 8 t capacity and winch to hold up the ropes, an inflatable boat or skiff, a trailer, a delivery vehicle, and harvesting tools. The cost for a boat is estimated at US$40 000-50 000 (R590 000 to R734 000) and the cost for a skiff US$ 5000-10 000 (R74 000-R15 000) (Barend Stander and Mark Rothman, personal communication), (Yarish, et al., 2017).

Figure 27: Work boats used in the shellfish farming industry
Source: Barend Stander

Labour required for farm operations include a skipper and four crew or cutters. A dive outfit will need to check the moorings and production system at least once a year.

Product standards include ISO 9001 certification for the harvesting and processing of raw kelp. Mandatory requirements include aquaculture rights, licenses and permits. Leases will be required for the sea water space and on-land facilities. The farm will also be expected to comply with environmental requirements and regulations, including submission of reports and information to the relevant departments.

7 LOCAL CONTEXT

7.1 Specified location

The proposed location for kelp cultivation is along the West Coast of South Africa, east of Agulhas to the mouth of the Orange River. The location includes Saldanha Bay, with an approved Aquaculture Development Zone of 884 ha. The ADZ consists of four areas including Small Bay (163 ha), Big Bay (409 ha), Outer Bay North (216 ha) and Outer Bay South (96 ha). Approved aquaculture activities include the following species:

- Bivalve shellfish (oyster and mussels)
- Abalone and scallop
- Indigenous and alien finfish
- Seaweed (*Gracilaria gracilis*).

Although the Environmental Authorization (EA) for the ADZ specifies *Gracilaria gracilis* as a seaweed species, the cultivation of kelp within the ADZ is not mentioned. A feasibility study would need to confirm whether commercial kelp cultivation (over 30 t p.a.) in the ADZ will need a Part 2 amendment process so that kelp species are included in the EA as a commercial aquaculture species.

The location also includes 15 of the 23 Seaweed Rights Concession Areas (SRCAs) in South Africa (Areas 5-19). Areas 5-9, 11-16, and 18-19 have existing kelp rights, and they form the basis of the current local kelp industry. Concessionaires collect beach-cast kelp, and harvest blades (from boats) or whole plants (utilising divers) and sell the kelp either fresh or dried to abalone farmers and manufacturers of value-added kelp products. Since 2017 these rights are allocated for a period of 15 years.

There is currently a dispute around the re-allocation of some SRCSs to Small-Scale Fishers (as recognised communities in certain areas) instead of commercial applicants. Based on a 2007 Equality Court judgement in favour of fishing communities, government developed a Small-Scale Fisheries Policy (SSFP) to grant access to certain resources to traditional fishing communities. Rights in Areas 5 and 8 were provisionally allocated to the Small-Scale Fishing Sector in 2017. However, since this Sector had not been activated at the time, previous rights-holders were given exemptions to continue harvesting (Rothman, et al., 2020). In the Northern Cape, community co-operatives in Port Nolloth and Hondeklipbaai applied for kelp rights in Concession Areas 16 and 15 (DAFF, 2018). Upon finalisation of this process, Grant of Right Letters will be issued to the co-operatives.

There are about 19 operational abalone farms in the study area. These represent potential markets for cultivated kelp.

Support services are available from stakeholders such as the aquaculture industry including various industry associations, government and its agencies, research and development organisations, and others.

7.2 Access to required resources

There are numerous cities and towns along the study area, with available resources such as labour, infrastructure, and services. The District and Metropolitan Municipalities bordering the study area include the Namakwa District Municipality (DM) in the Northern Cape province, and the West Coast DM, City of Cape Town Metropolitan Municipality, and Overberg DM in the Western Cape province. The population, matric schooling levels and unemployment rates for these municipalities are summarised in Table 17 (SA Government, 2022).

Ports are commercial, international junction points connecting land with water, are used for ships and their cargo, and are typically equipped with cranes, forklifts, warehouses, and docks. Harbours can be natural or man-made and imply places along the coast where ships or boats can anchor or take shelter. Harbours may or may not have onshore facilities available. Saldanha Bay and Cape Town contain the only two commercial ports along the study area (Transnet, 2022). South Africa has about 50 small harbours (including public proclaimed, non-proclaimed and potential harbours, private harbours, and landing sites (DoT, 2017).

Table 17: Description of district municipalities in the study area
Sources: **(SA Government, 2022)**, **(Transnet, 2022)**, **(DoT, 2017)**

	Namakwa DM	**West Coast DM**	**City of Cape Town Metropolitan Municipality**	**Overberg DM**
Population (2016)	115 488	436 403	4 005 016	286 786
Population with matric (%) 2016	24.2%	29.1%	34%	27.7%
Unemployment rate % (2011)	20.1%	14.6%	23.9%	17%
Coastal towns listed	• Alexander Bay • Port Nolloth • Kleinzee • Hondeklip Bay	• Lamberts Bay • Velddrif • Stompneus Bay • Paternoster • Saldanha Bay • Langebaan • Yzerfontein	• Melkbosstrand • Blouberg • Table View • Milnerton • Cape Town • Hout Bay • Kommetjie • Simon's Town • Fish Hoek • Muizenberg • Strand • Gordon's Bay	• Pringle Bay • Kleinmond • Hawston • Hermanus • Gans Bay • Pearly Beach • Agulhas • Struis Bay
National commercial seaports operated by Transnet National Ports Authority		• Port of Saldanha Bay	• Port of Cape Town	

	Namakwa DM	West Coast DM	City of Cape Town Metropolitan Municipality	Overberg DM
Small harbours	• Porth Nolloth	• Lamberts Bay • St Helena Bay • Saldanha Bay	• Gordon's Bay • Kalk Bay • Hout Bay	• Gansbaai • Arniston • Kleinmond • Hermanus • Struisbaai

7.3 Alignment with local economy

The towns and settlements along the study area have a history of maritime and fishing activities, with good logistical infrastructure such as roads, ports, and harbours. There are existing aquaculture activities especially in the Port Nolloth/Kleinzee area, Saldanha Bay/St Helena Bay area, and the Hermanus/Gans Bay area. Kelp harvesting and collection of naturally occurring kelp material already take place in approved seaweed concession areas. Kelp aquaculture would therefore align well with the local economy in the study area.

7.4 Supportive environment

Marine and freshwater aquaculture in South Africa is supported by government on national, provincial, and local levels. The Oceans Economy Master Plan currently under development, is building on the aquaculture support and development that took place as part of the Operation Phakisa Aquaculture Programme (2014-2019). The Master Plan makes provision for Aquaculture and Fishing as one of the sub-sectors to be supported. Policy instruments such as the National Aquaculture Policy Framework have been developed, and private and public investment of almost R2 billion into aquaculture projects resulted in an increase in aquaculture production to about 6400 t (DEFF, n.d.).

The key stakeholders involved in aquaculture development include the following:

- Aquaculture industry associations such as BSASA and AquaSA
- The aquaculture industry
- National Departments including:
  - Forestry, Fisheries, and the Environment (DFFE)
  - Trade, Industry and Competition (the dtic)
  - Agriculture, Land Reform and Rural Development (DALLRD)
  - Science and Innovation (DSI
- Provincial departments responsible for agriculture and economic development
- Research and teaching institutions such as universities and research councils
- Financial institutions
- Other support organisations.

Incentives for aquaculture development include financial and non-financial support provided through institutions and programmes such as the Aquaculture Development and Enhancement Programme (ADEP), Comprehensive Agricultural Support Programme

(CASP), the Industrial Development Corporation (IDC), the Micro Agricultural Financial Institutions of South Africa (MAFISA), the Small Enterprise Development Agency (SEDA), and the Technology Innovation Agency (TIA).

Apart from the Oceans Economy Master Plan, there are several national and international programmes and initiatives aimed at aquaculture development, that could provide support, dissemination of information, and incentives for the development of kelp aquaculture in South Africa. These initiatives include the following:

- The DSI/TIA Bio-Innovation Aquaculture Cluster Development Programme aimed at formation of strategic partnerships between government, industry/enterprises, universities, and research institutes; a current call for submission of proposals is focusing on the development of innovative products, processes and services that seek to address challenges in aquaculture industry/ value chain (https://www.tia.org.za/blog/2022/03/30/aquaculture-cluster)
- The All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture (ASTRAL) project (a European Union Horizon 2020 collaborative project that focuses on IMTA farming across the Atlantic area) (https://www.astral-project.eu)
- The Safe Seaweed Coalition has the intention of furthering the extent and ensuring the sustainability of global seaweed aquaculture (https://www.safeseaweedcoalition.org)
- The Global Seafood Alliance is developing a new set of Best Aquaculture Practice standards for seaweed (https://www.globalseafood.org)
- The Aquaculture Association of Southern Africa represents and promote the interests of the aquaculture industry in Southern Africa, and is hosting a conference in July 2022 (https://www.aasa-aqua.co.za)
- The Benguela Current Commission (BCC) is a multi-sectoral inter-governmental initiative of Angola, Namibia and South Africa promoting the sustainable management and protection of the BCLME (https://www.benguelacc.org).

The preliminary results of this study were presented to a group of stakeholders on 22 March 2022. Responses indicated interest and support from stakeholders, especially from industry including abalone farmers, value added product manufacturers, and concession holders.

7.5 Indication of fit

The kelp cultivation opportunity fits well with existing aquaculture activities such as abalone farming, and with the existing kelp industry based on harvesting and collection of natural populations of kelp.

Although there is an existing market for kelp in South Africa and abroad, it should be kept in mind that cultivation of South African kelp has only been tried on an experimental basis before, and that there is little information available about the technical and economic viability of commercial cultivation of the three species under consideration. Production and the processing of fresh kelp into high value commercial products is technically complex and will require substantial investment into research and development.

The pre-feasibility study indicates that there is a market for cultivated kelp, and that cultivation could be viable if a minimum of 1000 t fresh weight per year can be produced.

However, these conclusions and assumptions will need to be confirmed through a pilot kelp cultivation trial of all three species, in inshore (sheltered) and offshore conditions, for a period of at least one year to 18 months, and development of value-added products that are acceptable in local and global markets.

Kelp cultivation trials are planned for two sites in the Saldanha Bay ADZ, on existing bivalve shellfish farms with research permits and mooring infrastructure in place. This will allow for the collection of kelp growth data and information in relatively sheltered sites in a time-and cost- efficient manner. During these trials, efforts should also be directed at obtaining funding for an offshore trial, which will require more marine engineering inputs.

7.6 Potential business models

As this is a pre-feasibility study, it is not possible to predict which business models will be the best for investment into kelp cultivation opportunities. The best business models will be area- and situation specific, and will depend on the role players involved, the nature and size of the opportunity, the type of funding available, the objectives of the investment etc. The issues that will need to be taken into account, include the potential socio-economic and environmental sustainability, the potential economic impact or opportunities for existing or new farmers, and opportunities for expansion of agro-processing with surrounding communities.

There will be a need to investigate inclusive business models (IBMs) during the next phase, to ensure that the needs of poorer people and communities are included and recognized in the commercial development of the sector. IBMs are defined as "pro-poor, equitable and profitable business activities that integrate poor producers, processors, retailers, distributors and consumers in value chains whilst generating broader positive outcomes" (Kaminski, et al., 2020). These authors identified seven main types of IBMs commonly used in agriculture value chains, as follows:

1) Contract farming or out-grower schemes
2) Micro-franchising
3) Joint ventures
4) Farmer-owned businesses such as co-operatives, associations, or groups
5) Tenant farming or sharecropping
6) Public-private partnerships
7) Certification.

The best business model for a particular opportunity might be one of the above, a hybrid or combination of some of these models, or other business models not listed above.

8 FINANCIAL INSIGHTS

The financial insights are based on the assumptions that a 4-ha kelp farming area will be established utilising a longline production system, and that kelp will be sold into the South African market. It also assumes that cultivation will take place in the existing Saldanha Bay ADZ, on one of the aquaculture farms that already have marine aquaculture rights and permits, and a lease for sea water space in place.

Projected sales for three different kelp production scenarios are presented in Table 18. These scenarios are based on the following assumptions:

- Scenario 1: Annual production is 20kg/m FW (500t),
- Scenario 2: Annual production is 30kg/m FW (750t),
- Scenario 3: Annual production is 40kg/m FW (1000t),
- 70% of production is sold fresh to abalone farmers as abalone feed,
- 25% is sold fresh to plant growth enhancer manufacturers,
- 5% is sold dried to exporters and niche product manufacturers, and
- The fresh to dry kelp conversion rate is 10:1.

The actual production will depend on the specific environmental conditions of the kelp farm, production system selected, optimisation of production methods and other factors such as weather events. The product mix could be adapted to maximise sales, as products with higher selling prices will require more production and processing inputs.

Table 18: Projected sales for different production scenarios

		Scenario 1		Scenario 2		Scenario 3	
Product sold	**Selling price (ZAR/t)**	**Volume sold (t)**	**Projected sales (ZAR)**	**Volume sold (t)**	**Projected sales (ZAR)**	**Volume sold (t)**	**Projected sales (ZAR)**
Kelp blades for abalone feed (FW)	1 800	350.0	630 000	525.0	945 000	700	1 260 000
Whole kelp (blades and stipes) for plant growth enhancer (FW)	2 700	125.0	337 500	187.5	506 250	250	675 000
Dried, milled, graded kelp for export and local products (DW)	20 500	2.5	51 250	3.8	76 875	5	102 500
Total		477.5	1 018 750	716.3	1 528 125	955	2 037 500

The projected payback periods for different production scenarios are summarised in Table 19. The estimated investment needed to establish the production system is R7 335 000, with an expected lifespan of five years. The projected payback period for a 4-ha kelp farm with annual production of 1000 t is 3.6 years, which indicates a potentially viable operation.

Table 19: Projected payback periods

Assumption	Scenario 1	Scenario 2	Scenario 3
Cost of establishment of 4 ha farm (ZAR)	7 335 000	7 335 000	7 335 000
Potential sales per farm per year (ZAR	1 018 750	1 528 125	2 037 500
Payback period (years)	7.2	4.8	3.6

From the financial insights a kelp cultivation farm of about 4 ha, using a production system of 250 longlines of 100 m each, with at least two harvests and a minimum of 1000 t production of fresh kelp per year, indicated a potentially viable farming operation.

9 SUMMARY AND CONCLUSION

9.1 Short summary of opportunity

There is an existing kelp industry in South Africa based on the harvesting and collection of natural populations of kelp along the West Coast. However, expansion of the local market and meaningful access to the global market will depend on successful commercial cultivation of the three kelp species under consideration.

Potential areas for commercial kelp cultivation have been identified in the Saldanha Bay ADZ and offshore areas along the West Coast. There are existing plans for inshore cultivation trials in Saldanha Bay using rope rafts, depending on further funding. Offshore cultivation trials will require marine engineering capabilities and inputs, and further funding.

Laboratory-based kelp seeding, and cultivation experiments are ongoing, and will provide valuable insights and technical guidelines on 'force cultivation' to reduce kelp outgrowing time until harvest.

A 4-ha kelp farm using longline production system (250 lines of 100 m each), producing 20 kg FW/m/harvest, with two harvests (1000 t FW per year), could be potentially viable. These assumptions and the technical and economic feasibility of commercial kelp cultivation should be tested through pilot kelp cultivation trials in inshore and offshore locations, testing all three species, and operating for at least one year. The pilot should produce enough kelp for development of value-added products that could be tested in the market.

The study area includes existing aquaculture activities, facilities, town and harbour infrastructure, labour and logistical infrastructure that could support commercial kelp aquaculture.

9.2 Conclusion

The recommendation from the pre-feasibility study is to proceed with a techno-economic feasibility study of commercial kelp cultivation in South Africa. This is based on the indication for potential viability of a kelp cultivation operation producing 1000 t per year of fresh weight and selling fresh and dried kelp existing local markets.

There is an existing and growing kelp industry and market for fresh and dried kelp in South Africa, but further growth is constrained by biomass restrictions. There is also a growing global interest in kelp cultivation and new product development that bodes well for the development of commercial kelp cultivation in South Africa.

The pre-feasibility study achieved its original intent of assessing whether the opportunity for commercial kelp cultivation is worth investigating further through a feasibility study. The recommendation of this study and proposed way forward is therefore to proceed with a techno-economic Feasibility Study into commercial kelp cultivation along the West Coast of

South Africa. This should generate the data and information needed to support a decision to invest in a kelp farming opportunity. This study should include detailed market and technical research and financial modelling.

This will require follow-on funding from the pre-feasibility study phase, and should include the following:

1. Continuation of laboratory-based seeding and cultivation of all three species of kelp
2. Continuation of raft-based kelp cultivation trials in Saldanha Bay
3. Design, manufacture, installation, and operation of a pilot offshore kelp cultivation system in one of the areas identified during the pre-feasibility GIS study
4. Product and market development for kelp and kelp-derived products
5. Testing of kelp products in the market
6. Additional stakeholder engagement
7. Food safety testing/certification
8. In-situ environmental testing.

APPENDIX A REFERENCES

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APPENDIX B SPECIALIST REPORT – KELP AQUACULTURE

The potential for kelp (Laminariales) aquaculture on the west coast of South Africa, including a synthesis of available biological and ecological information.

Emeritus Prof. John J Bolton

Contract report to the Bivalve Shellfish Association of South Africa (BSASA) and the UK (FCDO), March 2022.

Executive summary

1. This is a detailed report on the potential for growing large brown laminarian algae (kelps) in South Africa, including information on the biology and ecology of South African kelps, their laboratory culture and potential for commercial aquaculture. This is discussed in the light of current trends in international aquaculture and usage of kelp, the availability of sites for kelp aquaculture on the South African coastline, choice of species, sustainability, and biosecurity considerations.
2. The Benguela upwelling system on the west coast of South Africa/Namibia is a globally significant region with high levels of available nutrients and sunlight.
3. There are three potential west coast species for kelp aquaculture, *Ecklonia maxima* and *Laminaria pallida* that grow predominantly in Southern Africa, and *Macrocystis pyrifera* which is globally widespread and rare in South Africa.
4. Around 7-10 000 tonnes of kelp are used in South Africa each year from natural kelp forests, mainly cut fresh for feed in abalone aquaculture and agricultural plant growth stimulant, with a little collected as washup and dried for overseas alginate production. Globally, there is a very long and rapidly growing list of actual and potential uses for kelp, and a move toward the use of the 'biorefinery principle' where seaweed biomass can be converted into different economic products, including a mixture of high-value niche products and low value commodities for increased economic efficiency.
5. Although seaweed represents more than half of world marine aquaculture production (ca. 35m tonnes, worth US$ 14.7 billion), this is almost all grown in East Asia. There are significant moves currently to expand seaweed production into the Western Hemisphere, and the background to this is explained.
6. Kelps have never been grown in commercial aquaculture in Southern Africa before, and there is limited information available on many aspects of local kelp growth in aquaculture.
7. Kelps release billions of tiny spores, which produce the microscopic stage of kelps, known as the gametophyte, and these and the resulting juvenile kelp plants must be cultivated for a period in land-based climate-controlled hatcheries. After several weeks, strings seeded with spores from the hatchery are placed on rope rafts in the sea. Methods used elsewhere for hatchery growth and rope raft construction are summarised.
8. Kelp raft cultivation is carried out elsewhere in relatively sheltered bays and inlets, although there is an international move, particularly in the North Atlantic, to grow kelps on larger structures further offshore in the open sea. This will require significant marine engineering input and many countries are mapping the space they have available offshore for these activities.

9. There have been a few local laboratory experiments on small kelp stages and the entire life history of *Ecklonia maxima* and *Laminaria pallida* has been completed (once) in the laboratory and the sea. *Macrocystis* is the only local species which can regenerate from its base (holdfast) and a short (3-month) experiment grew *Macrocystis* successfully from holdfasts on a rope raft in Saldanha Bay.
10. The logical place to begin kelp cultivation trials in South Africa is Saldanha Bay, where seaweeds have been cultivated before and aquaculture infrastructure is in place. A protected nearby area in St Helena Bay, where the red seaweed *Gracilaria* has been successfully grown before, is also a possibility.
11. Two main biosecurity concerns with kelp aquaculture involve the potential for spreading kelp diseases and the possibility of affecting the genetics of natural kelp forests if material (usually as cultured gametophytes) is moved between different regions. Although biosecurity measures can be implemented, all three relevant species grow in or close to Saldanha Bay, so these need not be initial concerns here.
12. Unlike 'fed' aquaculture (e.g. fish and shrimps) kelp is 'extractive' aquaculture. The major kelp nutrients, especially the potentially polluting macronutrients nitrogen and phosphorus, are present dissolved in the water and are removed by the kelp. This has given rise to the idea of IMTA (Integrated Multi-Trophic Aquaculture) where seaweeds such as kelp are grown close to, and linked with, other aquaculture facilities, thus removing dissolved waste nitrogen and phosphorus released by other aquaculture activities. Saldanha Bay would be a good site to test these ideas locally.
13. Kelps have regular seasonal growth patterns which are critical in kelp aquaculture. From the limited local literature available it appears that local kelp growth correlates with available sunlight, growing fastest in summer. This is different from kelps grown elsewhere which tend to grow fastest in late winter/early spring, with slow growth in summer. In the North Atlantic, levels of major kelp nutrients in seawater are very low in the summer, whereas on the South African open west coast these nutrient levels are high due to summer upwelling.
14. In the North Atlantic there is evidence that some kelp species store nitrogen and carbon seasonally for use in later growth. *Ecklonia maxima* can store nitrogen in the short-term (at upwelling events) but there is no evidence that local *Ecklonia* or *Laminaria* have a seasonal pattern of nitrogen (and hence, protein) storage.
15. The four main potentially limiting environmental factors for kelp growth in aquaculture in South Africa are seawater temperature, water flow/wave action, levels of dissolved nutrients (usually negatively correlated with water temperature), and light (linked to depth).
16. Local west coast kelps are generally limited in their distributions, not present where monthly mean seawater temperatures are over 20°C. Small hatchery stages of local *E. maxima* and *L. pallida* grow well at 15°C. Unlike those two species, *Macrocystis* does not grow east of the Cape Peninsula, possibly because of its more limited tolerance to high temperatures, and elsewhere a temperature of 12°C is recommended for growth of small stages of this species.
17. Wave action has both beneficial and negative effects on kelp aquaculture. Kelps require sufficient water flow to enable them to take up the required dissolved nutrients and *E. maxima* thrives in quite considerable water motion. *Macrocystis*, on the other hand, only grows in South Africa in particularly wave-sheltered habitats.

Extreme wave action can be very detrimental to kelp raft infrastructure and reliable anchoring of rafts is critical.

18. In the open sea on the South African west coast levels of the major macronutrient nitrogen are inversely correlated with seawater temperature and are generally available year-round. This is not the case in the Inner Bay in Saldanha where around March stratification occurs, with a warm, nutrient-poor layer of water floating on top of a cooler nutrient-rich layer (the latter around 6m deep). Previous aquaculture operations growing the red seaweed *Gracilaria* were successful year-round apart from crashes of seaweed biomass in March, which may also affect kelp cultivation in the Bay.
19. Seawater absorbs light, and turbid seawater absorbs light much faster than clear water. Kelps are generally grown elsewhere fairly shallowly, e.g. from 0.5 to 2m in Japan. The red seaweed *Gracilaria* grew fastest at 0.5m depth in Saldanha Bay. It is recommended that initially kelp aquaculture operations include angled lines from 0.5 to 4m depth to ascertain comparative growth rates with depth.
20. Low salinity is only likely to be a problem with kelp aquaculture in South Africa close to river mouths. Low oxygen events (especially 'black tides') and perhaps periodic warm events can damage kelps and must be considered as sporadic risks to kelp aquaculture in certain parts of the South African coastline.
21. Epiphytes (other seaweeds and marine animals growing on the kelp) tend to become a problem in kelp aquaculture when kelp growth slows down. It is hypothesized that this may occur in later summer/early autumn in South Africa, but we have no data so far. In natural local kelp forests there are few epiphytes except on kelps a few years old, and then they mostly consist of 4 specific epiphyte seaweed species which grow on particular species of kelp.
22. The limited available information on the chemical composition of local kelp species is summarised. Kelps generally have a high ash content and are very good dietary sources of micronutrients. They have a relatively low (10-12%) crude protein content.
23. Apart from the alginate content and the occurrence of plant hormones in *Ecklonia maxima*, which have been commercially exploited for many years, there are recent studies on the potential for nutraceutical products from this species. There is a move in the North Atlantic to increasingly produce human food and nutrition products from kelps.
24. The main commercially used kelp in South Africa has always been *Ecklonia maxima*, and that species should be a target of cultivation. A local abalone farm has begun supporting trials for the cultivation of *Macrocystis*, which is the only local species which has been cultivated on a large scale elsewhere (particularly in Chile) and appears also to be good feed for the local aquacultured abalone. Relatives of local *Laminaria* are the target of cultivation trials elsewhere, and it is recommended that all three species should be tested locally.
25. We are at a very early stage in potential cultivation of South African kelps and there are many things we do not know. Which of the three species grows best in aquaculture conditions? How easy are they to propagate on a large scale? What are the characteristics and potential commercial benefits of 8-month-old cultivated plants of the different species, and are they different from adult plants from natural kelp forests? Can new uses be found for cultivated kelp material? Can local kelp

cultivation be economically viable at scale? There is much work to do before we have a viable kelp aquaculture industry in South Africa.

Contents

6. Discussion

Uses and potential uses and benefits of seaweed aquaculture
Gap analysis: what don't we know
Potential of South African kelp aquaculture

7. References

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1. Introduction

What are kelps?

Kelps are large brown seaweeds (seaweeds are large algae which live in the sea and estuaries), usually defined as being limited to the order Laminariales (Phaeophyceae). This group includes the largest of the algae, which form large kelp forests on around 25% of world coastlines (Krumhansl et al. 2016). There are other large brown algae, generally not as large as kelps, which are ecologically and economically important in some parts of the world (particularly in the order Fucales, such as *Fucus*, *Ascophyllum*, *Sargassum*, *Durvillaea*), but kelps here are defined as the Laminariales (Bolton 2010, Krumhansl et al. 2016) which form the largest component of global seaweed use and aquaculture (Cottier-Cook et al. 2021).

Kelps do not grow in warmer, tropical waters or the Antarctic, and are confined to cold and warm temperate seas around the world, and the Arctic. A reasonable generalisation is that they do not grow where seawater temperatures are above 20°C year-round. They do grow in a few places in the geographical Tropics where the seawater is cooler, for example in regions with upwelling of cooler water (e.g. northern Namibia), or in cooler deeper water where there is sufficient light (e.g. the small kelp *Ecklonia radiata* grows at 50-60m in clear water off SoDWana in extreme northeastern South Africa, in southern Mozambique, Wernberg et al. 2019, and formerly in Oman, Coleman et al. 2022).

Large kelps (with plants several to many metres in length) form considerable kelp forests attached to rocky shores on temperate and Arctic coastlines. Most of the African inshore coastline is too warm for kelps, but there are large and significant kelp forests in the Benguela upwelling region on the west coast of South Africa and Namibia, and smaller kelp forests (*Laminaria ochroleuca*) in northwest Africa (Rezzoum 2000). Kelp forest ecosystems are economically extremely important where they occur (Blamey and Bolton 2018, Filbee-Dexter and Wernberg 2019), and are being affected by climate change in many regions, with 38% showing evidence of recent decline (Krumhansl et al. 2016). Kelps are known as 'ecosystem engineers', as they are dominant species which form the basis of the entire ecosystem, providing habitat and food for a high biodiversity of marine life. Without at least one kelp species, there is no kelp forest. Kelp forests are amongst the most productive ecosystems globally with respect to photosynthesis (carbon fixed) per unit area per year.

Which kelps do we have in South Africa?

Most kelp diversity is in the northern Pacific Ocean, with most genera in the northeast Pacific (Bolton 2010). There are few species in the southern hemisphere. We have 4 kelp species in South Africa (for detailed distribution data, see Rothman et al. 2017b) (Fig. 1)

Figure 1. Kelp (Laminariales) species in South Africa. A. *Ecklonia maxima*. B. *Laminaria pallida*. C. *Macrocystis pyrifera*. D. *Ecklonia radiata* (Photos A, B Sam Bolton; C, D John J Bolton).

- **Ecklonia maxima ('sea bamboo': Fig 1A)** is one of the largest kelps (maximum length 17m, although usually several metres long, depending on habitat), which dominates in areas of kelp forest from around the southern tip of Africa (Cape Agulhas) to southern Namibia (just north of Lüderitz). It has a long, stemlike portion (the stipe), which is hollow and at the top has a broadened hollow gas-filled portion (float) which holds the photosynthetic blades near the water surface to attain maximum light for photosynthesis. It is the dominant kelp inshore in the Western Cape province, but further north it becomes less abundant, and is not common in Namibia. Species of Ecklonia, especially E. cava, known as 'arame' in Japan, are traditional foodstuffs in Japan and Korea. E. maxima only occurs in Southern Africa and some nearby oceanic islands. Plants are individual, with one plant growing from a single base (holdfast).

- **Laminaria pallida ('split fan kelp': Fig 1B)** is smaller, but still a large kelp (ca. 2-3m long in the southwest and can reach at least 5m long in Namibia). It is closely related to kelps being used economically, and grown in Europe, most closely related to the warm temperate Laminaria ochroleuca of southern Europe (Rothman et al. 2017a), but also to L. digitata, L. hyperborea. On the southwest coast of South Africa it is mostly a subtidal kelp, dominating from ca. 6-10m depth. There it has a long, solid stipe. Further north the stipe becomes longer and partially hollow, although it doesn't float as successfully as Ecklonia maxima. In the Northern Cape and Namibia it dominates rocky shore communities in shallow water, and occurs as far north as Rocky Point, close to the Namibian border with Angola. Laminaria pallida also only occurs in Southern Africa and some nearby oceanic islands. Plants are individual, with one plant growing from a single base (holdfast).

- **Macrocystis pyrifera ('giant kelp' elsewhere, known as 'bladder kelp' in South Africa: Fig. 1C)** is rare in South Africa, only occurring in a few isolated patches along a ca. 200km stretch of coastline, from the Cape Peninsula to Jacobsbaai (Fleischman et al. 2019). Elsewhere in the world it can grow to prodigious lengths (>50m long), and it occurs along most of the temperate west coasts of the Americas, as well as around the Southern Hemisphere in cooler waters. The plant is much more complex in form than the other kelps described here, consisting of a series of multiple branched stems, with each branchlet terminating in a small gas-filled float from which arises a single, ribbed blade. Each plant thus has very many stems and blades. It has been the basis of major kelp industries from natural populations in Chile and Mexico, and formerly in California. In South Africa it is much smaller with plants in most populations having a maximum length of 2-3m. The largest population is on the leeward side of Robben Island, in Table Bay, where plants can reach 7m in length. It has a spreading base of the plant (the holdfast), and many upright branched stems arise from each holdfast.

- **Ecklonia radiata (spiny kelp in South Africa, golden kelp in Australia: Fig. 1D)** is a smaller kelp, usually 1-2m in length. The same species occurs in other parts of the world, being particularly widespread on temperate coasts of Australia and New Zealand. It is the dominant kelp in the 'Great Southern Reef' of Australia (Bennett et al. 2015). There are isolated populations of small Ecklonias in some other regions: those from Oman in the Arabian Sea have been shown to be E. radiata by DNA sequencing (Coleman et al. 2022), whereas those in northwest Africa (particularly Mauretania) have not yet been studied by these methods. In South Africa it occurs sporadically in small populations in the immediate subtidal to a depth of 1-2m along the south coast (the westernmost population being at 18m in False Bay). East of Port EDWard, it only occurs on deeper subtidal reefs. A 30km long reef system with an E. radiata kelp forest has recently been discovered using a remotely operated vehicle (ROV) off St Lucia in KwaZulu-Natal on the east coast (Kerry Sink and Jean Harris, pers. comm.). Similar looking, and closely related, Ecklonia species (particularly E. cava) are harvested from natural ecosystems for human food in Japan and Korea. Plants are individual, with one plant growing from a single base (holdfast).

Kelp aquaculture

Aquaculture is the aquatic equivalent of agriculture and involves growing species which live in water for commercial purposes. Marine aquaculture, sometimes called mariculture, is the commercial cultivation of species which live in the sea and estuaries. More than 99% of the world's seaweed production is grown in aquaculture totalling over 35 million tonnes with a value of US$ 14.7 billion in 2019 (Cottier-Cook 2021). Over 99% of the production is in East Asia, with over 97% in five countries (China, Indonesia, the Philippines, Republic of Korea and Japan). Only a small number of species make up most of world seaweed aquaculture. In tropical regions, red seaweeds are grown, mostly for colloids (carrageenan, agar; especially in the genera Eucheuma, Kappaphycus, Gracilaria), as well as smaller amounts of various specific seaweeds for human food in different regions. In temperate regions, most seaweed biomass produced in aquaculture is ‘sugar kelp’, mainly Saccharina japonica. This is known as ‘kombu’ in Japan. A lot of research and numerous commercial start-ups are progressing in the North Atlantic currently growing the closely related European sugar kelp Saccharina latissima. Another major kelp species grown widely in temperate East Asia is ‘wakame’ (Japanese name), which is a high-value product for human food (Undaria pinnatifida). Finally, a major human food product is the red seaweed formerly known as Porphyra (Japanese name ‘nori’), which is widely eaten in Asia and in sushi bars in the west (the blackish seaweed around rice). Most of the commercial species now have a different scientific name and are classified in the genus Neopyropia (Guiry & Guiry 2022).

Kelp forests are major dominant ecosystems on shallow rocky shores on the west coast of South Africa and Namibia. Despite the long history of kelp commercial use from natural kelp forests in South Africa (Rothman et al. 2020) there has never been commercial kelp aquaculture (cultivation) in Southern Africa. Numerous scientific experiments have been carried out on growth of various growth stages of Southern African kelps, and these will be summarised in this document.

Kelp is currently used primarily in three ways in Southern Africa (Rothman et al. 2020). Around 4-7000 tonnes p.a. is harvested from natural kelp forests and used as feed on abalone aquaculture farms, and ca. 3000 tonnes is used to make plant growth enhancers in agriculture and horticulture (e.g. Kelpak®, Afrikelp®¬). In the past (from the 1960s) large amounts of washup kelp were collected from beaches, dried, and sold overseas for alginate production. Currently, this has DWindled to very small amounts, due to economic constraints.

The aquaculture of seaweeds in Southern Africa began in the early 2000s, with commercial raft culture of the red seaweed Gracilaria in Lüderitz Bay, Namibia, where 280-360 tonnes were produced p.a. for a few years. This was grown as an addition to a long-established industry collecting washup Gracilaria in the Bay. It eventually proved uneconomic (Dawes et al. 1995, Rothman et al. 2020). Successful experiments were conducted on similar aquaculture in Saldanha and St Helena Bays in South Africa (e.g. Anderson et al. 1996, Wakibia et al. 2001).

Currently the only successful commercial aquaculture of seaweeds in Southern Africa occurs in several land-based abalone farms, where the green sea lettuce Ulva lacinulata is grown in ca. 30m long paddle raceways. Five farms produce a total of ca. 2000t p.a. of Ulva, which is not sold but is fed to the abalone. Most of this seaweed is grown in abalone effluent, and on two farms the removal of toxic ammonia from the abalone effluent by the seaweed enables up to 50% recirculation of water, greatly reducing pumping costs (Neveux et al. 2018). This is one of the few long-term fully commercial examples of Integrated Multi-Trophic Aquaculture (IMTA) in the Western Hemisphere (Bolton et al. 2009, Nobre et al. 2009). IMTA is the integrated aquaculture of more than one species, taking advantage of ecological interactions between the species, for example the ability of Ulva to take up ammonia excreted by abalone. This enables system recirculation of both water and nitrogen (fed in formulated feed to the abalone, released into the water, taken up by the seaweed, and eaten again by the abalone).

There has been an explosion of research in Europe and North America in the last few years on kelp aquaculture using sea-based rope raft systems as in Asia, and on IMTA combining kelp rafts with cage and raft aquaculture of fish and other seafood products (Troell et al. 2009). There is also a huge increase in current and potential uses for seaweeds, including food and food supplements, health benefits and nutraceuticals, functional foods, fertiliser and plant growth enhancers, textiles, bioplastics, potential for biofuel, integration in climate change mitigation and carbon credits. There is considerable current discussion on the importance of the biorefinery principle (Magnusson et al. 2016, Zhang et al. 2021), where seaweed biomass can be converted into numerous different economic products. This includes stress on the importance of scale and need for a mixture of high value niche products and low value commodities for increased economic efficiency. There are new organisations arising recently with the intention of furthering the extent and ensuring the sustainability of global seaweed aquaculture, for example the Safe Seaweed Coalition (https://www.safeseaweedcoalition.org/).

Aims of this report

Global seaweed cultivation is a rapidly growing industry, having grown by 6-8% per year for the last 50 years. Most of this production is kelp in temperate regions. It is mostly confined to East Asia, but there is a great impetus in the industry to spread it to other parts of the world. Kelps have never been commercially cultivated in Southern Africa, although the region has more than 1500km of coastline with globally significant kelp forests, four species of native (indigenous) kelps in three genera, extremely high levels of coastal light, and one of the world's major upwelling regions on the west coast with high, consistent nutrient supply. The aim is to review the available relevant literature on the biology and ecology of South African kelps, their laboratory culture and potential for commercial aquaculture, and place this in an international context. This will be discussed in the light of current trends in international aquaculture and usage of kelp, the availability of sites for kelp aquaculture on the South African coastline, choice of species, sustainability, and biosecurity considerations.

2. Why grow kelp in South Africa?

Global kelp aquaculture

The global seaweed aquaculture industry has grown at a rate of 6-8% p.a. over the last 50 years (Fig. 2). Over 95% of total global production is grown in 7 countries in East Asia, with more than half in China (Fig. 2; Cottier-Cook et al. 2021). Seaweed represents ca. 51% of current world marine aquaculture production, by weight.

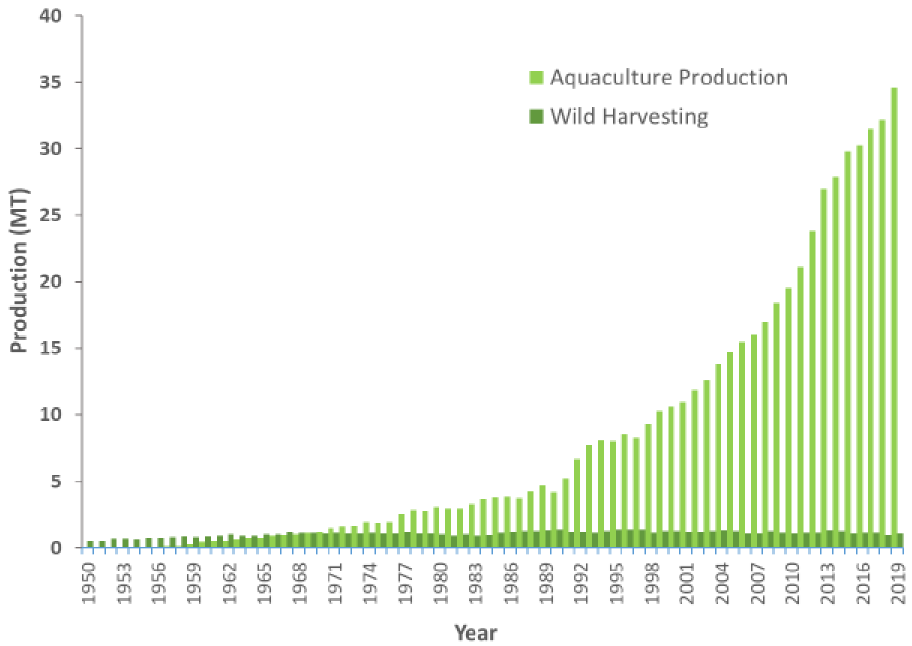

Figure 2. Global seaweed production from aquaculture and natural populations 1950-2019 (Cottier-Cook et al. 2021).

The largest product in world seaweed aquaculture by weight is the kelp *Saccharina japonica* (formerly known as *Laminaria japonica*: the 'Japanese sugar kelp', known in Japan as kombu). Another Asian kelp, *Undaria pinnatifida* (known as wakame in Japan) is also one of the major seaweed aquaculture products. Several other kelp species are cultivated in Asia, and experimental and pilot commercial kelp farms occur throughout the world currently, where kelps grow naturally. In the North Atlantic the main species grown are the Atlantic sugar kelp (*Saccharina longissima*) and Dabberlocks (*Alaria esculenta*), whereas where the giant kelp (*Macrocystis pyrifera*) occurs, considerable research has been carried out on its cultivation (e.g. for abalone feed in Chile, Camus et al. 2016). *Laminaria* (not including *Saccharina*) species have been cultivated in experimental systems in the North Atlantic, including the closest relative of *L. pallida*, *L. ochroleuca* (e.g. Azevedo et al. 2019). Recent studies on aquaculture of *Ecklonia* species have been carried out both in East Asia (Kim et al. 2019b) and in Australasia (Stenton-Dozey et al. 2021).

The recent imperative to grow seaweeds in the Western Hemisphere

A large movement to grow seaweeds has arisen in the western hemisphere, particularly Europe and North America, over the last 2-3 years. This has been designated a 'Seaweed Revolution' by the 'Safe Seaweed Coalition' an international group of scientists and seaweed industry professionals that was formed in 2020 to monitor and work to achieve sustainability in what they consider a nascent major industry (https://www.safeseaweedcoalition.org/). Enormous interest has been engendered online, with new articles on most large relevant websites on the potential benefit of seaweed cultivation in general and kelp cultivation specifically, for example:
https://seaweedsolutions.com/environment,
https://theconversation.com/how-farming-giant-seaweed-can-feed-fish-and-fix-the-climate-81761

The most common reasons put forward for the likely rise of a 'seaweed revolution' in the west are:

- The large successful industry in East Asia, particularly the major role seaweeds play in the human diet.
- The need for a 'blue revolution' to utilise the marine environment more fully, particularly for human food and nutrition provision.
- The potential for seaweeds to be introduced as part of integrated multitrophic aquaculture (IMTA), reducing nutrient loads in animal marine aquaculture systems.
- The many uses of seaweeds, and the potential for the use of seaweed biomass using a 'biorefinery concept' producing numerous products from the same material, both high-value extracts and lower value commodities.
- The health benefits of consumption of a plant-based rather than an animal-based diet.
- Specific health and other benefits of various seaweeds both as food (nutrients, beneficial effects on microbiome and the immune system, nutraceuticals etc.) and fodder (e.g. reducing methane emissions in livestock by feeding the red seaweed Asparagopsis).
- Potential for carbon sequestration by large-scale seaweed farms, and thus potential benefits in a world warming due to anthropogenic carbon emissions.

These points have a large and rapidly growing scientific literature and all are largely supported, with the possible exception being the proposed benefits of seaweed farming for carbon sequestration, which is currently much debated (Hurd et al. 2022). Kelp forests do not have sediments which store carbon in the same way as other inshore marine ecosystems such as mangrove forests, salt marshes and seagrass beds. Nevertheless, kelp forests are among the biggest carbon fixers per area of any natural ecosystems, and much of this fixed carbon may find its way into the deeper sea where it could be stored. A great deal of research is going on currently on trying to estimate how much carbon fixed from kelp forests is sequestered (stored long-term) in this way (Queiros et al. 2019). There has also been criticism of the “hype” surrounding these claims of enormous western potential for seaweed aquaculture, pointing out that the ‘seaweed revolution’ is still, so far, an East Asian phenomenon (Costa-Pierce and Chopin 2021). This explosion of interest has certainly spread to Southern Africa, with a huge increase in searches for information on seaweed aquaculture, evidenced by the high numbers of recent requests to seaweed biologists (JJ Bolton, pers. obs.). Most regions of the world where there are significant kelp forests are currently considering kelp aquaculture.

South African kelp forests: economic value, conservation and biodiversity

Kelp forests dominate the west coast of Southern Africa (South Africa and Namibia) in the shallow subtidal on rocky coasts. Of the three main kelps growing in this region, one is known as ‘giant kelp’ elsewhere and is the largest marine plant (*Macrocystis pyrifera*), and another is the main forest-forming kelp in southern South Africa, *Ecklonia maxima*, which is among the longest kelp species in the world. Kelp forests have a multitude of economic benefits and this ecosystem, in South Africa only, has an estimated value of US$ 434 million year^{-1} (currently ZAR 6.6 billion year^{-1}), of which c. US$ 290 million year^{-1} (ZAR 4.4 billion year^{-1}) contributes to the South African gross domestic product (GDP), with ecotourism (almost 40%), recreational fishing (28%), and commercial and illegal fishing (c. 15–16% each) being the major contributors (Blamey and Bolton 2018).

South African kelp forest ecosystems have been severely over-exploited by the fishing industry. The West Coast rock lobster biomass is estimated to be at <3% of pre-exploitation values with similar figures for the local abalone, and many linefish stocks are considered collapsed or over-exploited (Blamey and Bolton 2018). In contrast kelp harvesting has been a relatively minor and fairly well controlled industry. A minimum estimate of kelp biomass in South Africa was calculated by Anderson et al. (2007) at almost 600 000t fresh weight, with some areas not estimated and only surface kelp included. It is likely that that there is over 1m tonnes of kelp on the South African west coast, of which a maximum of ca. 7000t (Rothman et al. 2020) has been harvested in any one year (<1% of standing stock). It has been reported that kelp harvesting has occasionally approached the maximum legal harvesting quota of 10% of standing stock in some Concession Areas (stretches of coastline for which permission to harvest is obtained; Troell et al. 2006, Rothman et al. 2020).

Kelp forests form a major Southern Africa ecosystem on the west coast, but they are overwhelmingly dominated by two species. The loss of kelp would result in the loss of the kelp forest. These two species represent the vast majority of the biomass present in the shallow rocky subtidal (Field et al. 1980; Fig. 3).

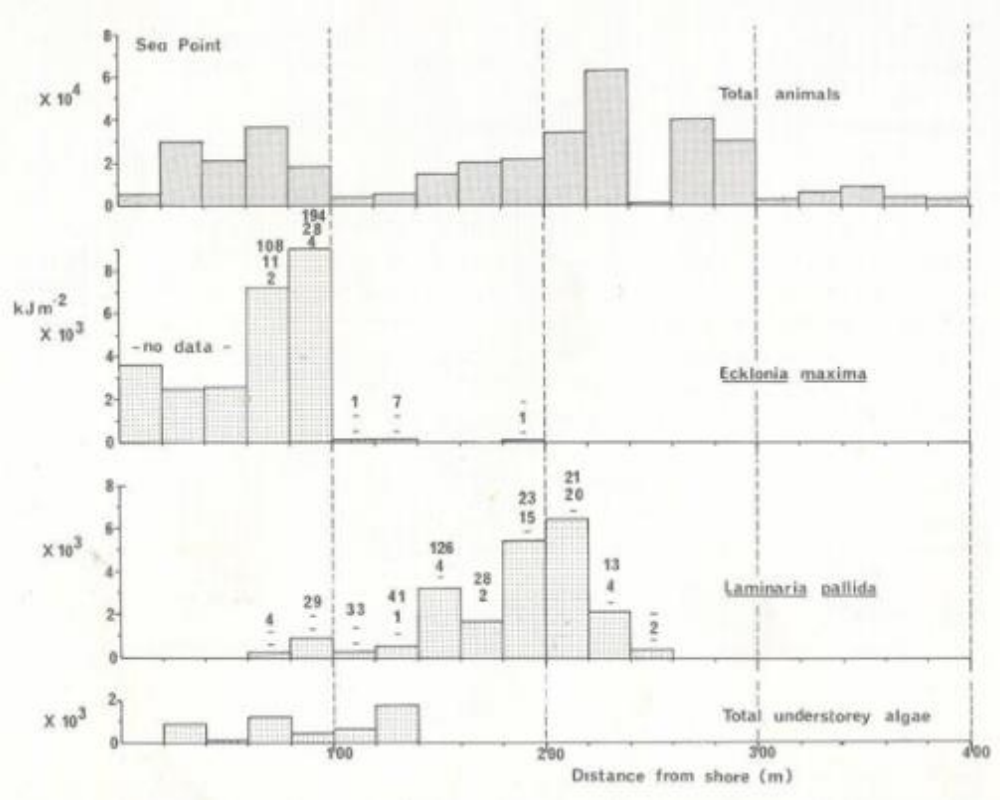

Figure 3. The standing stock of kelps, understorey algae and animals in a line to 400m (ca. 19m depth) from shore at Sea Point, Cape Peninsula. Note: the scale for animals is multiplied by 10 compared to that of kelps and understorey algae. Numbers of large, medium and small kelp plants are indicated along each histogram bar (Field et al. 1980).

In 38% of world regions, kelp forests are declining (Krumhansl et al. 2016). Over-exploitation of marine animal stocks has been a long-term problem, particularly large increases in sea urchins which eat kelps, caused by removal of their predators in many world regions (Eger et al. 2022). More recently, warming sea temperatures have removed kelp forests, or changed their species composition (Wernberg et al. 2016), and other damaging effects such as eutrophication (large nutrient input), sedimentation, and increasing ocean acidification are adding to threats to these ecosystems. So far, Southern African kelps have proved resilient to these factors, due to several mitigating circumstances:

- The dominant sea urchin on the west coast, Parechinus angulosus, unlike destructive sea urchins elsewhere, cannot eat adult kelps, although it reduces kelp abundance and removes much of the understorey seaweed biomass where it is abundant (Anderson et al. 1997, Leliaert et al. 2000). It is also not very abundant on much of the west coast.
- On much of the west coast (particularly the southwest coast) the sea temperature is not warming. The evidence suggests that in recent years southeasterly winds have increased overall, causing a greater degree of upwelling, which reduces mean annual sea temperatures (Blamey et al. 2015).
- Recent molecular work on Laminaria pallida throughout its Southern African range gives evidence that genetic patterns are governed by oceanographic currents (Assis et al. 2022). The Benguela Current has been established at its current intensity for 2-3 million years, and this evidence suggests that in previous cooler periods at both the mid-Holocene (ca. 6000 years ago) and the Last Glacial Maximum (ca. 20 000 years ago) the kelp habitat was much larger, with kelp forests possibly extending along the south coast as far as East London.

Nevertheless, any threats to one or two species (the two kelps) could cause the disappearance of Southern African kelp forests and their replacement, as in other regions (e.g. Wernberg et al. 2016) with much less productive turf seaweed-dominated ecosystems. There has been considerable recent activity elsewhere on the possibility of re-introducing kelps in regions where they no longer occur, and kelp aquaculture has been proposed to have a critical role in the future, linking the future 'blue economy' (kelp aquaculture) with kelp conservation (Filbee-Dexter et al. 2022).

A particular threat to kelp forests around the world are shorter-term 'warm events'. *Ecklonia maxima* in False Bay near Cape Town is occasionally affected in the summer by inshore movement of the warmer Agulhas current, with damage to surface canopies causing areas of 'bald kelps' with secondary blades dying off (Fig. 4), leaving the float and primary blade (Elston et al. 2015).

Figure 4. 'Bald kelps' (*Ecklonia maxima*) at De Hoop Nature Reserve (see Elston et al. 2015). Photo: John J Bolton

3. Methods of kelp aquaculture

How does kelp grow? (life history)

Kelp exists are two separate life forms, known as the SPOROPHYTE and the GAMETOPHYTE (See Fig. 5).
What we normally call kelp is the SPOROPHYTE. When it is fertile, a darker, raised area appears on specific blades on the plant, in a different position in different species. This is most visible when the blade is help up to the light. This is the SORUS, generally on both sides of the blade, and is the reproductive tissue.

In *Laminaria* the sorus is in patches on the upper parts of the blades (appearing as darker areas).
In *Ecklonia maxima* this occurs in the secondary blades which are somewhat older (attached to the sides of the mid-part of the primary blade). The blades near the stipe are too young, and the ones near the tip of the primary blade are older and generally senescent.
In *Macrocystis* the sorus is harder to find, and only occurs on specific small blades, attached to the holdfast or close to it – these blades differ from all the other blades as they do not have a float at the base.
When the kelp sporophyte reproduces, minute microscopic spores are released into the water from the sorus. These are extremely small, around 5 µm in length (5 millionths of a metre – only visible on a high-powered microscope at 400x magnification). Huge numbers are produced – a single *Ecklonia maxima* plant can produce 30 billion spores per year (Joska and Bolton 1987).

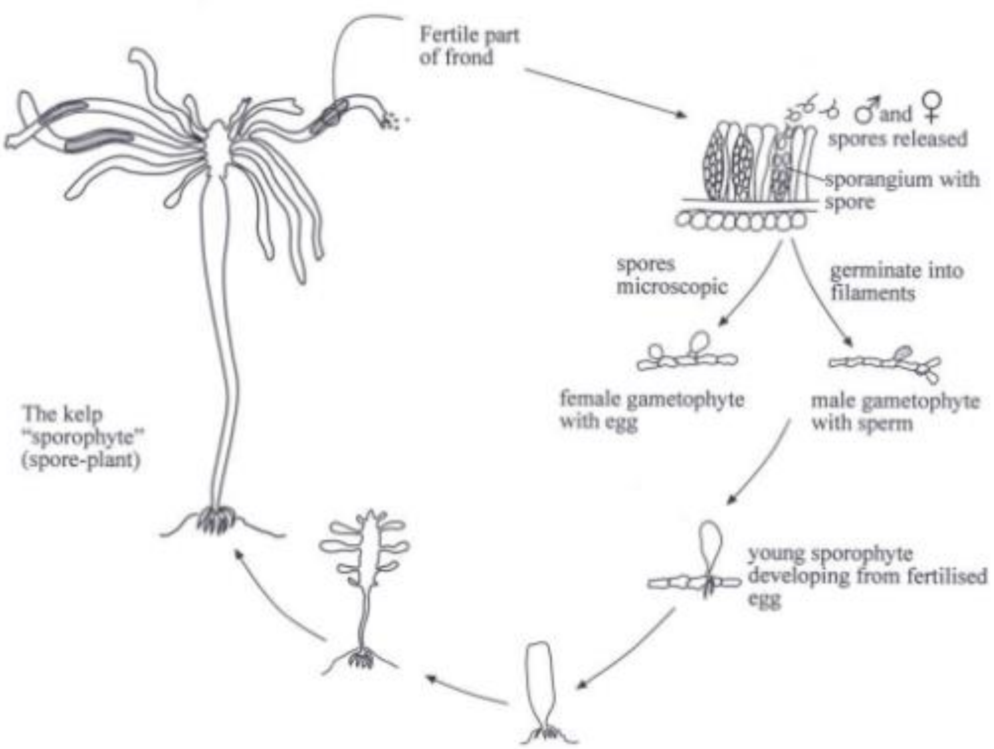

Figure 5. Kelp life history (*Ecklonia maxima* pictured here, although small stages are similar in all kelps). For explanation, see text. From Anderson and Rothman (https://www.dffe.gov.za/sites/default/files/legislations/guidetokelp_harvestinginsouthafrica.pdf).

Those few spores which reach the rock are able to settle, attach and grow into the GAMETOPHYTE. The gametophyte is MICROSCOPIC – cannot be seen without a microscope. There are two types: FEMALES and MALES. Under good conditions (particularly sufficient light), gametophytes only live for 2-3 weeks. The female produces eggs which are fertilised by sperm produced by the males, and the resulting cell grows into a microscopic sporophyte, which soon begins to look like a small kelp.

The life history is critical to aquaculture of kelps, as they are almost always grown from spores (always commercially so far), and the gametophyte and small sporophyte stages take place in the hatchery before the older new sporophytes (when a few mm long) are planted out on raft structures in the sea.

Seeding kelp ropes: the hatchery stages of cultivation

Kelps are grown in aquaculture from spores, with the initial stages (gametophytes which produce small sporophytes) being carried out in land-based hatcheries where environmental conditions such as temperature and light are artificially maintained (Redmond et al. 2014). These facilities must be kelp cool (e.g. for Japanese kombu at temperature of 12-13°C is maintained; Kawashima 1993). Detailed background information for setting up a seaweed hatchery is included in the 'New England Seaweed Culture Handbook', Redmond et al. 2014).

In the traditional method of seeding, fertile kelp plants with sorus are collected, kept damp in paper in a cool place overnight, and in the morning exposed to fresh seawater and light to stimulate spore release. The spore suspension produced is seeded onto strings, which are generally wound around a structure: in Japan they use a triangular structure made of plastic pipe (Fig. 6), whereas in New England they use cylindrical PVC spools.

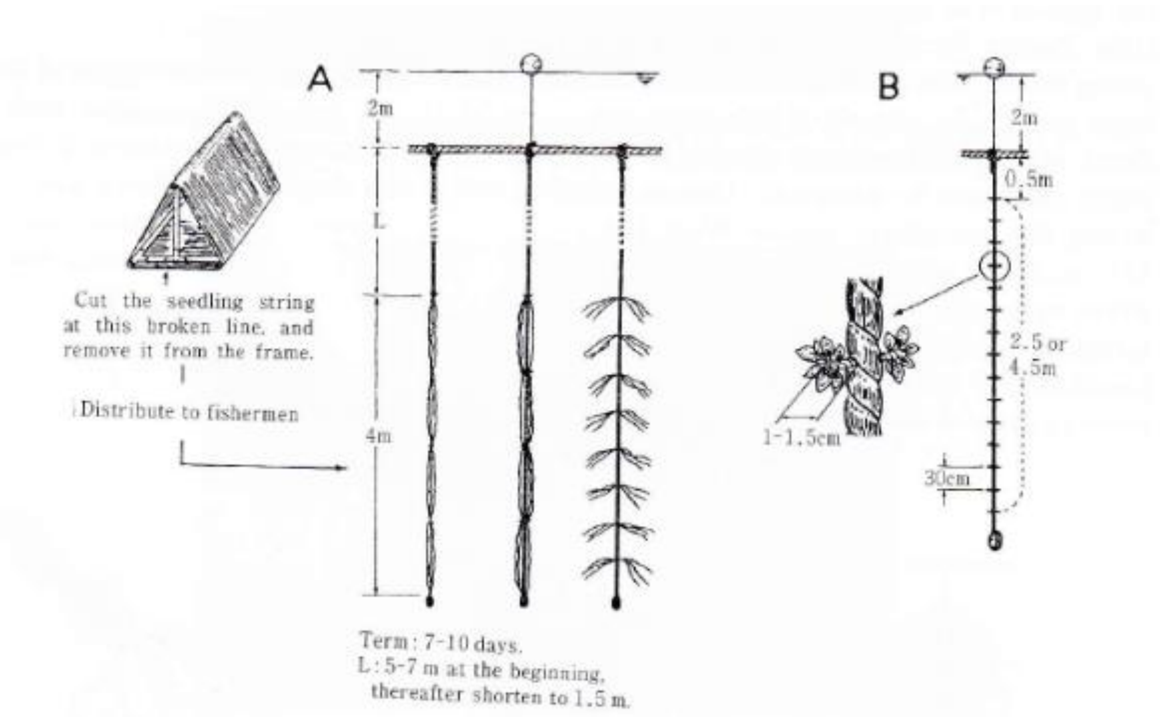

Figure 6. Process for the outplanting of seedlings; A. Three methods of hanging seedling strings for provisional outplanting, B. Fixation of seedling strings to cultivation rope by the insertion method for regular cultivation (from Kawashima. 1993).

The seeded 'seed collectors' are placed in culture tanks with light, and are given nutrient medium, changed regularly. For *Saccharina japonica*, juvenile kelp sporophytes should be 3-5mm long after about 45 days. In regions of Japan and China it is too warm for good kelp growth in the summer, and the seeded strings are placed on kelp rope rafts in the sea when the seawater temperature drops below a certain value (e.g. in southern Hokkaido below 18°C usually around the middle of October; Kawashima 1993). The seeded strings are placed in the sea for 7-10 days to strengthen attachment of the small kelps, and then seeded strings are cut into short lengths and inserted into the cultivation ropes. In Japan natural populations of kombu take 2 years in nature before harvest. In aquaculture this period has been reduced to less than a year, to produce Ma-kombu (force-cultivated *Saccharina japonica*).

In the longer term it is possible to keep and store kelp gametophytes in conditions which enable them to grow without becoming fertile (producing eggs and sperm), eventually producing small sporophytes (kelp plants) when required. This is sometimes known as the 'European method' (Redmond et al. 2014). Careful laboratory work is required to isolate cultures of separate male and female gametophytes. This makes use of the fact that gametophytes of some species have been shown to grow without producing eggs and sperm if there is not blue light available (Lüning and Dring 1975). They are grown in red light (lacking blue light), and individual gametophytes grow into small balls of male or female tissue. When grown up sufficiently these red-light produced gametophyte balls can be gently broken up in seawater in a mortar and pestle, and use as a suspension to seed kelp strings, as with the spores. This is a long-term procedure, which requires long-term, reliable culture systems, and skilled hatchery staff.

Kelp rafts in the sea: how is kelp grown elsewhere?

Seaweeds have been grown commercially in East Asia for many hundreds of years. Subtidal seaweeds such as kelps, which cannot survive more than a very brief period out of the water, are grown on ropes hanging below specialised raft structures. In many temperate regions of the world in recent years marine aquaculture scientists have grown kelps experimentally and in pilot commercial systems, often using Japanese and Chinese models for rafts structures and systems.

The basic structure of a floating seaweed raft consists of three components: the rope raft structure, some method of flotation, and some method of anchoring.
Following the Japanese method, **the raft structure** itself consists entirely of rope, lacking any shackles or other connecting devices, to minimise damage through wearing of the ropes. Shackles are replaced by knots.
The **floats** can be anything which is functional, locally available and cheap. Plastic floats are commonly used, although glass floats have been used in China, bamboo in various regions, and because of the unavailability of other flotation material in Lüderitz, Namibia, the company purchased used cooldrink bottles for this purpose.
The **anchoring** is a critical part of the structure, and marine engineers have many ways of anchoring maritime structures. In Namibia the demise of the *Gracilaria* (red seaweed) aquaculture industry was the result of several incidents where Lüderitz Bay filled up considerably (at low spring tide with specific wind or other conditions), followed by rapid emptying which physically removed the rafts. The final event was linked to the 2004 Indonesian tsunami. This occurred despite the use of 5t concrete blocks and specially designed pipe anchors in the sandy substratum (Dawes 1995). Molloy (1998) commented: "The problem of anchorage still has to be overcome".

This sort of raft was used successfully commercially for a few years in Namibia, and experimentally in Saldanha Bay and St Helena Bay in South Africa to grow *Gracilaria* (Dawes 1995, Anderson et al. 1996, Wakibia et al. 2001). The raft structure is shown in Fig. 7 below.

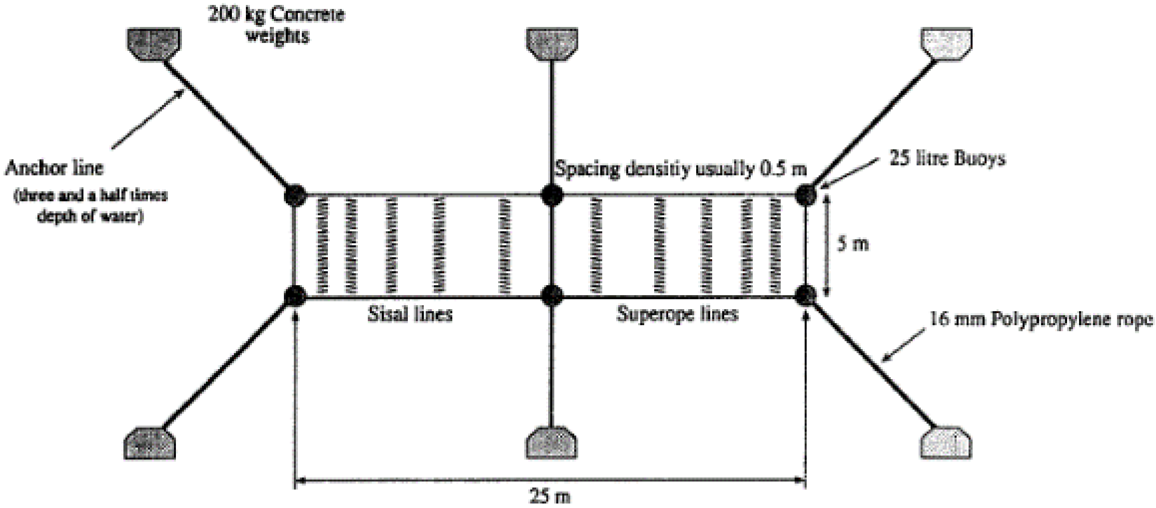

Fig. 7. Diagram (plan view) of the basic test cell rope system used in lagoons in Namibia and South Africa to test growth of the red seaweed *Gracilaria* attached to sisal or Superope lines (Dawes 1995).

The rafts were constructed as arrays of 25m x 5m units, which assists with seeding and harvesting, and at the height of cultivation the systems covered 10ha in 1994 (Molloy 1998). At its peak 280-360t of Gracilaria was grown annually on these rope rafts in Lüderitz Bay (Rothman et al. 2020).

Kelp rafts are similar to the *Gracilaria* rafts described above, in their general construction. Details of Japanese rafts can be found for kombu (*Saccharina japonica*, previously known as *Laminaria japonica*) in Kawashima (1993), Fig. 8 and for wakame in Ohno and Matsuoka (1993), Fig. 9.

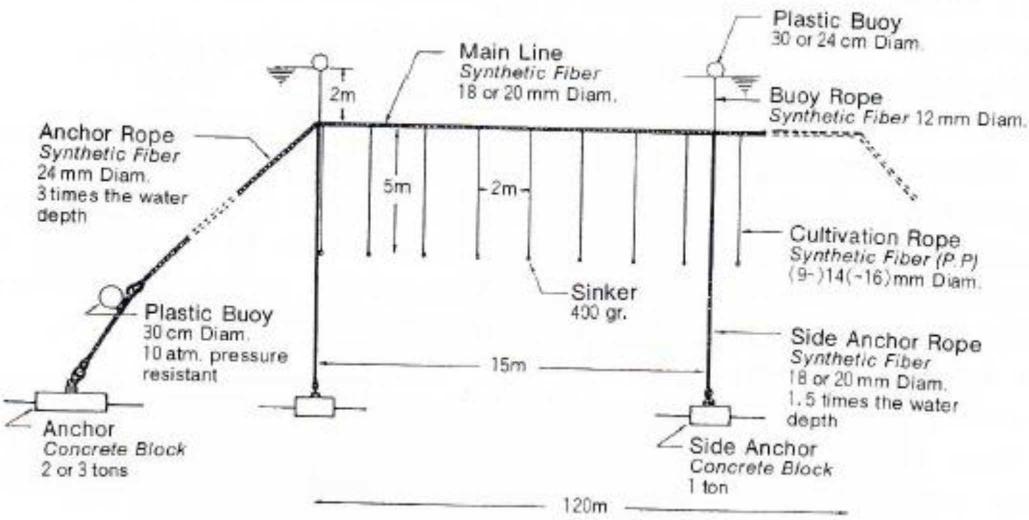

Figure 8. Standard kombu cultivation raft (vertical hanging type). From Kawashima (1993).

Wakame is also grown from individual floating, anchored ropes (as opposed to a 'raft' structure), and also long, narrow rafts with bamboo flotation (Fig. 9).

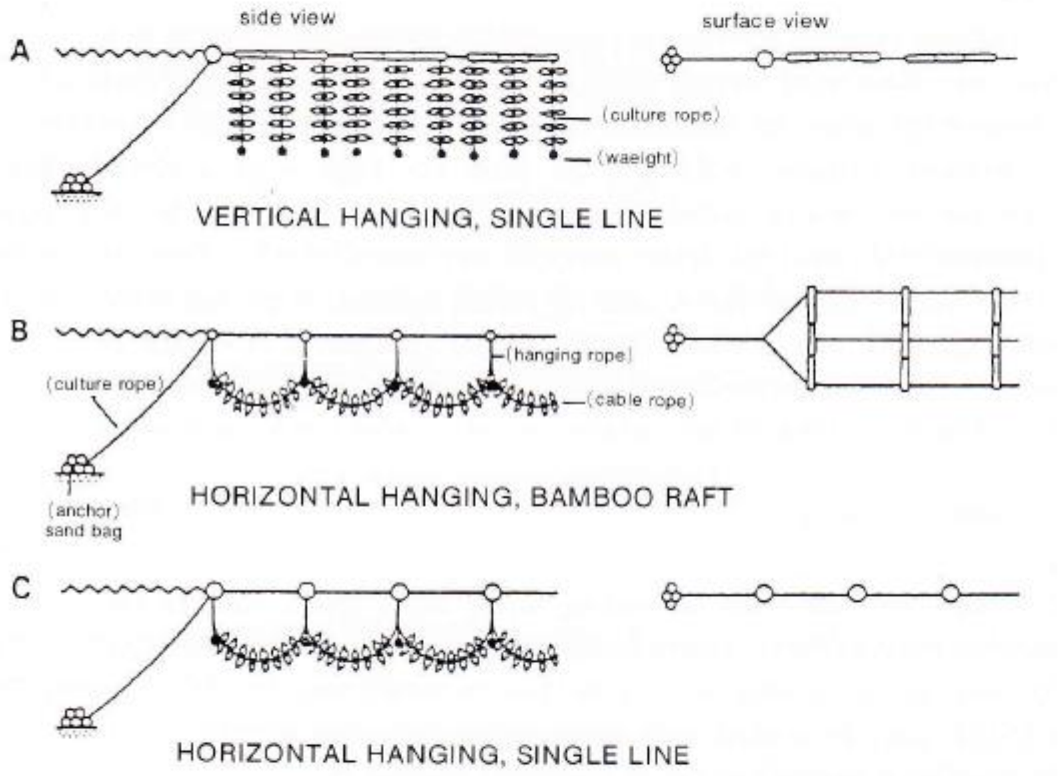

Figure 9. Floating rope method for *Undaria* cultivation, with different methods of rope hanging. A. Vertical hanging from a single floating rope; B. Horizontal hanging from bamboo rafts; C. Horizontal hanging from a single floating rope (Ohno and Matsuoka 1993).

The strings seeded with small kelp sporophytes from the hatchery are attached to the rafts in one of two methods: either hanging vertically from the main line (vertical hanging type) or parallel with the main line (longline method). These are shown in Fig. 10.

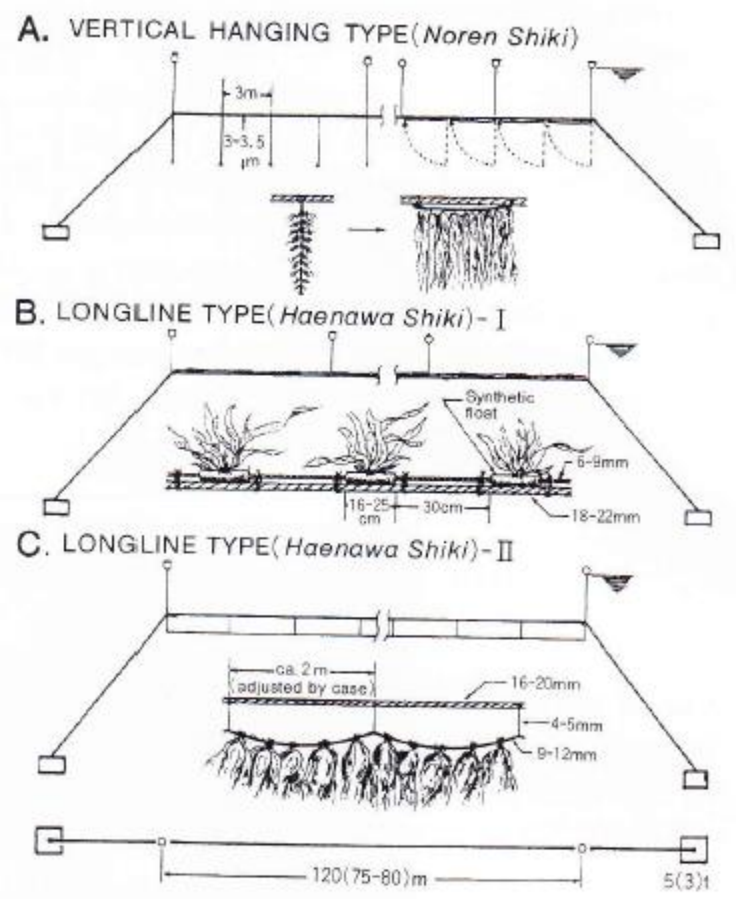

Figure 10. Types of kombu cultivation in Japan. A = Vertical hanging type, B and C variations of longline type. From Kawashima (1993).

Following an acclimatisation period of 7-10 days in the sea, seedling strings (with attached small sporophytes from the hatchery) are cut into pieces and inserted into the main cultivation ropes for cultivation. Sometimes in wakame (*Undaria*) cultivation in Japan, the small sporophytes on seeded strings are placed for a while in the sea to grow before final attachment to the main cultivation ropes.

Recent international kelp culture initiatives

In many countries with kelp forests in the North Atlantic and northeast Pacific Oceans, considerable research was done into kelp cultivation in the 1970s-1990s, without leading to significant commercial success. However, in the last decade there are a growing number of commercial start-ups, growing kelp. For example in the eastern USA, there are now is now a flourishing kelp cultivation industry in Maine and Long Island Sound, and on the Pacific coast new start-ups in California and Alaska (Kim et al. 2019b). A major seaweed cultivation research program (MARINER: Macro Algae Research Inspiring Novel Energy Resources) was initiated in the USA in 2017. There has been a great deal of research into the cultivation of *Macrocystis* pyrifera in both the USA (Kim et al. 2019b) and Chile (Camus et al. 2016). In Chile large amounts of *Macrocystis* are harvested for abalone feed from natural populations, but large-scale cultivation has not yet begun to replace this using aquaculture. Large-scale *Macrocystis* cultivation has been shown to be feasible, and an economic analysis carried out (Camus et al. 2019). *Macrocystis pyrifera* has been introduced in major world regions where it does not grow naturally, for experimental cultivation, including Brittany, France in

the 1970s (Boalch 1981), and numerous attempts in China. There is no available evidence so far that *Macrocystis* has been introduced into natural populations either in the northeast Atlantic or the western Pacific. A new commercial venture intends to grow *Macrocystis pyrifera* on a large scale in offshore systems off the coast of Namibia (https://kelp.blue/namibia/) but is still in the early pilot stages. This would be an introduction into Namibia, but not to the Benguela system as it grows naturally in southwestern South Africa.
Species of *Ecklonia* are cultivated on a small scale elsewhere. In Korea, *Ecklonia cava* is eaten by humans so is a relatively high-value product (Kim et al. 2019a). Research has begun into the cultivation of *Ecklonia radiata* in New Zealand (Nepper-Davidsen et al. 2021). There appears to be little literature on the potential for cultivation of *Laminaria ochroleuca* in Southern Europe (genetically the closest relative of *Laminaria pallida* in South Africa). Experimental studies have been carried out on cultivation of the related *Laminaria digitata* in Europe (e.g. Ratcliff et al. 2016, Purcell-Meyerink 2021).
Wakame (*Undaria pinnatifida*) from Asia has been widely introduced around the world, sometimes for cultivation but also accidentally in moving animals for aquaculture of the Pacific oyster (Graf et al. 2021). In some places where it has been introduced it is used economically and is now being grown in aquaculture operations (e.g in Europe, Peteiro et al. 2016; New Zealand, Stenton-Dozey et al. 2021). Although described by Graf et al. (2021) as “ubiquitous”, it does not grow in Southern Africa (yet!).

Expanding seaweed aquaculture on a very large scale in the future would require expanding the potential sea area outside of that available in the few sheltered bay areas in the region. In other parts of the world, particularly the North Atlantic and USA, there is considerable interest in the prospect of **offshore** seaweed (particularly kelp) aquaculture. Bak et al. (2018) define ‘offshore cultivation’ as “the execution of activities in sites that are subject to ocean waves, which is linked to distance from shore or lack of shelter from topographical features such as islands or headlands that can mitigate the force of ocean and wind-generated waves and sites with significant wave heights of two meters or above”. This would open up a considerable area of sea for cultivation but would of course require considerable marine engineering to make it possible. As an extreme example, Kim et al. (2019b) comment that “the exclusive economic zone (EEZ) of the United States offers opportunities for expansion of seaweed aquaculture in an area greater than the entire land mass of the United States and with limited user conflicts”. It is clear from extensive studies in Europe and the Faroe Islands (Bak et al. 2019) that growing kelp offshore is feasible. As an example, the European sugar kelp (*Saccharina longissima*) is capable of growth in sheltered bays and thrives in conditions of extreme shelter from waves in sea lochs in Scotland. Nevertheless, the species was successfully grown, with good growth rates, in an offshore site off the coast of Portugal where significant wave height ranged between 0.5 and 6.2 m, and maximum wave height ranged from 0.9 to 12.6 m (Azevedo et al. 2019).

Previous attempts to grow South African kelps

There have been very few attempts towards South African kelp aquaculture thus far. The gametophytes of *Ecklonia maxima* (Bolton & Levitt 1985, Bolton & Anderson 1987) and *Laminaria pallida* (Rothman 2015) have been grown in culture dishes in the laboratory, and some experiments done on their environmental tolerances, such as temperature and light (see Section 4). Rothman (2015) is the only person to have seeded strings with kelp juveniles grown from spores and to have successfully grown large plants of South African kelps in the sea (both *Laminaria pallida* and *Ecklonia maxima*), although it was a small, experimental apparatus (see Fig. 11).

Macrocystis pyrifera is the only kelp in South Africa which can regenerate new stipes from a long-lived holdfast (Fleischman et al. 2019, 2021). Aquaculture experiments have been carried out in Chile. attempting to grow this species by the regeneration of holdfasts rather than from spores (Westermeier et al. 2013). This was attempted in a 3-month experiment in Saldanha Bay by Fleischman (2021; Fig. 12). The holdfasts grew and attached themselves around the culture lines, and new upright systems were produced from the holdfasts during this short period. In addition, the uprights on the *Macrocystis* almost doubled in size during the three months (from 55.6 to 102.2 cm in length) and grew at a relative growth rate of ca. 1% per day.

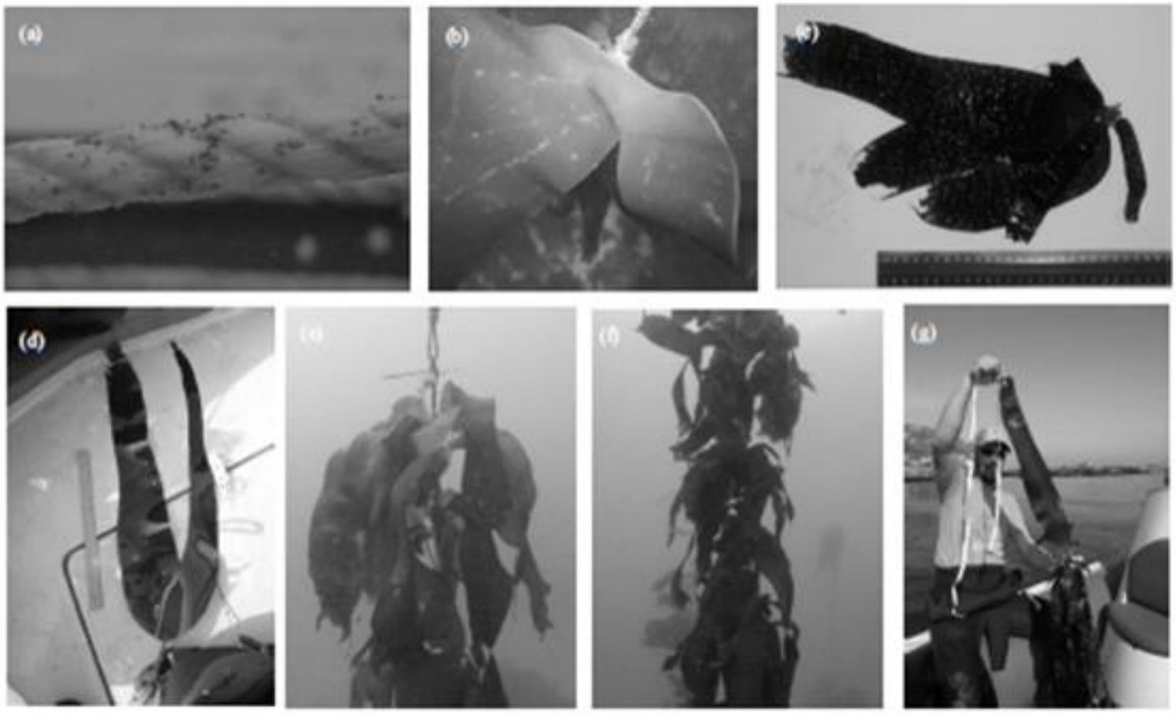

Figure 11: (a) Small developing sporophytes after 3 months on the ropes in the aquarium (b) A *Laminaria pallida* sporophyte starting to split, 4 months after it has been put in the sea. Note the perforations in the blade where it will split next; (c) An *Ecklonia maxima* juvenile sporophyte after 4 months on the ropes in the sea (d) An *L. pallida* after 8 months in the sea on the ropes (e) Underwater picture of *L. pallida* sporophytes on the ropes (f) Underwater picture of *E. maxima* sporophytes on the rope (g) An *E. maxima* sporophyte beginning to develop secondary blades after 8 months in the sea (Rothman 2015).

Figure 12. Michael Fleischman with *Macrocystis pyrifera* growing from holdfasts on ropes in Saldanha Bay. Photo: John J Bolton

Where can kelp be grown in South Africa?

In parts of Asia, particularly China, kelp is sometimes grown in regions where it does not and cannot occur naturally. These places have seasonal fluctuations in sea temperature, and the small growth stages are grown in cooled hatcheries in the warm months of the year with the juvenile kelps put out in the sea when the seawater temperature is low enough for kelp growth. Nevertheless, most global kelp aquaculture occurs in regions where kelp occurs. Kelp is often grown in the sea for only part of the year, and this growth season needs to be timed so that:

- It is the main seasonal growth period of the kelp
- There are sufficient nutrients (especially the major macronutrients, dissolved nitrogen and phosphorus) in the water throughout the growth period.

In addition, aquaculture structures are traditionally placed In relatively sheltered waters, with lower potential for damage in storms etc. This requires growing a species which is capable of growth in relatively sheltered waters, often inside bays or lagoons.

In South Africa we have a remarkably straight coastline, with very few large bays, and also few large rivers with considerable areas of estuary/lagoon where marine organisms could be grown. Almost all the commercial sea-based aquaculture in South Africa (mostly oysters and mussels, with some finfish) currently occurs in Saldanha Bay on the west coast, although previously other areas have had commercial aquaculture ventures (e.g. Algoa Bay, Knysna Lagoon). The only large-scale experiments growing seaweeds on rope rafts in South Africa were on the red seaweed *Gracilaria* in Saldanha Bay (Anderson et al. 1996) and an adjacent relatively sheltered section of the open coast in St Helena Bay (Wakibia et al.

2000). In these studies, *Gracilaria* grew well year-round in Saldanha Bay, apart from a period in late early autumn (March). In this period the water at the site, in the inner bay of Saldanha known as 'Little Bay', stratified. This means that there was a separation of shallow (to 6m depth) surface water with warmer temperatures and low nutrients, and a lower layer with cooler temperatures and higher nutrients. This meant that the *Gracilaria* starved due to lack of nutrients in that period, and to continue growth the rafts had to be restocked with material from elsewhere in the Bay system. Nevertheless, apart from the loss of the seaweed at that time of year, *Gracilaria* was grown on rope rafts in Saldanha Bay for over 4 years (Anderson et al. 1996).

The logical place to grow large seaweeds in South Africa is the west coast. The three most important factors to grow any plants are continually available water, nutrients and sunlight. A case could be made that the Benguela upwelling system is one of the best regions in the world for year-round nutrient and light supply. Indeed, this is the main reason why KelpBlue (https://kelp.blue/namibia/), a company intending to grow *Macrocystis* offshore on a large scale, chose Namibia to set up their operations (Daniel Hooft, CEO, *pers. comm*.). In the North Atlantic, for example, there is a seasonal mismatch between sunlight and nutrients, with high levels of nutrients in the winter and very low levels in the summer. *Laminaria* species in that region grow most in late winter/early spring and have low growth rates in summer. In addition, Some North Atlantic kelps can store nitrogen and carbon on a large scale, to enable them to grow for a short period when nutrients or light are limiting. In contrast, on the South African west coast nutrients are relatively available year-round, particularly due to upwelling of nutrient-rich water from the Benguela current in the summer months in the Southern Benguela and aseasonally in the Lüderitz region. Thus, Southern African kelps appear not to store nitrogen or carbon in large amounts, and the available evidence suggests that they have most growth in the summer, when most light and nutrients are available through upwelling.

Therefore, the obvious place to start experiments on kelp aquaculture in South Africa is Saldanha Bay, which has considerable aquaculture infrastructure already in place and is the only large, sheltered bay on the west coast. The proviso is that there is a possibility of a low nutrient event in late summer/early autumn, which could cause problems if the kelp is still in position in the bay over that period. There are also areas marked out by government regulations for seaweed aquaculture in Saldanha Bay, which will make regulatory aspects initially easier. In addition, it could be worth investigating kelp aquaculture in the sheltered area of St Helena Bay where *Gracilaria* was successfully grown for a 15-month period, with growth rates ranging from 4-11 % per day (Wakibia et al. 2000). The latter site has had problems with low oxygen events in the past, and this is something which needs to be considered for any sea-based seaweed cultivation in South Africa (see oxygen discussion in section 4).

There are considerable areas around the South African west coast where the sort of offshore structures used elsewhere for kelp aquaculture (Bak et al. 2018, 2019) could be operated. If such operations are successful in Europe and elsewhere (including possibly KelpBlue in Namibia) there will undoubtedly be further interest in offshore cultivation of kelp in South Africa.

Biosecurity and sustainable kelp aquaculture

With the rapid expansion of actual and proposed kelp aquaculture operations in the North Atlantic and Eastern Pacific, there has been concern over biosecurity, particularly the

possible introduction of species and spread of pathogens. A policy document was recently produced, presenting a vision for the sustainable future of the rapidly expanding global seaweed aquaculture industry (Cottier-Cook et al. 2021).
Major threats to seaweed aquaculture around the world are pathogens and factors associated with climate change. A general pattern which emerges in aquaculture is that a new species can be grown for several years with few problems with pathogens, but diseases eventually arise in long-term monocultures. For example, there are several diseases in the nori industry in South Korea, which cause significant crop losses (Ward et al. 2019). Warming of the sea has had considerable negative effects on what is by far the largest seaweed aquaculture operation in Africa, the culture of the red seaweeds *Eucheuma* and *Kappaphycus* for carrageenan in Tanzania (Msuya et al. 2022). Droughts resulting in less run-off from neighbouring rivers has also resulted in considerable crop losses through low nutrient effects in South Korea (Hwang et al. 2020).
Ward et al. (2019) list 19 diseases which cause problems in kelp aquaculture in Asia, 13 of them bacterial, 2 associated with small brown algae growing on the kelps, 2 with animals (amphipods or copepods) and 2 associated with environmental problems (low nutrients, low salinity or excessive light). We are not yet aware of diseases of South African kelps which may cause problems, but this is usual in the initial stages of cultivation.

4. Environmental aspects of South African kelp aquaculture

Seasonality of kelp growth and aquaculture

The seasonal patterns of kelp growth are critical in kelp aquaculture, as kelps are generally temperate organisms, with distinct annual growth patterns. Almost all kelps are perennial, although the economically important *Undaria pinnatifida* (wakame) and the ecologically important Northeast Pacific species *Nereocystis luetkeana* have annual sporophytes. The latter is a large kelp, and sporophytes can grow to around 20m long in a single year. The same species may have different seasonal characteristics in different sites, with *Macrocystis pyrifera* being generally perennial, but annual populations existing in parts of Chile (Schiel and Foster 2015). Despite most kelps being perennial in nature, seaweed aquaculture systems are mostly stocked with new sporophytes on an annual basis.

Unpublished data (N.G. Jarman, pers. comm.) suggests that *Ecklonia maxima* can live for 5-6 years and probably longer. This is likely to be similar for *Laminaria pallida*, although data are lacking. South African *Macrocystis* is different, as new growth of branched stems (uprights) can occur continually from the holdfast (Fleischman et al., 2019). This is because local *Macrocystis* has a spreading holdfast with many uprights, unlike the other two species, which grow as single individuals (one stipe per holdfast). It is possible that holdfasts of Macrocystis can live for many years, but again local data are lacking.
The is a lack of seasonal data on Southern African kelp growth. We have no seasonal growth data (as elongation in length of blades) for either *Ecklonia maxima* or *Macrocystis pyrifera*. The only good data available is that produced by Dieckmann (1978) for *Laminaria pallida*. This was studied on the Cape Peninsula, in the extreme south of the distribution of this species, where it mostly grows at depths of 6-10m.

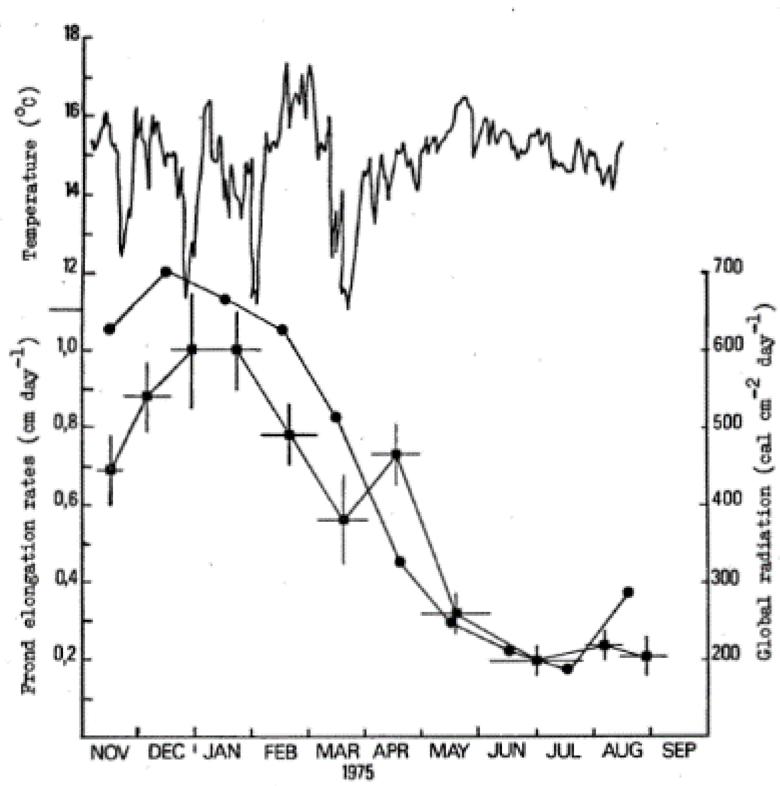

Figure 13. Elongation rates of blades of *Laminaria pallida* with season, at 3m depth at Robben Island (vertical bars are 95% confidence limits, horizontal bars are intervals between measurements). Included for comparison are seawater temperature, and seasonal light (irradiance) at Cape Town airport (Dieckmann 1978).

Laminaria pallida blades grew faster in summer and early autumn (November to April, Fig. 13). The blades grew at similar maximum rates (1.0-1.2 cm day^{-1}) from 3m at Robben Island down to 8m and 14 m at Oudekraal (Diekmann 1978). Growth rate was most closely linked to monthly amounts of light (as compared with total irradiance at Cape Town airport, Fig 13).

Although we have no seasonal growth data for *Ecklonia maxima*, Joska and Bolton (1987) reported on the seasonal production of secondary blades, and seasonal fertility and spore production. *E. maxima* produced most secondary blades in the late winter to spring, with a maximum in November. Numbers reduced drastically during the summer. Many kelps in other parts of the world have seasonal patterns of fertility, which means that spores to start aquaculture from wild material are not available for part of the year. From the available evidence, all three of the South African west coast kelps have at least some fertile material year-round. The only species studied in detail, *Ecklonia maxima*, showed maximum number of fertile secondary blades and maximum area of fertile tissue in spring (Joska and Bolton 1987).

The seasonality of growth is critical for aquaculture, as it is essential that kelps are at their ideal size for growth potential at the time of year when seasonal growth is fastest (for *Laminaria pallida*, in summer). The seeding of strings with spores needs to be timed in this way, bearing in mind the time needed for growth in the hatchery and initially when placed in the sea. In Europe growth is often started in the sea in winter to take advantage of high growth rates in spring, and kelps are sometimes harvested in late spring due to growth of epiphytes (see later) on the plants reducing seaweed quality in the summer. These sort of seasonal patterns and their aquaculture consequences need to be worked out for South

African species, and may differ between species and sites (e.g. March drop in nutrients due to stratification may inhibit kelp growth in Saldanha Bay, but not in St Helena Bay).

Kelp environmental tolerances: general comments

Of the many environmental aspects of the coastal marine environment, only a few are especially important in optimizing kelp growth and aquaculture potential. The four main ones are seawater temperature, dissolved nutrients (especially the main macronutrient nitrogen), water flow/wave action, and light. Some of these are interactive, for example nutrient levels affect phytoplankton growth, which can affect turbidity and, hence, light levels at depth. Similarly, flow rates can affect nutrient availability (see below). Also, there is a strong negative correlation on the South African west coast between dissolved nitrogen and water temperature (Waldron and Probyn 1992). Seasonal growth, as mentioned, may also be controlled by internal physiological rhythms in the kelp triggered by seasonal daylength, which would mean that there could be times of year when the kelp does not grow quickly, even if ambient environmental conditions are optimal.
Not all life history stages of kelps have the same environmental tolerances and small initial stages (gametophytes and small sporophytes) often, for example, have lower light and/or flow rate requirements or ability to survive in a different (often wider) range of temperatures compared with large kelp sporophytes. The environmental conditions for small stages can, of course, be better controlled in a hatchery setting.

Salinity

Salinity can be a major factor in seaweed aquaculture in some world regions but is generally not very important in South Africa. The main aquaculture sites in both South Africa (Saldanha Bay) and Namibia (Lüderitz Bay, Walvis Bay) have minimal freshwater input from rain and the salinity varies very little, except in Namibia where in certain embayments the salinity may become too high through evaporation (hypersaline). The salinity of the open sea averages around 35ppt (parts per thousand), and kelps would have no problem with a salinity range slightly higher or lower (e.g. 32-38ppt). There is, however, no real experimental data on this for South African kelp species. Much aquaculture of marine species around the world is conducted in estuaries, with lower salinity ranges, or in areas where salinity is generally close to 35ppt, but with occasional rain run-off events where salinity drops. In some estuaries, and often after a large rainfall event, the water stratifies, with lighter low salinity water in a layer on top of heavier seawater. Kelps are sometimes grown slightly deeper (or lowered) to avoid occasional low salinity events.
In the South African context, salinity would only be a problem close to large river mouths (e.g. the Orange River, Branch et al. 1990), as we have few true estuaries where aquaculture is likely to be carried out. Oysters were formerly grown in Knysna Lagoon, which is not a typical estuary but has full seawater salinity for most of the time, with occasional flood events when the salinity drops. Kelps do not generally grow well in estuaries, and other aquaculture species are often selected as those which grow in estuaries and sheltered waters. Local *Gracilaria* (Engledow and Bolton 1992) and *Ulva* (Shuuluka 2011) can survive and grow well in much lower salinities than kelps.

Temperature

There are two complementary ways to estimate the temperature tolerances of kelps: under what temperature conditions do they grow well in nature, and what are their experimental temperature tolerances in laboratory culture. Most laboratory work locally has been carried out on *Ecklonia* species, with very little on *Laminaria* and *Macrocystis*. As *Macrocystis pyrifera* has a large global distribution, there is information available on its temperature and other environmental tolerances from elsewhere. As with light, it is often the case that microscopic stages have somewhat different temperature tolerance ranges for growth and reproduction than large kelps. There is evidence that some kelp gametophyte stages can remain viable during unfavourable conditions, reproducing and producing the next generation of kelp sporophytes when the conditions are better for kelp growth. It is extremely difficult to do controlled temperature experiments on growth of large kelps, although it is possible to measure parameters such as photosynthesis.

In laboratory conditions, the gametophytes of *Ecklonia maxima* survive a very wide range of temperatures (3-25°C) but did not develop at 3 and 25°C (Bolton and Levitt 1985). They became fertile (females produced eggs) from 5 to 22.5°C, with faster fertility (most cells producing eggs after 14 days) at 15 and 17.5°C. At 22.5°C egg production was a little slower, but gametophytes grew larger and eventually produced more eggs per gametophyte. Bolton and Anderson (1987) continued this work, but also included the south coast kelp species *Ecklonia radiata* (as *Ecklonia biruncinata*), and small sporophytes of both species grown from eggs in the laboratory (initial blade length of small sporophytes was 1mm, and they were grown for 2 weeks). Bolton and Anderson (1987) also managed to hybridize *E. maxima* and *E. radiata* in the laboratory and give data for inter-species hybrid small sporophytes. All small sporophytes survived and grew slowly at 4°C, and all grew well from 8-22°C. *Ecklonia radiata* had higher absolute growth optima (15-22°C) than *E. maxima* (8-15°C), with the hybrids with intermediate tolerances. *Ecklonia maxima* small sporophytes died at 26°C, whereas *E. radiata* and the hybrids survived and grew at that temperature.
There is no similar laboratory data available for *Laminaria pallida*. Rothman (2015) conducted gametophyte experiments on this species successfully at 15°C, producing healthy sporophytes. There is also a lack of data for South African *Macrocystis pyrifera*, although different populations of the species have been studied around the world. Shiel and Foster (2015) summarise tolerance of abiotic requirements of *M. pyrifera* gametophytes (their Table 2.1), including survival from -1.5-26°C and optimal range for egg production from 10-17°C.

As discussed by Shiel and Foster (2015) extrapolating the temperature tolerances of large kelps from temperature regimes in their distribution in nature is problematic due to temperature gradients with depth, in particular the temporal presence of thermoclines which can cause very rapid temperature/depth changes. Most available data are sea surface temperatures, which can be very different to the temperature near the rock substrate in a large kelp forest. From laboratory studies and general distributions it is clear that *Macrocystis pyrifera* is more cold tolerant than South African *Ecklonia* and *Laminaria*. As seawater temperatures in South Africa are never below the temperature of upwelled water near the coast (7-8°C), and coastal monthly means at the surface are not below 10°C (Rothman et al. 2017b), it is unlikely that cold water limits distribution or growth of local kelp species, especially as both *E. maxima* and *L. pallida* grow and develop most rapidly in southwestern South Africa in summer, when temperatures are coolest due to upwelling.
The effects of warmer temperatures in limiting kelp distribution are also complicated by the clear inverse relationship between temperature and nutrients, particularly in upwelling regions (for data from the South African west coast, see Waldron and Probyn 1992). Shiel and Foster (2015) comment that is it “generally thought that adult giant kelp do not grow well above 20°C” but noted that populations in Baja California and also in Chile may experience higher temperatures than this for several weeks at a time. Fleischman et al. (2019) carried out thermal stress experiments on adult blades of *E. maxima* and *M. pyrifera* in the

laboratory and showed that photosynthesis of *M. pyrifera* was highest at 15°C, declining above 17.5, whereas with *E. maxima* photosynthesis was high and not significantly different at 15-20°C, declining at 22.5°C. There is also evidence (Shiel and Foster 2015) that genetic differences exist between populations of the same species of kelp with regard to temperature and/or nutrient requirements and it is not recommended to, for example, relate tolerances of *Macrocystis pyrifera* in Baja California to those in South Africa. Nevertheless, Fleischman et al. (2019) consider that the southeastern limit of South African *Macrocystis* (at the Cape Peninsula) may be limited by warmer temperatures.

The relative distributions of *Ecklonia maxima* and *Laminaria pallida* with respect to temperature (and by correlation, nutrients) in South Africa are complicated by clear patterns of evolution in form and habitat by *Laminaria pallida* along the coastline. In the southwest, *Laminaria pallida* is predominantly a subtidal species (dominating from 5-20m) with a solid, upright stipe (Rothman et al. 2017b). North of Cape Columbine stipes of *Laminaria* are longer and predominantly hollow, and the species dominates in shallower water. South African populations on either side of this break are genetically distinguishable (Assis et al. 2022). *Laminaria pallida* (the solid-stiped type) is rare east of Cape Point, and confined to cooler, deeper water, which suggests it may not thrive as well as *Ecklonia maxima* in the warmer seawater conditions. On the contrary, in the northern distribution of these two species, only *Laminaria* (the hollow-stiped form) is present and *Ecklonia* absent in northern Namibia, where the water is again warmer than on most of the west coast but more turbid. The northern Namibian *Laminaria* shows significant genetic variation from that in southern Namibia and South Africa (Assis et al. 2002).

Nutrients

In nature on the open coast most of the available dissolved nitrogen (the major limiting nutrient for growth of seaweeds in the sea) is present as nitrate, but kelps can also utilise other forms of nitrogen if it is available (e.g. nitrite, ammonium). Cyrus (2007) used stable isotopes of nitrogen, which can label different nitrogen compounds, to demonstrate that *Ecklonia maxima* plants nearby take up dissolved nitrogen emitted from the Green Point sewage effluent outfall on the Cape Peninsula. With *Macrocystis* in California Gerard (1982) showed that giant kelp required 1-2 µ mol L^{-1} to support a typical growth increase of 4% in wet weight per day. Probyn and McQuaid (1985) studied uptake of different forms of nitrogen from plastic bags around *Ecklonia maxima* plants. *E. maxima* took up nitrate and ammonia, but not urea, and showed only a weak preference for reduced nitrogen (ammonia). When upwelling occurred, the *Ecklonia* took up more nitrogen, resulting in increased nitrogen content in the kelps in upwelling periods. The uptake of nitrate did not saturate (reach a maximum) even at the highest values of >20µg-at N L^{-1}. Although more nitrogen was taken up in upwelling periods in this study, it seems that there is no major seasonal storage pattern of nitrogen in *Ecklonia maxima* (see Section 5).

Some kelps in the North Atlantic have the capacity to store carbon and nitrogen in some seasons, to be used for growth in other seasons when light or nitrogen may be limiting (Chapman and Craigie 1977). It appears that this is not the case with *Macrocystis pyrifera* in the northeast Pacific, where Shiel and Foster (2015) suggest it is possible that the "southern distributional limit of giant kelp may, in part … be the results of its limited ability to store nutrients". They also suggest that the northern limit in the northeast Pacific, may "reflect the inability to store carbon when sufficient light is available". Although *Ecklonia maxima* can increase its uptake of nitrate to some extent during upwelling periods (Probyn and McQuaid 1985), it seems that this species is also not capable of large seasonal storage of nitrogen. Monthly nitrogen levels in this species were similar throughout the year, with no clear seasonal pattern. ranging from 1.6-1.8%N, which using the standard conversion factor of x6.25 is equivalent to a crude protein content range of 10-11.25% protein (Smith 2007).

There is some evidence (Smith 2007) that *Ecklonia maxima* may store a small amount of carbon seasonally, with maximum carbon content in summer (35-37%C) and generally lower levels for the rest of the year (averaging 31-33%C). Diekmann (1978) measured total nitrogen content of fronds of Laminaria pallida at four different times of year, and showed a range of 1.64-2.10%N, which again using the standard conversion factor of x6.25 is equivalent to a crude protein content range of 10.25-13.13% protein. The single high value was in July.

Water flow/wave action

There are two main effects of seawater motion on seaweeds.

Seaweeds gain their nutrients from the water, through the whole plant. The surface of a body in water has a very thin 'boundary layer', from which the nutrients are extracted. If nutrients in this layer are depleted and not replaced the seaweed will not be able to obtain sufficient nutrients for growth. Going from still water and gradually increasing flow increases seaweed growth, until growth reaches a maximum. Adding high levels of nutrients to the water enables seaweeds to grow with less water flow (as is done when making nutrient media in the laboratory, for example small sporophytes in a hatchery). Different species of seaweeds are adapted to different levels of water flow and, for example, a few species which can grow unattached, with little water flow, in estuaries and other sheltered waters make the best seaweeds to grow in tanks or raceways on land (for example species of *Ulva* and *Gracilaria*). Aeration, or water movement using a paddle wheel, is used in these land-based systems to increase availability of nutrients and dissolved gases (CO_2 and O_2) to the seaweeds.

Once water flow/wave action is sufficient for maximum nutrient uptake, the other effect is a negative one: the potential for damage by high wave energy. Most seaweeds are adapted to wave action. All three main groups of seaweeds (brown, green and red seaweeds) contain a significant proportion of their dry weight (up to 30-40%) as long chain carbohydrates, known as phycocolloids. These are variously known as alginates (brown algae), agars and carrageenans (red algae) and compounds such as ulvan (the green seaweed *Ulva*), when they are extracted and used in a wide variety of industries. Their uses are based on their gel properties, and in the seaweeds they provide elasticity assisting in survival in high-energy environments. Different seaweeds have differing abilities to survive high energy waves, and also different species of kelp differ in this aspect.

Among South African kelps, *Ecklonia maxima* is abundant even on the most exposed of headlands, and in shallow water on wave exposed shores, where the waves break. It is clearly well adapted to high wave action. *Laminaria pallida* is again more complicated, as in the southwest it grows in deeper water as well as in shallower water in small embayments and harbours, both habitats where there is less wave action. Further north, however, it has a longer stipe and dominates inshore where waves break. Rothman et al. (2017b) provide some evidence that average and maximum wave height are higher in the southern Benguela than in the northern Benguela.
Large amounts of kelp plants wash up in winter storms, but these are mostly older, heavily epiphytised plants. It is interesting that in two large storms with very high waves in the last couple of years, large piles of *Laminaria pallida* were washed up (JJ Bolton and RJ Anderson, pers. obs.). These plants grow deeper than the usually detached *Ecklonia maxima*, and presumably are more impacted by these bigger swells. *Macrocystis pyrifera* tends to grow in more sheltered open coast habitats. In South Africa it only grows in the lee side of Robben Island and Dassen Island, as well as a few small populations in relatively

sheltered embayments, growing inside large forests of *Ecklonia maxima* (e.g. at Gifkommetjie, Kommetjie, Melkbosstrand, Jacobsbaai; Fleischman et al. 2019). In California large canopies of giant kelp can be extensively damaged by large storms, and the canopy coverage can become a small percentage of the original forest, which recovers between storms. Placing sea-based aquaculture facilities deeper can reduce impacts of wave action. The most important impacts of wave energy on these systems are not on the seaweeds, but on the infrastructure. These are effects of major events (especially high tides, storm waves, and even tsunamis), such as those that brought the end of the *Gracilaria* aquaculture in Namibia.

Light

Seaweeds need light to grow, and especially the amount of light received during the day is important, linked to both irradiance and daylength. Light controls many physiological processes in seaweeds, varying on different time scales from hours to seasonal patterns. Some seaweeds have seasonal light triggers for reproduction and/or growth and are in fact 'short-day or long-day plants'.

Good summaries of light and seaweed physiology and growth are in Lüning (1990) and Hurd et al. (2014). Very high light can damage some seaweeds, particularly the effects of UV (Hurd et al. 2014) and growing a metre or more below the surface can be beneficial provided there is sufficient light to saturate photosynthesis. This is also linked with water quality, with optimal growth depth being shallower in turbid water than in clear water.

When new aquaculture operations are conducted, it is usual to carry out initial experiments with the seaweed ropes at different depths to test the optimum depth for growth at different times of year. For example, in *Saccharina* cultivation in Japan the kelps are initially grown at 2m depth, but later in the growing season are gradually raised to 0.5m as the kelp are larger, competing for light, and sunlight becomes less (Kawashima 1993). One way to test this is to position some kelp ropes at an angle and measure growth of individual kelps along the depth gradient.

Rothman et al. (2017b) hypothesized on what environmental parameters might be driving the evolution of form and habitat in *Laminaria pallida* along the South African west coast. The environmental parameter which best correlated with the change in form of the kelp appeared to be water turbidity (measured using satellite data, as chlorophyll *a*, particulate inorganic and organic carbon). Inshore waters become more turbid northwards, and these authors speculated that *Laminaria pallida*, which grows deeper in the south and shallower in more turbid waters in the north, may be tolerant of lower light levels than the competing *Ecklonia maxima*, but there is no experimental evidence available as yet to back up this hypothesis.

Oxygen

It is unlikely that dissolved oxygen is ever a limiting problem in coastal waters in the Benguela upwelling system except in specific low oxygen events, which occasionally happen caused by upwelled water and the degradation of large phytoplankton blooms. Certain parts of the west coast are particularly susceptible to these 'low oxygen events' (Cockcroft 2002). An extremely drastic low oxygen event, known as a 'black tide', occurred during the *Gracilaria* raft aquaculture experiments of Wakibia et al. (2001) in St Helena Bay. They report that these events killed most of the inshore biota in 1994 and 1998, and their frequency should be considered when planning aquaculture operations, where they occur.

pH

Seaweeds can be affected by ocean acidification, and there is some evidence of lower pH benefiting smaller seaweed communities ('turfs') over kelps (Connell 2018). However, pH is rather a complicated factor in seaweed aquaculture and seaweed-dominated communities. Photosynthesis of seaweeds in the day in kelp forests removes dissolved carbon from the water, raising the pH considerably, and respiration of seaweeds and animals removes dissolved CO_2 lowering the pH at night, resulting in a daily rhythm of pH in the water. Thus, kelps can, to an extent, control pH around them and they are capable of ameliorating effects of ocean acidification for animals, both in natural ecosystems and integrated aquaculture systems (De Prisco 2022).

Epiphytes and grazers

An 'epiphyte' is a living species which grows on a plant, in this case on a large brown seaweed. Epiphytes of seaweeds are often other seaweeds, but can also be different types of sedentary animals such as bryozoans, barnacles, juvenile mussels etc. Very heavy infestations of epiphytes can affect the growth and health of seaweeds and also large amounts can affect the quality of an economic seaweed and its sale price.

In nature, young and fast-growing seaweeds generally have very few epiphytes, and have biological mechanisms to prevent fouling by these epiphytes. As kelps in South African kelp forests get older, they gradually lose their ability to prevent epiphyte fouling, and old plants often have heavy epiphyte loads.

A few species of seaweeds almost always grow on kelps and are species-specific. For example, blades of old plants of *Ecklonia maxima* often have large growths of the red seaweed *Carpoblepharis flaccida*, whereas blades of *Laminaria pallida* have a different, closely related species on the blades (*Carpoblepharis minima*). These red algae are closely linked to the kelps in another way: they attach within the tissues of the kelps and obtain some of their nutrients from within the kelp (in fact they are 'semi-parasites'). Other abundant epiphytes grow on the stipes of older *Ecklonia maxima* plants, particularly the red seaweeds *Gelidium vittatum* and *Carradoriella virgata*. In the study of Fleischman et al. (2019) local natural populations of *Macrocystis pyrifera* were free of epiphytes and other associated organisms, apart from a few animals inside the holdfast.

In Europe kelps generally have much larger infestations of animals and, particularly in sheltered waters, fine threadlike brown algae ('ectocarpoids') on occasions. In kelp aquaculture in Europe time of harvest is often linked to epiphyte loads. For example, in Denmark (Marinho et al. 2015) good growth is obtained in August and September, but if kelp is to be used for human food (high quality) it is harvested earlier (in May) before high loads of epiphytic animals appear on the blades. We will only know how much of a problem epiphytes can be in South African kelp aquaculture once we have grown kelp in different locations. For example, greater wave action may reduce epiphyte loads in some seaweeds, and seasonal patterns in growth and susceptibility to epiphytes may be critical in some localities.

Large biomass of seaweeds on an aquaculture raft for some months can become an 'artificial ecosystem' which may contain animals which eat the seaweed. In nature in South Africa, the animals which eats most kelp is the Cape sea urchin (*Paracentrotus angulosus*). Where it occurs in abundance (e.g. in False Bay) it consumes much of the biomass of seaweeds on the rock below the kelp forest, but this local urchin cannot eat adult kelps. In many other parts of the world, infestations of sea urchin species have devastated kelp forests, removing them from large stretches of coastline. A large settlement of urchins on a kelp raft could be a problem. Also it is possible that large settlements of juvenile mussels could grow over kelps in aquaculture, especially in Saldanha Bay, where large amounts of mussels are cultivated nearby. In the short (3 month) study of Fleischman, where Macrocystis was grown on a rope raft in the Bay, the kelp was completely clear of epiphytes, despite heavy overgrowths of mussels and other animals and seaweeds on the ropes. The kelp has biological mechanisms to keep it clean, when it is healthy and fast-growing.

Potential choice of kelps for local aquaculture and methods

As kelp aquaculture in South Africa is in its infancy, we will need to decide which species to grow, and we may need to try to grow all three species initially to find out which produce the best growth rates. Obviously, the market demand for the seaweed produced is also critical, which is difficult when we do not know what local and global seaweed markets may be like in 10 years or longer.
Below are some possible factors which may be borne in mind in considering this choice:

Ecklonia maxima

- Around half of an adult Ecklonia maxima plant weight (2 years old or older) consists of the long, hollow stipe, but it is likely that this is not produced in the first year of growth. It is possible that material in the first year of growth will have slightly different properties, composition and potentially markets than wild-harvested material?
- This is the most economically used species in South Africa, currently, and has proved to be an excellent feed in local abalone aquaculture.
- It grows on all coastlines, appears to prefer clearer water and is well suited to high wave action (may be a good potential species for offshore cultivation).
- Most blades get close to the surface at low tide, so a good candidate for growth on shallow ropes.
- Appears to be the most warm-tolerant of the three species at the southern end of its distribution.
- Other species of Ecklonia have been grown elsewhere, particularly in Japan and Korea for human food and increasingly for health foods, nutraceuticals and cosmetics.

Laminaria pallida

- Some genetic difference north and south of Cape Columbine, which coincides with a difference in form and habitat (in the south it has a solid stipe and grows mostly below 6m depth, in the north it has a partially hollow stipe and dominates inshore). These strains/forms may have different characteristics for growth on aquaculture rafts?
- Used as abalone feed in the Northern Cape, but anecdotal evidence from some abalone farmers suggests it may not be as good for abalone feed as Ecklonia maxima (this needs to be tested scientifically).
- Related to European Laminaria species, some of which are being increasingly grown in aquaculture (e.g. Laminaria digitata), and most closely related to southern European Laminaria ochroleuca, which is also grown to a small extent and considered a potential human food in southern Europe.

Macrocystis pyrifera

- Globally widespread species and large volume of scientific studies on the aquaculture of this species in Chile and California/Alaska.
- Several past attempts to introduce this species into both Europe (Brittany) and China for aquaculture purposes.

- Despite all these attempts, there is no evidence of large-scale Macrocystis cultivation globally, as yet. Macrocystis in Chile is still almost all harvested from natural populations as abalone feed. This may be a matter of economic scale (Camus et al. 2019).
- Much of the pressure for cultivation of this species revolves around its status as ‘giant kelp’, the largest and fastest growing plant in the Oceans, but South African populations are much smaller. Can South African Macrocystis grow larger and at growth rates achieved elsewhere?
- It has been tested as abalone feed with the local species (Haliotis midae) and found to be at least as good as Ecklonia maxima.
- A local abalone farm has already invested in attempts to cultivate Macrocystis and have built a hatchery to further this aim.
- The only one of the three kelps discussed here which can regenerate from the holdfast after a partial harvest. This has been shown to be possible over a short period on a rope raft in Saldanha Bay.
- Macrocystis is the intended species for offshore kelp aquaculture on a large scale by the new company KelpBlue in Lüderitz, Namibia (https://kelp.blue/namibia/), although the species does not grow naturally in Namibia (it does of course grow in the Benguela Large Marine Ecosystem, though, in southwestern South Africa). KelpBlue intend to grow the species deeper (ca. 20m) and intend that it will grow up towards the surface, enabling mechanical harvesting of near-surface material (the species was harvested in a similar way from natural forests in e.g. California in the past). Their idea is to produce an ‘artificial kelp forest’ offshore, which can be continually harvested. This method would not be possible with the other two Southern African west coast kelp species, as when their blades are removed the individual kelp dies.

Because all three potential west coast species have benefits, as well as potential drawbacks, it seems logical to initially attempt to grow all three. If we do not, we will not gain information on which are easiest to grow and which grow fastest in different available environments. There is potential for different markets for different species, but well-planned growth trials are necessary to make eventual informed decisions.

5. South African kelp nutrition and chemical composition

General constituents

Fresh kelps are ca. 15-20% dry matter, ca. 80-85% water. Diekmann (1978) gives a figure of oven-dried weight of 15% for *Laminaria pallida*, whereas Table 1 below gives a figure of ca. 20% dry matter for *Ecklonia maxima*, using frozen samples which may have affected the values. Seaweed products for human food are often sold with a water content of ca. 10-15% (Fleurence 2016). Smith (2007) documented a seasonal pattern in water content of *E. maxima*, with higher values in summer (December to March) and lower values for the rest of the year. Kelps have high levels of minerals and carbohydrates, with about 70% of dry weight consisting of ash and carbohydrates (predominantly alginate with some mannitol and laminaran), and generally close to 10% crude protein. Because of the high content of alginate, kelps are a good source of fibre (estimated as 30-40% of dry weight of *E. maxima* in Table 1), with fibre content greater than that in vegetables or fruits. Most of this fibre is soluble fibre (Fleurence 2016). Generally lipid content in seaweed is “very low” (Fleurence 2016), averaging ca. 1-2% in kelps (around 1% in *E. maxima*, Table 1). Compared to land vegetables, seaweeds contain “significantly higher levels of polyunsaturated fatty acids,

which act as strong antioxidants, such as omega 3 and omega 6 (Baweja et al. 2016). Kelps, and algae in general, are “low-calorie foods” (Fleurence 2016).
Kelps, and seaweeds in general, contain ca. 56 different minerals and trace elements which are required for the human body’s physiological functions (Baweja et al. 2016) and are particularly good sources of calcium and magnesium. Kelps and other seaweeds concentrate potassium to a much greater extent than sodium: the latter is present in seawater in much higher amounts. This makes them a useful source of ‘low-sodium salt’ for the health food industry (Magnusson et al. 2016).

Table 1. Average major constituents of *Ecklonia maxima*, collected monthly from April 2004 to June 2005. A total of 80 samples were analysed from the West coast (Jacobsbaai Sea Products Abalone Farm) and 199 samples from the South West coast (HIK, AVUKA and I&J abalone farms). Significant differences using ANOVA between location (coasts) and seasons (month) are indicated by *. From Smith (2007). Note: Moisture content values are perhaps a little low, as these samples were pre-frozen and some water may have been lost (Smith 2007).

		South West	West	Sig. in location	Sig. in month
Percentage wet weight	Moisture content	79.39 ± 0.75	81.95 ± 0.877.74		*
Percentage dry weight	Carbon	33.82 ± 0.17	31.17 ± 0.22	*	*
	Nitrogen	1.77 ± 0.015	1.70 ± 0.022		
	Crude protein	11.00 ± 0.17	11.13 ± 0.17		*
	Fat	1.16 ± 0.09	1.01 ± 0.06		
	Ash	19.41 ± 0.29	22.70 ± 0.56	*	*
	Fibre(ADF)	41.34 ± 1.21	28.64 ± 1.22	*	
	Calcium	1.17 ± 0.02	1.12 ± 0.02	*	*
	Phosphorus	0.23 ± 0.005	0.3 ± 0.006	*	
	Magnesium	1.46 ± 0.14	0.89 ± 0.011	*	*
	Sodium	2.70 ± 0.06	3.08 ± 0.07	*	*
	Potassium	2.95 ± 0.67	3.94 ± 0.12	*	*
	Copper (ppt)	0.0003 ± 2.01E-05	0.0002 ± 2.75E-05	*	
	Zinc (ppt)	0.0014 ± 6.59E-05	0.0016 ± 0.0001		*
	Manganese (ppt)	0.0006 ± 5.11E-05	0.0004 ± 4.82E-05	*	*
	Iron (ppt)	0.01021 ± 0.001	0.006 ± 0.0006	*	

Seasonal nitrogen (protein) and carbon (energy) content

As mentioned earlier, some kelps in the North Atlantic store nitrogen and carbon seasonally within their tissues, to enable them to grow at times of year when major nutrients (nitrogen) and sunlight (carbon) are otherwise limiting. There is no good evidence that South African kelps store nitrogen seasonally in this way. Smith (2007) calculated the % protein content of *Ecklonia maxima* seasonally, using material collected as feed by abalone farms, by the usual food and feed industry calculation of % crude protein = % nitrogen x 6.25. There was no seasonal pattern in protein content, with values varying between 10-12% of dry weight, averaging ca. 10.6%. Dieckmann (1978) found values of ca. 1.7% nitrogen (10.6% crude protein) in fronds of Laminaria pallida for most of the year, with slightly higher values (2.1% nitrogen; 13.2% crude protein) in winter.

Smith (2007) did, however, find a slight seasonal pattern in carbon content in *E. maxima* with higher values in summer (34-37% of dry weight, December to March) and lower values the rest of the year (31-33%). Dieckmann (1978) gave lower values for carbon content of fronds of *Laminaria pallida*, being ca. 25% of dry weight with no seasonal pattern.

Carbohydrates and bioactivity

Kelps have been collected and harvested around the world for many decades for the extraction of alginates, long chain carbohydrates which are a mixture of units of mannuronic and guluronic acid (Stiger-Pouvreau et al. 2016). Brown algae have cell walls composed of cellulose with alginic acid, which also contain the polysaccharide fucoidan. Fucoidan is a general term for a class of sulphated fucose-rich polysaccharides with a complicated chemical structure. Alginate can form up to 40% of the dry weight of brown seaweeds. The main storage compounds in kelps are two linear polysaccharides laminaran and mannitol. The latter is synthesized as a major primary product of photosynthesis and is used for both translocation (the movement of carbon from where it is fixed by photosynthesis to where it is used in growth in the kelp blades) and as a carbon storage compound. Laminaran has no commercial scale use, although mannitol is used as a food additive (E421).
Among the coloured pigments that absorb light for photosynthesis, and which make brown seaweeds brown, is the carotenoid fucoxanthin. This is a xanthophyll pigment (oxygenated group of carotenoids) and is abundant in all kelps.

Wash-up drift kelp has been collected commercially from South African west coast seashores since 1953, dried and shipped overseas for alginate extraction. A maximum collection of around 5000 dry t per year was exported in the mid-1970s (Anderson et al. 1986), but this has DWindled to a figure of a few hundred tonnes per year currently (Rothman et al. 2020). The alginate content of the three main west coast kelps was documented by von Holdt et al. (1955) and Hay et al. (1983).

Many carbohydrates in kelp have been shown to have bioactivity and biomedical use and potential. High-fibre diet supplements have protective effects against cardio-vascular disease risk factors, and the high alginate content of kelps contributes to the large content of soluble polysaccharides. Alginate is widely used in the medical industry in slow-release capsules for the controlled delivery of bioactive molecules, as well as assisting in wound healing (alginate plasters), and even as the active ingredient in the indigestion remedy Gaviscon®.
Both fucoidans and fucoxanthins have been documented in the scientific literature to have beneficial effects in cancer prevention or treatment (Déléris et al. 2016). These authors state that "fucoidans from various seaweed sources have been widely documented to be beneficial for impairing tumour progression", and that "immune response enhancement is another aspect of fucoidan antitumour activity". They also note that "fucoxanthin and its deacetylated metabolite exhibit several anticancer effects", including antiproliferative effects, induction of cell cycle arrest, induction of apoptosis and antiangiogenic effects.

Several specific potential medicinal properties have been noted in species of the genus *Ecklonia*. A category of phenols known as eckols, from Asian *Ecklonia* species, have been shown to have antiallergic capacity (Fleurence and Ar Gall 2016). Eckols were reported in *Ecklonia maxima* (Rengasamy et al. 2013, 2015), who suggest that this species "could be a natural source of potent antioxidants and alpha-glucosidase inhibitors. This … could facilitate effective utilization of *E. maxima* as an oral antidiabetic drug or functional food ingredient with a promising role in the formulation of medicines and nutrition supplements".

Liquid kelp extract and natural growth regulators in agriculture

South Africa has a long history of the use of kelp to produce liquid kelp extract as a crop growth enhancer for use in agriculture. Kelpak ® and other products have been produced by Kelp Products limited in Simon's Town since the 1970s, using a patented cold process using pressure changes (rapid reduction) to extract liquid concentrate from macerated, whole *Ecklonia maxima*. There is a considerable literature on the benefits of application of these products on numerous crop species, and they have been shown to produce a wide range of responses in plants including increased root and shoot growth, improved nutrient uptake, increased flower and fruit set leading to higher yields, delayed senescence and longer shelf life of fruits, as well as increased resistance to insect and pathogen attack and abiotic stress such as drought and frost (Stirk et al. 2014). It is thought that the active ingredients in the liquid kelp extract are natural plant growth regulators present in both seaweeds and land plants, and that the "cocktail of natural PGRs present in Kelpak® may act individually or in concert and thus contribute to the numerous favourable physiological responses elicited by Kelpak®" (Stirk et al. 2014). Polyamines have also been studied in Kelpak® and shown be produced seasonally and in response to stress. These may also be implicated in the effects in agriculture (Papenfus et al. 2012). There are now also other companies producing kelp extracts in South Africa (e.g. Afrikelp®) and ca. 3000t of kelp p.a. is cut from natural kelp forests currently for this purpose (Rothman et al. 2020).

Kelps as food and fodder

Most kelp grown in aquaculture is used either for food or feed in animal aquaculture and also in the South African kelp industry most harvested kelp from natural kelp forests is used for feed in land-based abalone aquaculture (Rothman et al. 2020). The use of kelp in the human diet is in its early stages in the western world, although much of rapidly growing kelp industry in the northwestern Atlantic (e.g. in the USA https://gmri.org/stories/maine-grown-kelp-opportunity-impact/) is aimed at kelp aquaculture for human food.

Evidence for the collection and use of seaweeds for human food and medicines goes back at least 14 000 years, and probably most human coastal populations ate seaweeds traditionally. Today this includes most maritime Asian nations, as well as those of Polynesian heritage across the Pacific Ocean from the Philippines and New Zealand to Hawai'i, Chileans, Celtic peoples in Europe (e.g. in Ireland, Wales, Brittany, parts of Spain etc.) and many more. Of 18 species of seaweeds authorized in France as Sea Vegetables or ingredients, 3 of them are kelps, including 2 species of *Laminaria* ((Fleurence 2016). All kelp species are likely to be edible, although it is generally preferable to choose relatively young plants or young parts of plants. For example, in *Macrocystis* the tips of the shoots where young blades are forming are the youngest and tenderest tissue, whereas in *Ecklonia* it is the lateral, secondary blades nearest the stipe. Cheney (2016) documented the very few known incidents of the consumption of raw seaweed causing illness or death. Apart from a few incidents of 'mozuku' poisoning in Japan all of these are in tropical seas, and none involved kelp. Many of these poisoning incidents appear to have involved toxic microalgae attached to the seaweeds. Cheney comments that "this author concludes that there is no proof that any of the illnesses or deaths were caused by toxins produced by the seaweed itself".

There is surprisingly little evidence of traditional seaweed consumption in sub-Saharan Africa, probably because this has not been properly investigated. Why would coastal peoples on the west coast of southern Africa not have eaten easily available, tasty and extremely nutritious seaweed? The Benguela upwelling system on the west coast has been active, similar to its current extent, for around 2-3 million years, and it has been estimated that *Laminaria* has been present in the region for around 1 million years (Rothman et al. 2017b). On the west coast of North America the kelp forests have been implicated in the original populating of the region by humans, in what is known as the 'Kelp Highway Hypothesis' (Erlandson et al. 2015).

A key component of material for aquafeed is protein, and a sufficient protein content in feed is essential for animal growth in aquaculture. Kelp is relatively low in protein (close to 10% of dry weight) and thus is not a good protein source unless processed, For example, Magnussen et al. (2016) provide an Australian example of the use of the 'biorefinery principle' with seaweed material, where after extraction of salt and polysaccharides (with their own industrial uses) the remaining material is highly enriched in protein content for use in animal feed. Many abalone farms in South Africa are, however, convinced of the value of including "natural feed' in the diet, and go to great lengths to obtain fresh kelp as feed, although they also use formulated feed with extra protein (fish meal and/or agricultural plant protein) to increase growth rates. In contrast, Naidoo et al. (2006) showed higher growth rates of cultivation abalone with fresh kelp than with the normally used formulated feed (with much higher protein content), with the best growth rates using a mixed seaweed diet (kelp plus the red seaweed *Gracilaria* and the green seaweed *Ulva*). A significant proportion of the extremely large Chinese cultivated sugar kelp production (*Saccharina japonica*) is used for feed in their abalone aquaculture industry.

In kelp production, as in other types of agriculture and aquaculture, the quality of the product depends to a considerable extent on the quality of the environment in which it is grown. Seaweeds absorb nutrients and dissolved gases from their aquatic environment via their entire surface and can absorb, or be host for, unwanted materials also.
Seaweeds, including kelps, bioaccumulate dissolved metals in seawater, including potentially toxic heavy metals. Indeed, many studies have recommended the use of concentrations of metals in seaweeds as bioindicators of concentrations of dissolved contaminants in the seawater over time (Rainbow 1995). Food products made from seaweeds are tested for contaminants in the same way as other marine products, such as filter feeders, which can also bioaccumulate such toxins (e.g. mussels, oysters, scallops etc.). Similarly, fresh seaweed may have attached bacterial contaminants from the seawater and collections, or cultivation, for human use should not be close to urban runoff or sewage outlets, for obvious reasons.

Two potential specific problems with high consumption of kelps by humans are the relatively elevated levels of iodine and arsenic. Brown algae have higher concentrations of these elements than other seaweeds, and some brown algae have more than others.

Consumption of brown seaweeds, including kelps, can be beneficial where there is iodine deficiency, but there are a small number of reports that daily consumption of kelp, particularly by postmenopausal women in Japan, could increase the risk of papillary carcinoma (thyroid cancer) due to the high iodine content, although two previous studies did not find such an association (Cheney 2016). Teas et al. (2004) estimated iodine concentrations in kelps from Namibia (*Laminaria pallida* and *Ecklonia maxima*) processed in different ways. They found that sun-bleached blades (ca. 500 µg g^{-1}) had much less iodine than freshly cut juvenile blades (ca. 6500 µg g^{-1}). While Teas et al. (2004) acknowledge the possibility that some Asian dishes may exceed the recommended tolerable upper intake level of 1100 µg day^{-1}, they also note that iodine is water soluble in cooking, making the average iodine content of prepared foods difficult to estimate.

Studies of concentrations of elements in prepared seaweed foodstuffs often highlight relatively high concentrations of arsenic in brown seaweeds. This is particularly critical in products made from the brown fucoid seaweed (not a kelp) known in Japan as 'hijiki' (*Sargassum fusiforme*) (Cheney 2016). Some seaweed food samples have also been reported with relatively high levels of cadmium. Arsenic occurs in both organic and inorganic forms in seaweeds, with the inorganic form being most hazardous to health as it is absorbed more easily in the human gut. The available literature on this project (Cheney et al. 2016) mostly concerns the consumption of hijiki, which can have levels of inorganic arsenic well above recommended maximum doses.

6. Discussion

Uses and potential uses and benefits of seaweed aquaculture

The uses of seaweeds are a seemingly never-ending list, and new uses are appearing very rapidly recently. Globally, the two main groups of uses are still for human food and in the phycocolloid industry (agars, carrageenans, alginates; with the latter mainly from kelps and the others from red seaweeds). Phycocolloids themselves are used in an extremely wide range of industries with alginates being used in, for example, textiles, foods, paper, welding rods, as biocatalysts, in medical dressings, as binders for animal feeds, for the controlled release of chemicals, pharmaceuticals, and confectionery. Kelp is increasingly important in animal feed, especially in aquaculture systems, as well as various aspects of agriculture (fertiliser, growth enhancers, compost, soil conditioner etc.). The potential use of seaweeds as a source of dietary protein was often not thought important, as protein levels are lower than in animal products, but removing other constituents first in a biorefinery system can significantly increase the protein content of seaweed feed addition.

Much of the new excitement and development around kelp aquaculture in the North Atlantic and northeast Pacific concerns the potential for human consumption. This is a high value product, and quality is paramount. This will require the development of niche markets for food and food additions, health supplements and nutraceuticals. Many websites of this sort are appearing, particularly in the Eastern and Western USA. There is considerable scientific and industrial effort, increasingly, both in the west and Asia (especially China) towards the use of the biorefinery principle with seaweeds, where the same biomass can be the source of high value products in addition to lower cost biomaterials, which could include bioplastics. Much research has gone into biofuels from seaweeds (including kelps), which is scientifically feasible but not yet economically viable. Who can predict the need for none-fossil fuels and bioplastics 20 years from now?

Much is being made by new kelp producers of the generally environmentally friendly nature of seaweed aquaculture. It is often done without fertiliser (although this is not always the case depending on natural levels of nutrients, which are generally high on the South African west coast). It requires little land and freshwater. Seaweeds are plants in the general sense, which grow by fixing carbon taken up from dissolved form in the water, using sunlight as an energy source. This means that seaweed aquaculture facilities could be carbon neutral or better. Systems of carbon credits in some countries may significantly improve prospects for seaweed aquaculture. Also, seaweeds remove major plant nutrients (especially N and P) from the water, much of which is added by other human activities. While Western scientists have discussed the construction of Integrated Multi-Trophic Aquaculture (IMTA) systems for more than two decades, we should not forget that any successful seaweed aquaculture operation removes nutrients and fixes carbon, even if it is not directly linked to an animal aquaculture operation. Removing nutrients causing eutrophication in a bay can still be beneficial if the nutrients concerned were released by human activity in a different part of the bay or upriver from the kelp rafts.

Aquaculture is often thought of as an environmentally damaging activity, and some aquaculture operations certainly have been. Most of these problems, though, have concerned fed aquaculture, in the marine environment particularly of crustaceans (shrimps, crabs) and finfish, not extractive aquaculture such as growing kelp. It is a sign of new times that kelp aquaculture operations in the Faroe Islands in the North Atlantic are now partly funded by the World Wildlife Fund.
(https://thefishsite.com/articles/wwf-invests-in-faroese-kelp-farming-firm).
In some sites, particularly where kelp rafts are not positioned above rocky shores bearing natural seaweeds, studies tend to show that adding a kelp raft system to a section of coastline can increase biodiversity, estimated by the usual measures. Positioning a kelp culture system above part of a stretch of sandy coast will add species which the kelp attracts that did not previously congregate there, including the potential to act as fish attractors (Langton et al. 2019). Research on this topic is much needed, and this possibility should be investigated in each new aquaculture venture.

Gap analysis: what we don't know

The accurate answer to "what do we know about growing South African kelps?" is "not much". As stated in a recent 'World Ocean Summit' panel discussion on the global seaweed industry "though seaweed operations are diverse, specialising in various species and operating in different economic circumstances, today's macroalgae practitioners need to stay grounded in science as they work towards their scale and sustainability goals for 2030" (https://thefishsite.com/articles/why-seaweed-growers-need-to-stay-rooted-in-science-world-ocean-summit). It may take more than a decade for a new aquaculture species to become the basis for a viable economic venture. Although cultivation and spawning of the local abalone, *Haliotis midae* began in 1981 it only began to fully develop as commercial aquaculture in the 1990's alongside the development of international aquaculture systems (Sales & Britz 2001), and only reached a production of over 100 tonnes in 2000. As international aquaculture systems for kelp are developing very rapidly in the western hemisphere, in South Africa we have a window of opportunity to become part of this development. What we need is accurate, scientifically documented information on seeding, growth and general aquaculture of South African kelps in available local environments. South Africa already produces over 2000 tonnes per year of the green seaweed *Ulva* in land-based raceway systems on abalone farms (Neveux et al. 2018), and we have good scientific literature on the growth of the local red seaweed *Gracilaria* on rope rafts in Saldanha and St Helena Bay (and a former successful commercial operation of this species in Lüderitz, Namibia). We have a viable and growing commercial mariculture industry, and available skills and expertise in these areas (although an increased supplied of personnel with aquaculture skills is likely to be in great demand in future).
Important questions which need to be answered include:

- Which of the three species grows best in aquaculture conditions? (and does this differ in different environments?).
- How easy are they to propagate on a large scale?
- Can seeding and hatchery growth of juveniles be carried out successfully and consistently? (is it viable to grow kelps seeded from natural populations in the future, by the traditional 'Japanese' method, or it is more controlled and successful to culture gametophytes in a laboratory setting and seed from selected parents, sometimes known as the 'European method').

- What are the characteristics and potential commercial benefits of ca. 8-month-old cultivated plants of the different species, and are they different from adult plants from natural kelp forests?
- Is seaweed material from Saldanha Bay (or other local sites) safe for human and animal consumption?
- Can new uses be found for cultivated kelp material?
- Who will carry out initial kelp cultivation? Will it be developed by members of the existing aquaculture industry, or is there a potential for community initiatives (or for a synergistic combination of the two)?
- Can funding be found to facilitate preliminary research and development initiatives?
- Can local kelp cultivation be economically viable at scale?

Potential of South African kelp aquaculture

In many parts of the world where kelps grow the potential for kelp aquaculture is being assessed or re-assessed. Some of this activity involves extension of traditional or recent uses of kelps, and there is considerable opinion expressed that the successes of seaweed aquaculture in East Asia can be repeated in other parts of the world. Some concern has been expressed also over the possibility of exaggeration of this potential (Costa-Pierce and Chopin 2021). Nevertheless, South Africa (and Namibia) have a globally significant kelp forest ecosystem along the west coast of Southern Africa, with many aspects of the environment particularly conducive to kelp growth. One drawback in the past has been the lack of sheltered, inshore coastal waters, with sea-based seaweed aquaculture experiments and activities (mostly with the red seaweed *Gracilaria*) confined to Saldanha Bay in South Africa and Lüderitz Bay in Namibia. The relatively recent mapping of Saldanha Bay and the provision of aquaculture space, including space flagged specifically for seaweed aquaculture, has provided an impetus for investigation of kelp aquaculture. In addition, the possibility in the future of extensive coastal and offshore kelp aquaculture is being actively trialled in the North Atlantic. If these systems were to be available, and economically viable, then the Benguela system is globally significant for its potential, with year-round available nutrient levels and sunlight. This is the reason for the company KelpBlue choosing Namibia, after a global study, as a site to initiate pilot studies for offshore *Macrocystis* cultivation.
Of our three available species of west coast kelps, only *Macrocystis* has been extensively growth on aquaculture systems elsewhere (particularly in Chile and the USA), but this aquaculture has not been economically successful so far. To grow *Ecklonia maxima* and *Laminaria pallida* will require a considerable amount of further scientific study, pilot farming and market assessments. These species are closely related to those being studied and grown elsewhere, and there is no biological reason why they cannot be grown using similar methods to those used with related kelps. Probably the success of large-scale kelp aquaculture in South Africa will require changes in the use of kelps globally, including western eating habits, the need for new sources of aquafeed, and the progression of seaweed biorefinery techniques and processes. In the USA and Europe kelp aquaculture appears to be starting at the local level, small farms growing several aquaculture products including kelp, with the kelp sold for small-scale, high-value products. Simultaneously the offshore kelp aquaculture industry is at the experimental stage, aiming towards economies of scale to enable production of large amounts of kelps for extraction of cheaper commodities. To pursue either of these aims in South Africa we first need to be able to grow local kelp species consistently. This is likely to require outside funding input in the early stages, and entrepreneurial vision. It is important that scientific input is maintained in these early stages, and that data obtained are properly monitored and widely available to encourage the growth of a new industry.

There is much work to do before we have a viable kelp aquaculture industry in South Africa.

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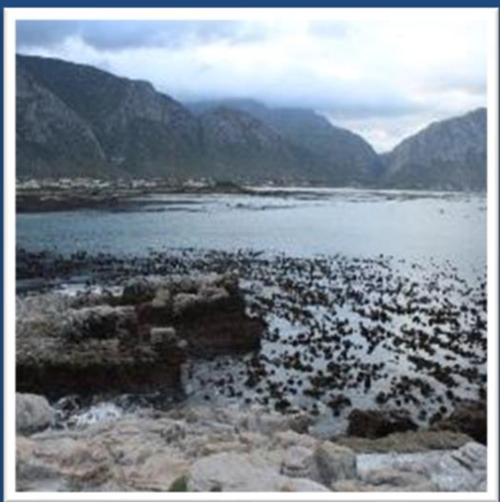
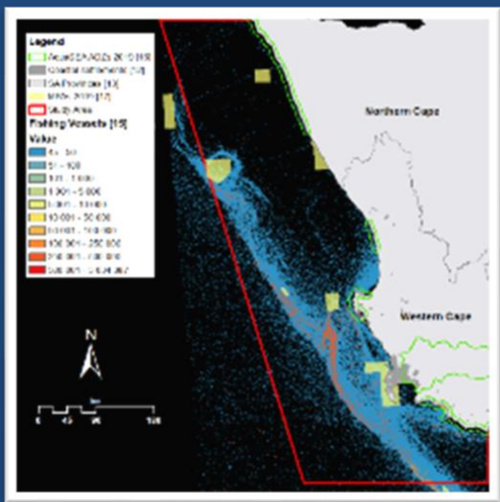
APPENDIX C OFFSHORE GIS STUDY

BSASA Pre-feasibility study on the potential for commercial cultivation of seaweed (with focus on African kelp) along South Africa's West Coast.

Offshore GIS study of available area for commercial kelp cultivation along South Africa's west coast





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CSIR
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List of Figures

List of Tables

1 Background & Introduction

The Bivalve Shellfish Association of South Africa (BSASA) appointed the CSIR and its collaborators to assist with a four-month project, from December 2021 to March 2022, to synthesize and collate baseline data to inform the understanding of the potential to commercially cultivate seaweed (focus on African kelp) along the Southern Africa's West Coast in a pre-feasibility study.

The Pre-feasibility Study was to involve a high-level assessment, through secondary and primary data gathering and analysis, of the opportunities for sea-based aquaculture, geospatial data on the features relevant for farming of seaweeds, as well as the constraints, market potential and value chain opportunities for seaweed farming along South Africa's West Coast.

The prefeasibility consisted of the following key activities:

Activity 1: Co-ordination and collation of relevant reports, outputs and monthly progress reports
Activity 2: Secondary data gathering
Activity 3: Primary data gathering
Activity 4: Data analysis and interpretation
Activity 5: GIS study of available offshore area for kelp cultivation
Activity 6: Inputs/Results for preparation of deliverables

This report presents the report on the Activity 5: GIS study of available offshore area for kelp cultivation.

The work conducted in this activity included the following sub-activities:

- Identification of key environmental requirements for kelp growth, together with kelp ecology expert within the project (Prof John Bolton); the three species that will be investigated include *Ecklonia maxima, Laminaria pallida* and *Macrocystis pyrifera*;
- Based on the mapping the identified thresholds of the respective environment parameters, identification of "hotspots" where kelp farming is feasible;
- Identification of environmental conditions required for offshore kelp farming, together with the wider project team, and translation of existing geospatial information thereof into a Geographic Information System (GIS);
- Identification and sourcing of existing information on non-ecological requirements for seaweed farming, and translation thereof into a GIS;
- Source existing information on conflicting use areas, such as (marine) protected areas, vessel traffic areas etc. and translation thereof into a GIS.

Based on the collated information the following results were produced:

- Delineation of "hotspots" where kelp farming is biologically feasible
- Delineation of "cold spots" where non-biological factors inhibit or hinder kelp farming.

These final outputs will form part of the final pre-feasibility report.

2 Study area

The study area for this pre-feasibility study is the west coast of South Africa. A recent remotely sensed map of kelp forests available for South Africa's coasts from Dunga (2019), derived from 10m resolution Sentinel-2 imagery was used as baseline for the present distribution of kelp forests in South Africa (Figure 28).

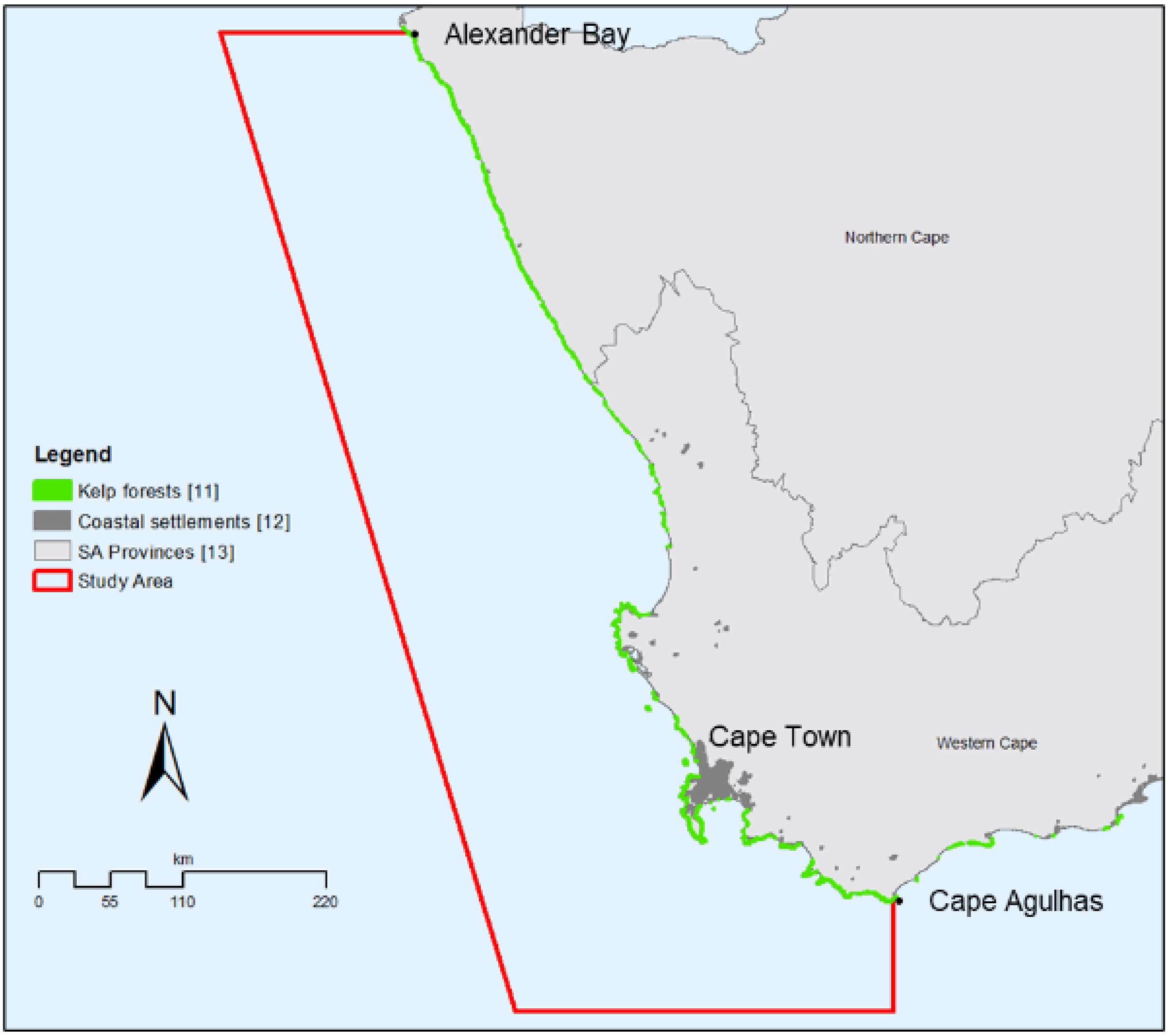


Figure 28: Present occurrence of kelp forests in South Africa and location of study area (Source: Dunga, 2019).

According to Dunga (2019), kelp occurs along vast areas of South Africa's west coast, from Alexander Bay in the north to Cape Agulhas in the south. Somewhat more interspersed kelp forests are mapped east of Cape Agulhas until just west of Mossel Bay. These occurrences, however, are made up of species beyond the focus of this study.

The study area for this project was therefore limited to the area between Alexander Bay and Cape Agulhas (Figure 28).

3 Key environmental requirements for kelp growth

The literature review conducted in the context of this project provided information on the key environmental requirements for kelp growth. These are listed in Table 20 below. For these key parameters, GIS datasets were sourced, where accessible and the optimal and tolerated parameter ranges (or range gradients, where no optimal and tolerated ranges could be defined) were displayed. The results are unpacked in the sections below.

Table 20: Optimal and tolerated ranges of physical and chemical key parameters for kelp growth

	Key Parameter[2]	optimal range	tolerated range	Comments
Physical	Depth [1]	0-20m	< 150m (farms)	
	Wave energy [2]			
	Current strength [3]			No GIS data available for this project phase, for next phase, investigate: https://www.ncei.noaa.gov/access/data/global-ocean-currents-database/category.html
	Sea Surface Temperature (SST) annual mean [4]	8 - 15°C	0-20°C	
	SST monthly max [5]	10-15°C	Monthly max 20°C	No SST monthly max data available for this project phase.
	Turbidity [6]	The less the better		
Chemical	Mean dissolved Oxygen [7]	The more the better		
	Mean Nitrate [8]	The more the better	minimum: 1-2 µmol L-1	
	Mean Phosphate [9]	The more the better		
	Salinity [10]	35ppt	32-38ppt	

No analysis was conducted for the coast type, i.e. rocky shores versus sandy shores because it is well established that kelp naturally requires a solid, i.e. rocky substrate to grow on and secondly, for the offshore farming, there is no dependence on natural substrate, as the plants will be tied to ropes on rafts.

3.1 Depth of kelp occurrence

The GEBCO 2021 bathymetric dataset was used as reference for the depth of sea. This data set has a pixel size of about 400m x 400m, which is relatively coarse. For those areas where Dunga (2019) detected kelp forests, the bathymetric depth was extracted from the GEBCO dataset. Figure 29 shows the frequency with which kelp occurred on which GEBCO depth. According to this figure, kelp occurs up to a depth

[2] *Numbers in brackets refer to the source of the related GIS layer provided in the Appendix*

of about 20-25m depth and the majority of the kelp occurs at a depth of about 4m. This is in accordance with the literature, which states that turbidity of the water, leading to lack of light in greater depths might be the underlying factor, as in very clear waters, kelp occurs to greater depths.

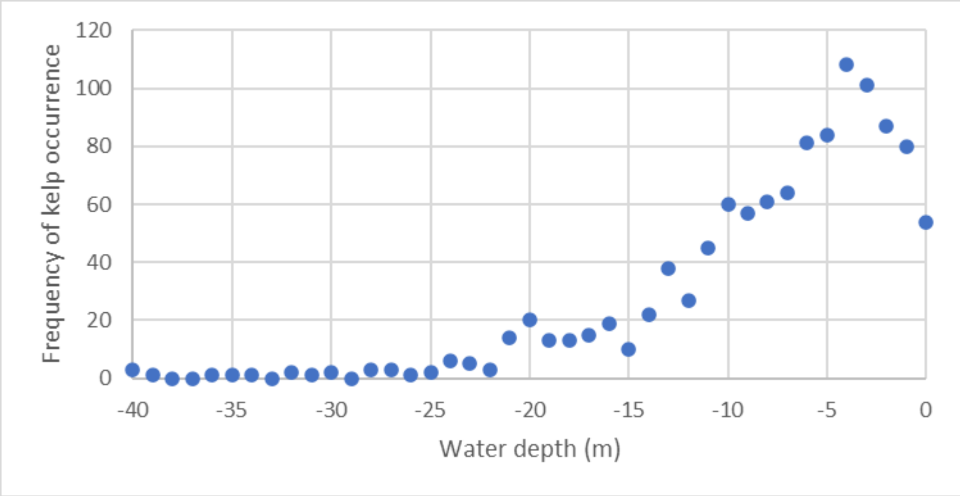


Figure 29: Water depth at places where Dunga (2019) detected kelp

In Figure 30, the GEBCO depth ranges of 0-20m, 20-50m, 50-100m and 100-150m are indicated. The 0-20m zone is the area where kelp occurs naturally, according to the findings in Figure 29. The deeper depth zones are the areas where installation of kelp rafts might be feasible, as in other countries, kelp is farmed in waters to a depth of 120m.

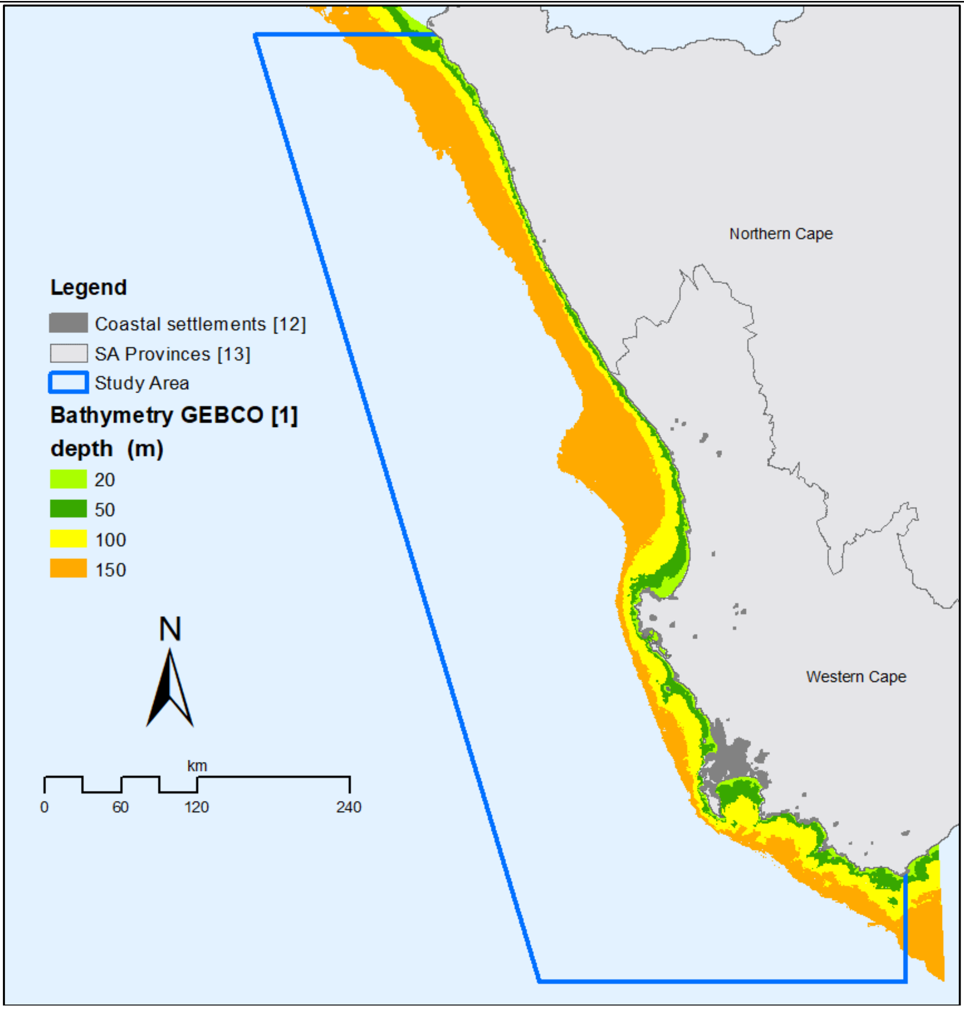


Figure 30: Bathymetric depth zonation up to the -150m contour.

However, increasing depth will increase the technical effort and distance to the shore, which will have implications for the boats and fuel required to service the rafts.

3.2 Wave energy

3.2.1 Annual mean energy

For wave energy, the Wave power Atlas for South Africa from 2019 was used as input [2]. The spatial dataset is provided as a point shapefile and indicates the average annual and seasonal wave power (kW/m of wave crest). Model outputs were produced on a 500m resolution (nested numerical grid approach) and written out at the 7m and 15m bathymetry contour lines. False Bay is the exception, with output on a 200m resolution. The numerical code, Simulating WAves in the Nearshore (SWAN) was used for the present study. The simulation period is at a three-hourly resolution spanning from 1997 until 2013. The data over about 70% of the South African coastline.

In Figure 31 below, the mean annual wave data are displayed for the wider Saldanha area and the southern Cape Peninsula, together with the mapped occurrence of kelp (Dunga, 2019) and the GEBCO depth range between 20-50m, which might become relevant for raft-based farming. **These figures highlight that the natural kelp occurrence seems to be independent from the annual mean wave energy**

regime, i.e. kelp is occurring at low wave energy at the 7m bathy contour (0 – 8.16 kW) up to the highest mean annual wave energy areas with 36.6 – 68.69 kW.

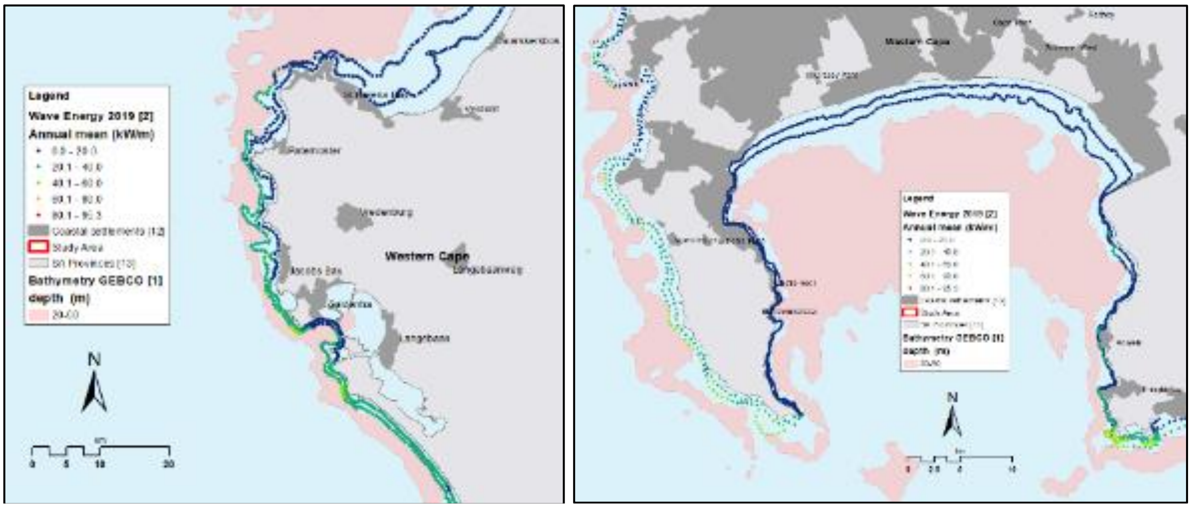


Figure 31: Annual mean wave energy for the greater Saldanha area (left) and the southern Cape Peninsula (right)

Figure 32 below shows the annual mean wave energy for the entire study area. There is a large data gap at the border between the Northern and the Western Cape, where no modelling took place. Given the homogenous nature of that stretch of coast, the wave conditions can be assumed however to be in the same range as in the modelled area north and south of the data gap. This figure also shows that the areas with the lowest wave energy are St Helena Bay, the eastern part of False Bay, and some small pockets on the Northern Cape coast. The highest annual mean wave energy occurs on the coast south of Paternoster.

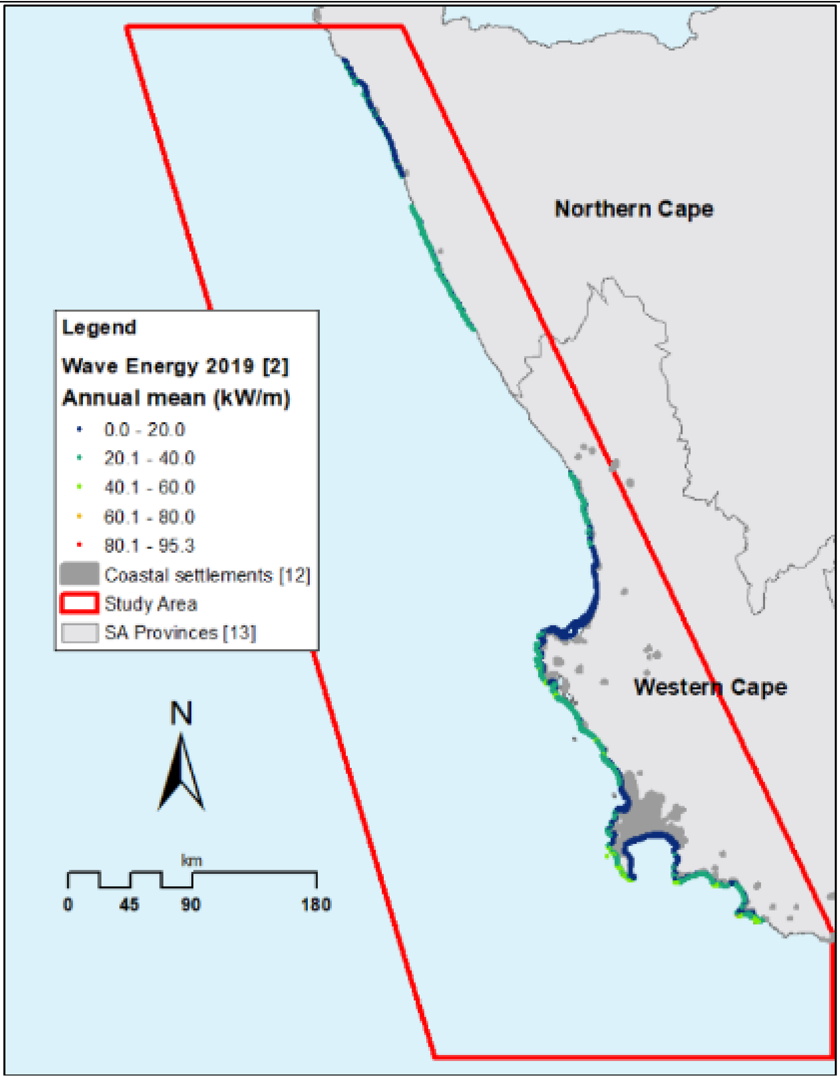


Figure 32: Annual mean wave energy for the entire study area.

3.2.2 Annual maximum energy

Important for offshore kelp farming is also the expected maximum wave energy, as high energy storm events can damage and/or dislocate the raft structures. The highest wave energy occurs on the southwestern Cape peninsula and the southwest facing land tips south of the peninsula (Figure 33). Danger point, close to Gansbaai has the highest wave energy values on the 7m bathy contour of the entire study area, with 95kW per m wave crest (Figure 34). The map shows, that the natural kelp occurs even in these rough waters.

However, for offshore rafts it will probably be recommendable to choose areas with less extreme wave energy, in order to allow for safe anchorage of the rafts and safer access of the rafts for maintenance.

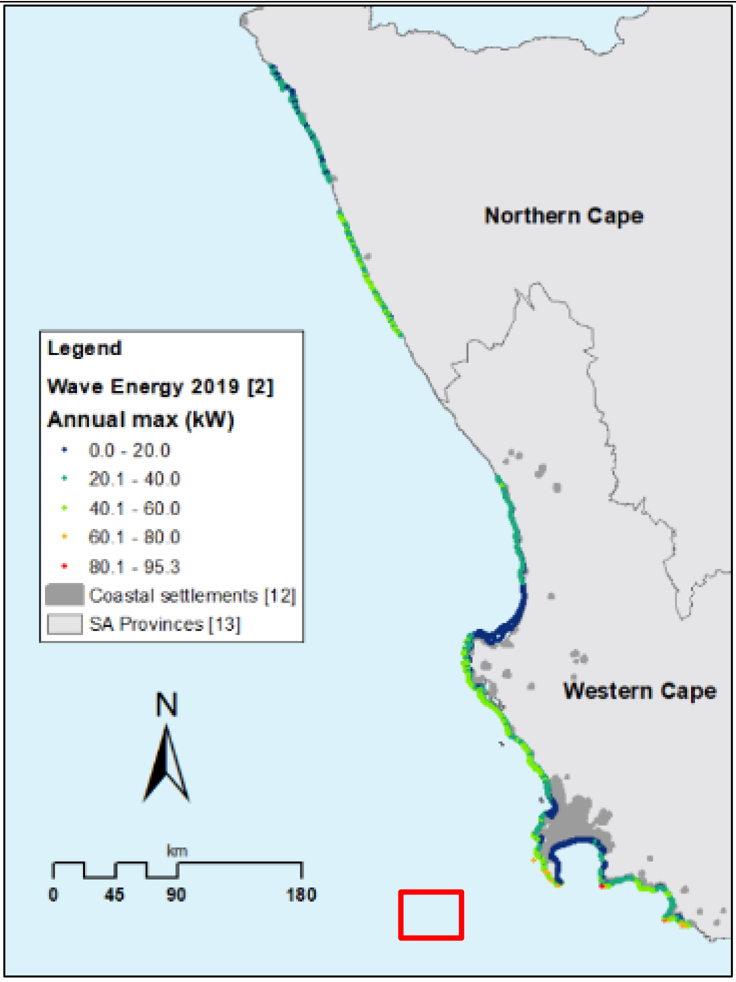


Figure 33: Annual maximum wave energy for the entire study area (red rectangle, see figure below).

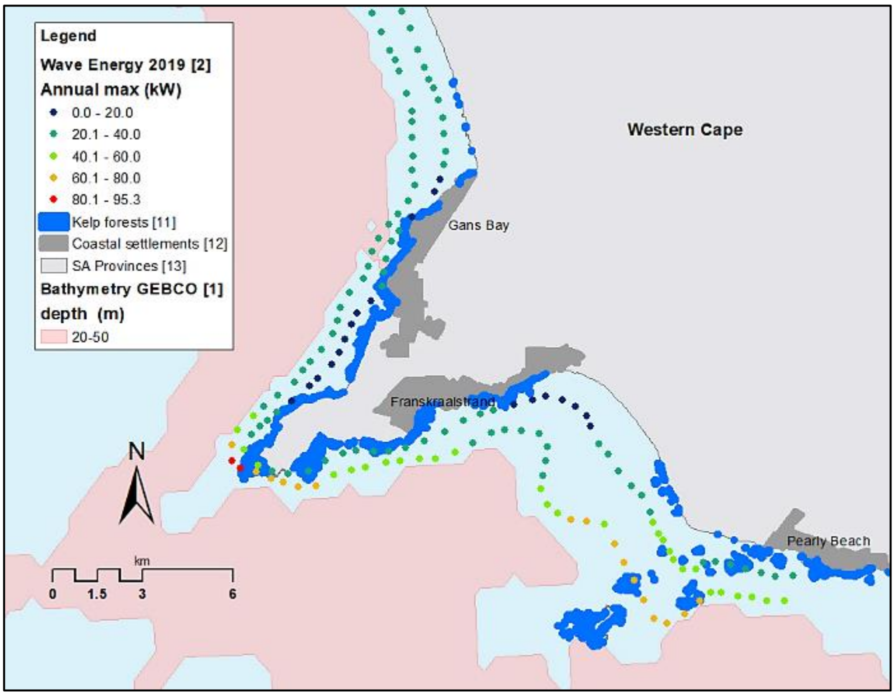


Figure 34: Annual maximum wave energy for the Gans Bay area.

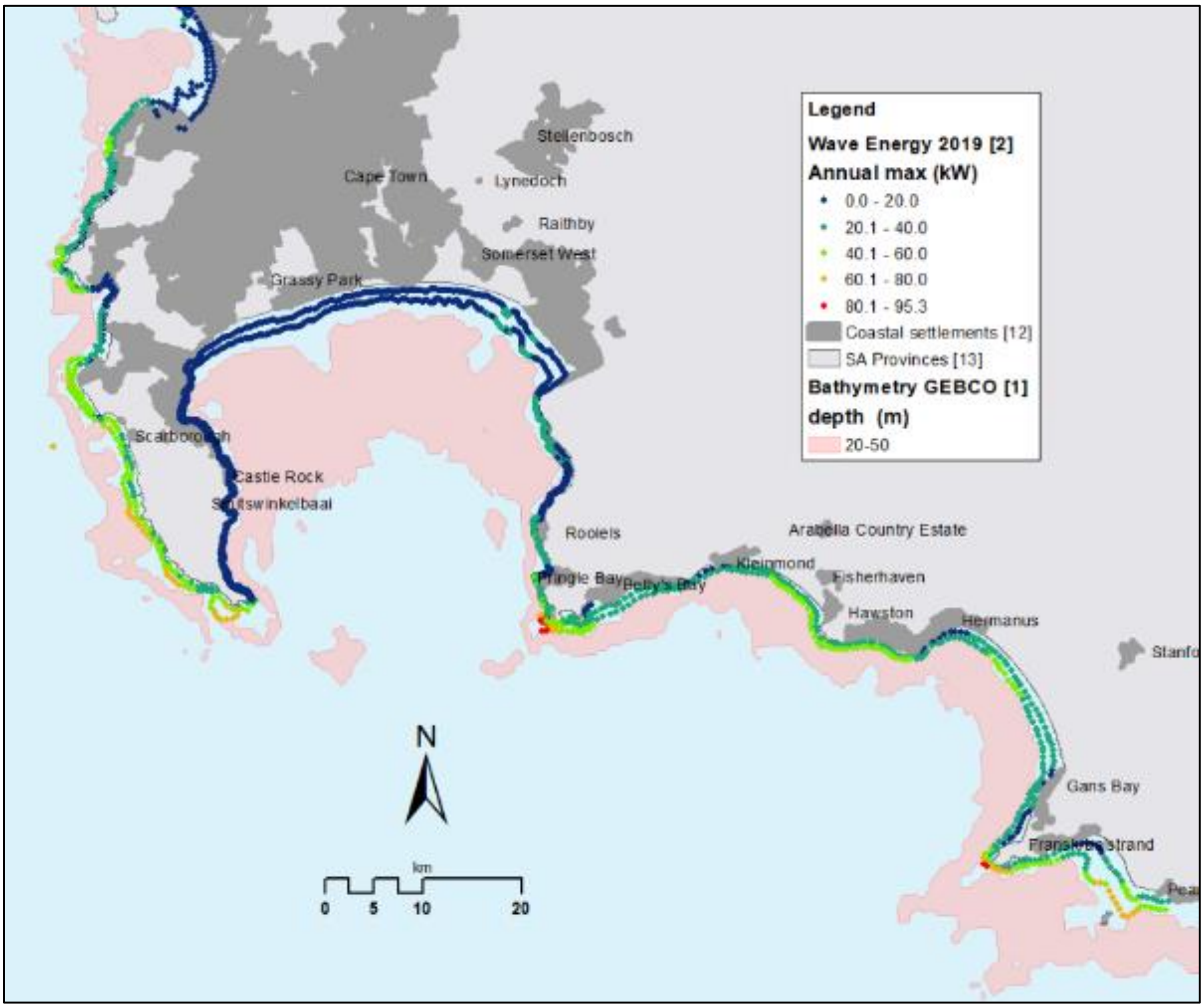
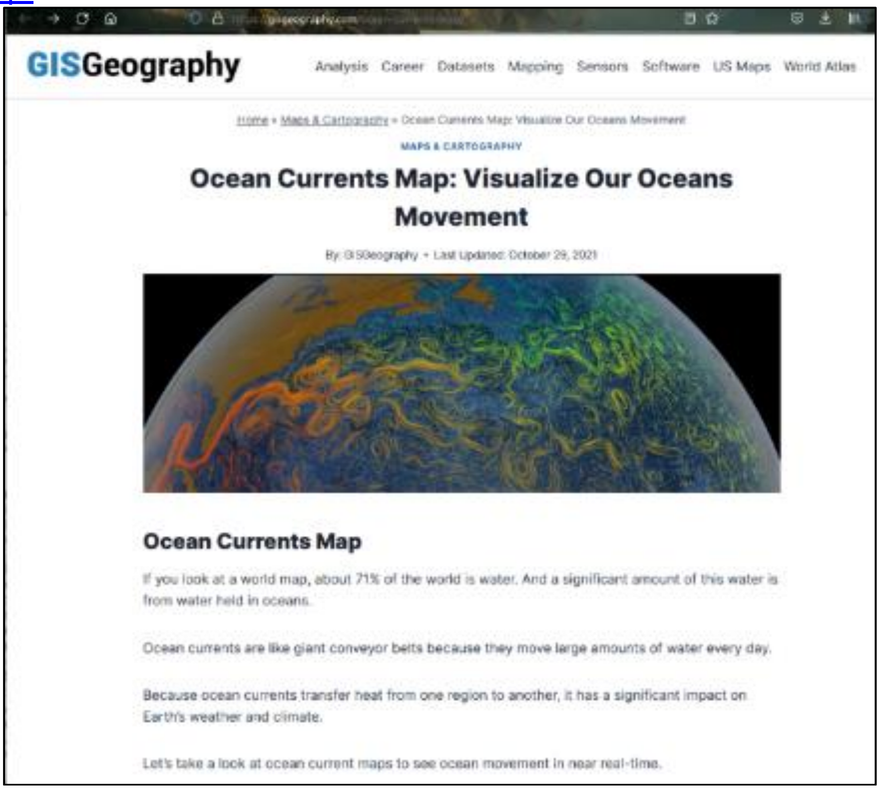


Figure 35: Annual maximum wave energy for the southern study area.

3.3 Current strength

analysis of current strength was not conducted in this assessment because of the brevity of the project which required to focus on the most relevant environmental parameters.
Different current data sources are available however and should be considered for the next phase of the project. An example for a data source is NOAA: https://www.ncei.noaa.gov/access/data/global-ocean-currents-database/category.html

Another feasible data source is GIS Geography: https://gisgeography.com/ocean-currents-map/



3.4 Turbidity

While satellite derived Chlorophyll a data are usually used as measure for ocean turbidity, these were not readily available for this project phase. As a substitute, turbidity derived from the blue spectral band of Landsat TM timeseries were used. Figure 36 shows the number of occurrences of turbidity in pixels of 14 Landsat TM images acquired between 1984 and 2011. The main criteria for the selection of these images was the absence of clouds. In the figure below, red areas indicate ocean areas that had a turbidity signal in all 14 analysed images, magenta areas show areas with only one turbidity occurrence, which means in these areas the water is usually quite clear. The large black area in the image centre is an area where strong upwelling from the bottom provides clear waters. The map also shows that kelp (blue blotches) occurs in very turbid areas, but probably only to a limited depth.

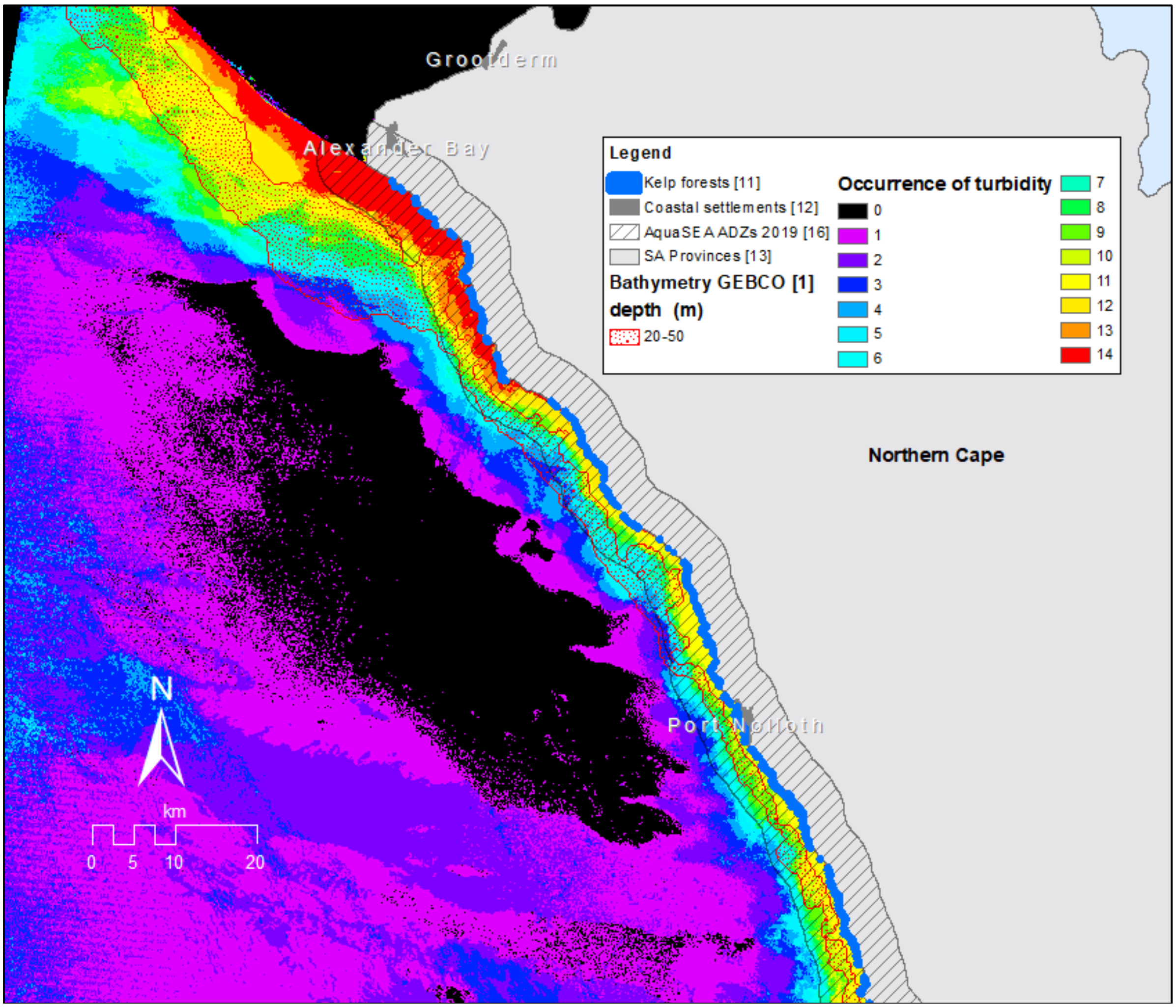


Figure 36: Occurrence of ocean turbidity derived from 14 Landsat TM images (scene 177-82) between 1984 and 2011 in the Northern Cape [6]

All the Northern Cape coast in this figure is a preliminarily identified ADZ (not yet formalized / designated). The zone between 20-50m bathymetric depth is indicated, too (red speckled area). It shows that turbidity in this area is generally

less than in the immediate nearshore, which might provide some potential for offshore kelp farming in these depths.

In the wider Saldanha Bay – St. Helena Bay area, a similar Landsat-derived turbidity data set was available, too. Here, 12 Landsat images acquired between 1996 – 2006 were used. The shallow nearshore of St. Helena Bay has a very high occurrence of turbidity (9-12 images) rapidly decreasing at the 20m bathy contour.

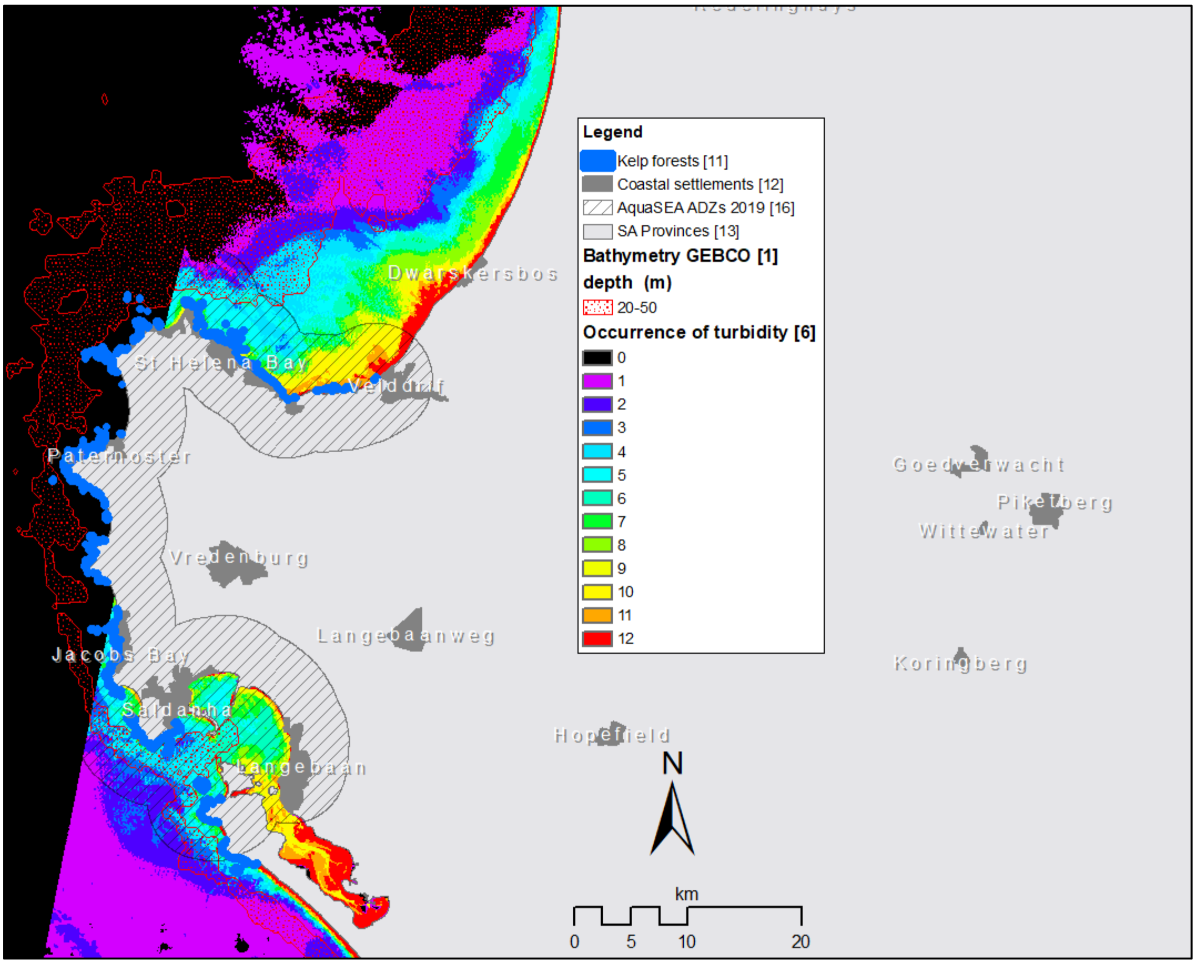


Figure 37: Occurrence of ocean turbidity derived from 12 Landsat TM images (scene 175-83) between 1996 and 2006 in the Langebahn-St. Helena Bay area [6]

In Saldanha Bay, i.e. Big Bay and Small Bay, turbidity occurs in about half of all assessed Landsat images. This is probably to the relatively sheltered waters in these areas.

Apart from Saldanha Bay itself, especially the protected bay west of Velddrift might be suitable for raft-based farming, as relatively clear waters occur at depths of 20m or less within 5km of the coast.

3.5 Sea Surface Temperature (SST)

Temperature profiles across the entire water column for the study area were not available for this project. Instead, MODIS satellite derived Sea Surface Temperate data were used. SST sensors as such measure only the temperature at the ocean surface, which is relatively meaningless for the growth of kelp in greater depth. However, Dingle & Nelson (1993) conducted a study on the South Africa West coast that provided temperature depth profiles (Figure 38). These profiles show that the temperature stays relatively stable in the upper 20-50 meters of the water column. This indicates that SST data are in fact representative for the depth range which is relevant for kelp growth.

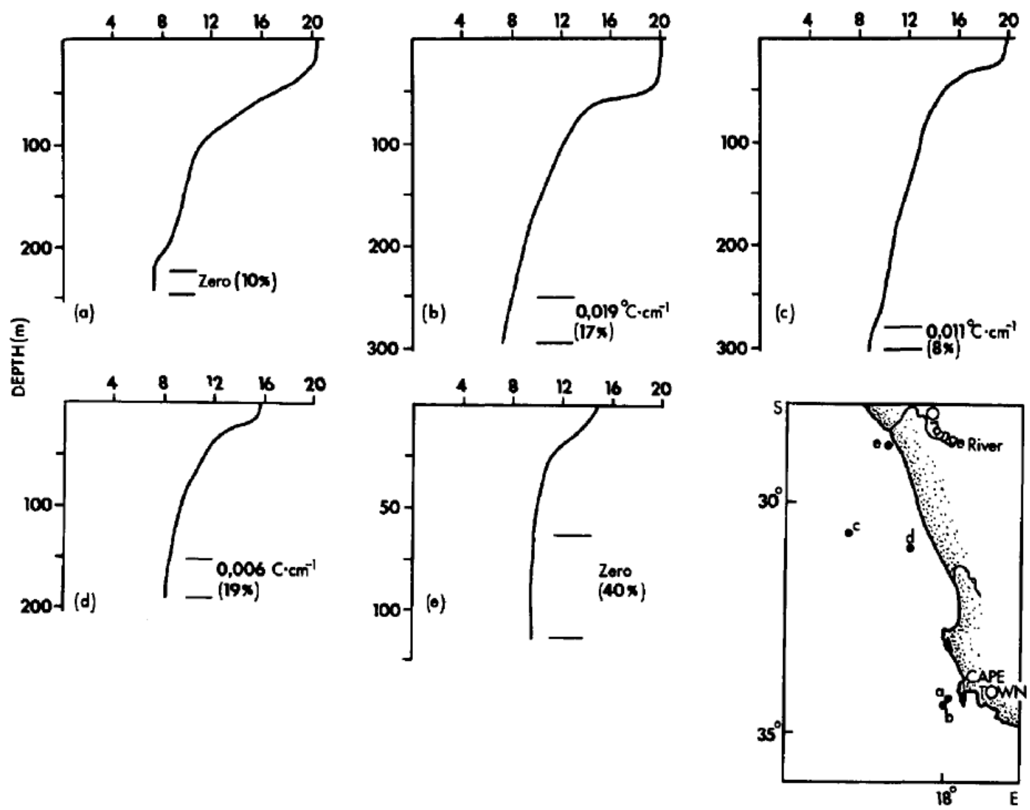


Fig. 5: Temperature profiles at representative locations on the continental shelf, showing the temperature gradient near the bottom and the percentage of water column over which it applies (all sections are from SFRI demersal cruise 088 in January 1991)

Figure 38: Ocean temperature profiles on Southern Africa's west coast. Source: Dingle & Nelson (1993).

Consequently, satellite derived SST data were sourced and analysed.

3.5.1 Mean Annual Sea Surface temperature (SST)

Mean annual SST data were available from the United National Environmental Program Ocean Data Viewer [4]. The dataset was created using remotely-sensed MODIS Aqua data from NASA's (National Aeronautics and Space Administration) Ocean Color database. The pixel size is about 8 x 8 km. The SST mean was derived from measurements between 2009 – 2013. Given the brevity of this project, no more recent SST data or longer time series could be sourced. This should be included in the next phase of the project.

Figure 39 shows that the mean temperature in the nearshore of the study area ranged between 10-12°C. This means that the mean temperatures are well within the optimal range for kelp growth along the whole study area. However, because of the coarse resolution of this dataset, no meaningful data can be derived for the immediate nearshore and Saldanha Bay (temperature values are mixed pixels with the much warmer dry coast).

3.5.2 Maximum Sea Surface temperature (SST)

Sea Surface temperatures above 20°C over prolonged periods might damage kelp. Technically, these statistical maxima (e.g. monthly maxima) can be extracted from existing SST data cubes. However, given the brevity and the limited funding of this pre-feasibility study, this processing could not be conducted. It is recommended however, to conduct this work in the next phase of the project.

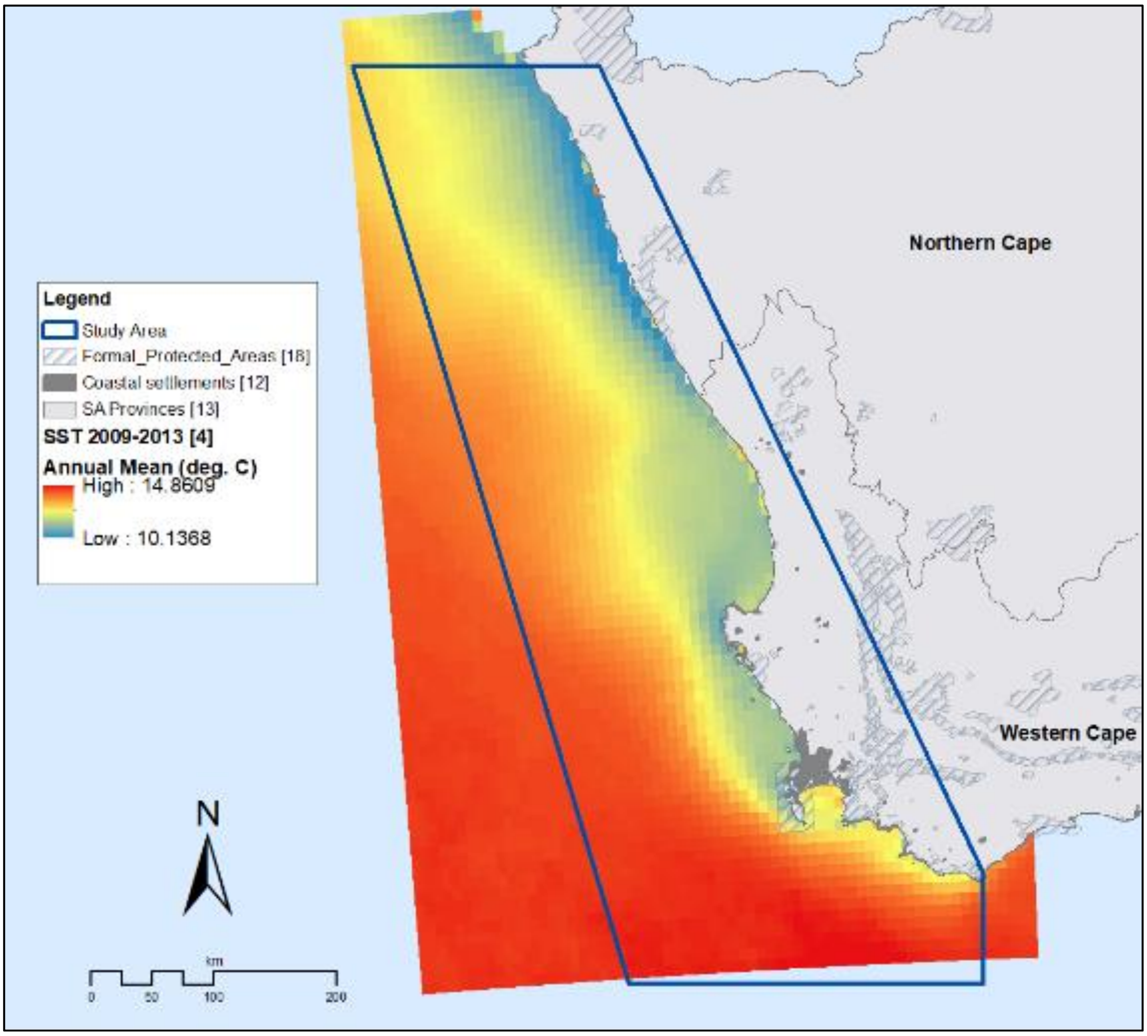


Figure 39: Annual Mean Sea Surface Temperature between 2009 to 2013 [4]

3.6 Mean dissolved Oxygen

Oxygen saturation data were available from the NOAA World Ocean Atlas 2018 [7] at 1 degree (~93km) grid spacing. No grid points were provided in the shallow nearshore where kelp actually occurs. Therefore, only a relatively superficial assessment of the Oxygen situation in the study area could be made.

The dissolved oxygen data were provided in slices across the whole water column (i.e. several depth-specific oxygen values were provided per point). The dataset is provided as annual mean values for each depth slice at each grid point. For this project, only the slices down to 20m depth were considered, given that kelp in our waters generally only occurs up to this depth.

From these depth slices, for each point the mean oxygen value across the 20m water column (provided in 5m slices) was extracted and the respective minimum value within each water column (i.e. point). Figure 40 below shows the minimum mean value per grid point, Figure 41 the mean dissolved oxygen value per grid point.

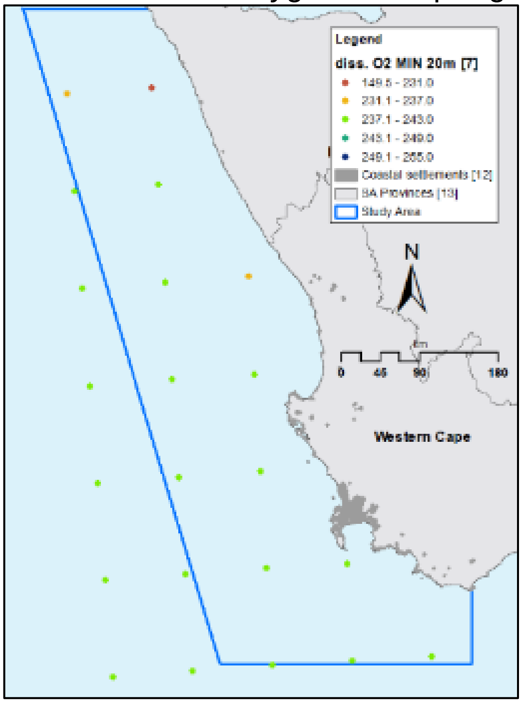


Figure 40: Minimum mean dissolved oxygen (in µmol/kg) across the water column till 20m depth

The total variation of concentration, ranging from 229 to 253 µmol/kg, is relatively narrow. The highest mean oxygen values occur at the open west coast. The lowest minimum values (near Port Nolloth in the Northern Cape and the NC / WC Province border) are related to the large oxygen-poor upwelling cell in that area.

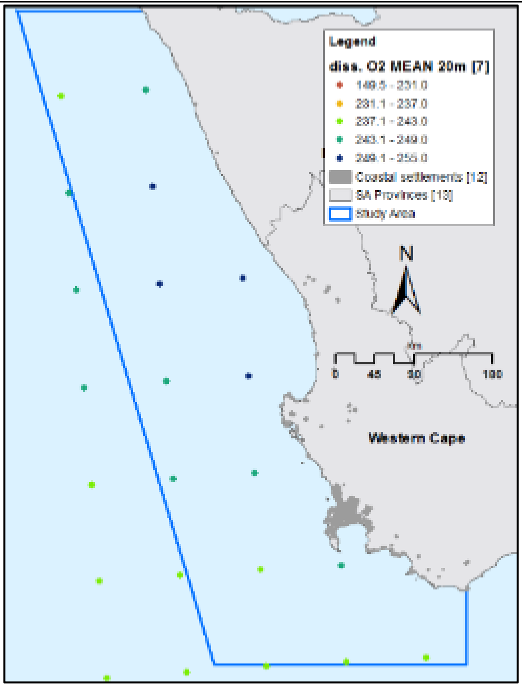


Figure 41: Mean dissolved oxygen (in µmol/kg) across the water column till 20m depth

Assuming that the generally strong wave action along the coast will lead to a good mixing of the upper water strata, generally good oxygen availability can be assumed for the whole study area. This does not however, consider the occurrence of short-term events such as black tides.

3.7 Mean Nitrate

Annual Mean Nitrate concentrations data were available from the NOAA World Ocean Atlas 2018 [8] at 1 degree (~93 km) grid spacing.

The annual mean nitrate data were provided in slices across the whole water column (i.e. several depth-specific nitrate values were provided per point). The dataset is provided as annual mean values for each depth slice at each grid point. For this project, only the slices down to 20m depth were considered, given that kelp in our waters generally only occurs up to this depth.

From these depth slices, for each point the mean nitrate value across the 20m water column (provided in 5m slices) was extracted and the respective minimum value within each water column (i.e. point). According to these data, the nitrate concentration is higher in the nearshore, particularly in the northern Northern Cape (Figure 42). Here, the concentration ranges between 4-6 µmol/kg. The minimum nitrate values across the nearshore water columns range between 3-4 µmol/kg (Figure 43). As the resolution of these data is very coarse, no clear assessment of the actual nearshore conditions can be made at this stage. It is to be expected that the concentrations vary more greatly in the nearshore due to small scale impacts from estuaries, local topography and vegetation and land use. Altogether, given the widespread occurrence of kelp on the coast, it is expected that nitrate is not a limiting growth factor in the study area.

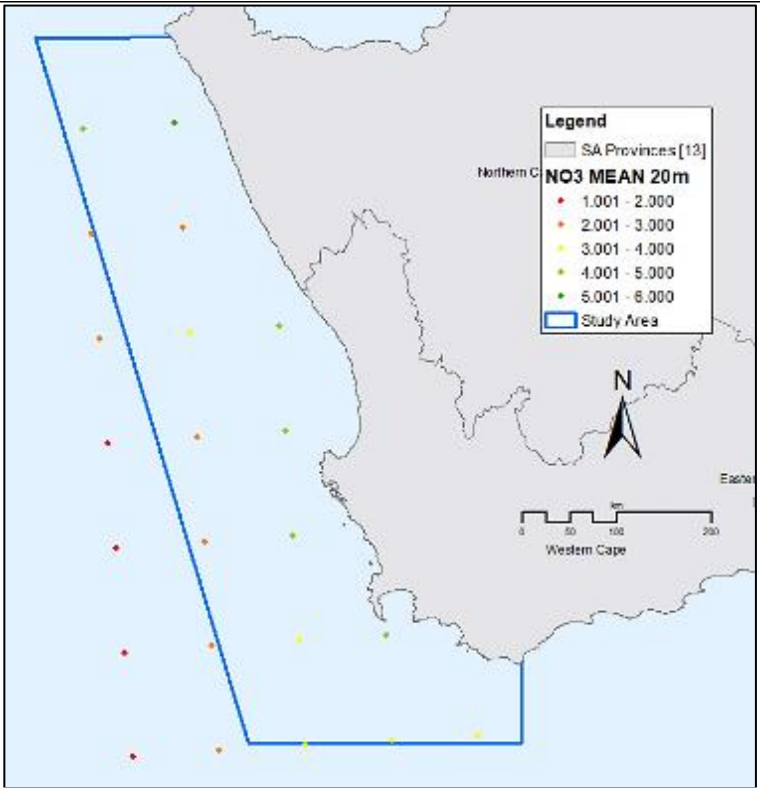


Figure 42: Mean Nitrate (in μmol/kg) across the water column till 20m depth

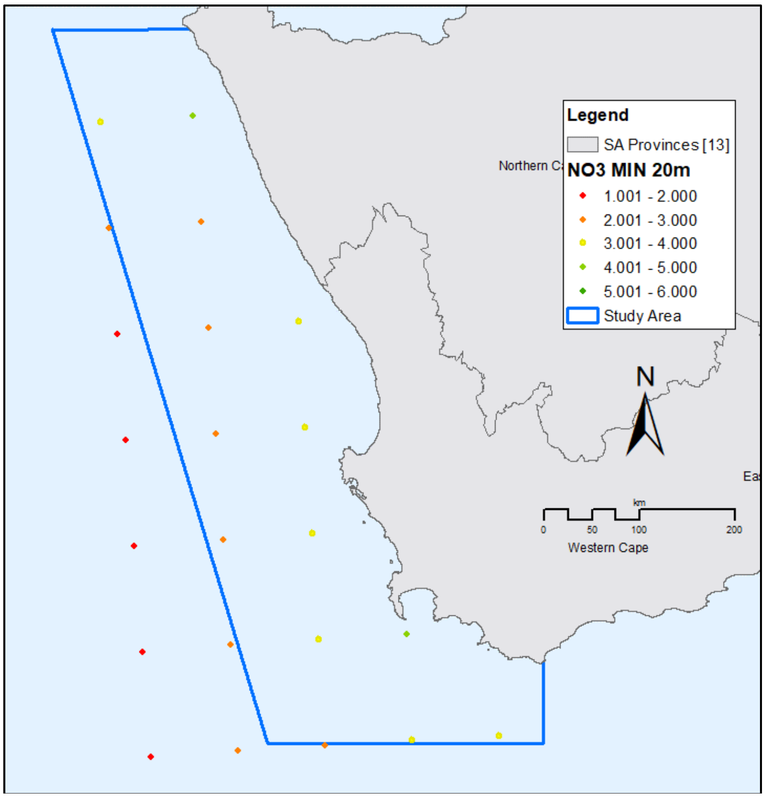


Figure 43: Minimum Nitrate (in μmol/kg) across the water column till 20m depth

3.8 Mean Phosphate

Annual mean phosphate data were available from the NOAA World Ocean Atlas 2018 [9] at 1 degree (~93km) grid spacing. The annual mean phosphate data were provided in slices across the whole water column (i.e. several depth-specific phosphate values were provided per point). The dataset is provided as annual mean values for each depth slice at each grid point. For this project, only the slices down to 20m depth were considered, given that kelp in our waters generally only occurs up to this depth.

From these depth slices, for each point the mean phosphate value across the 20m water column (provided in 5m slices) was extracted and the respective minimum value within each water column (i.e. point). According to these data, concentrations in the study area range between 0.115 – 1.1 µmol/kg water. Like the nitrate data, phosphate concentrations are the highest in the points nearest to the coast.

As the resolution of these data is very coarse, no clear assessment of the actual nearshore conditions can be made at this stage. It is to be expected that the concentrations vary more greatly in the nearshore due to small scale impacts from estuaries, local topography and vegetation and land use. Altogether, given the widespread occurrence of kelp on the coast, it is expected that phosphate is not a limiting growth factor in the study area.

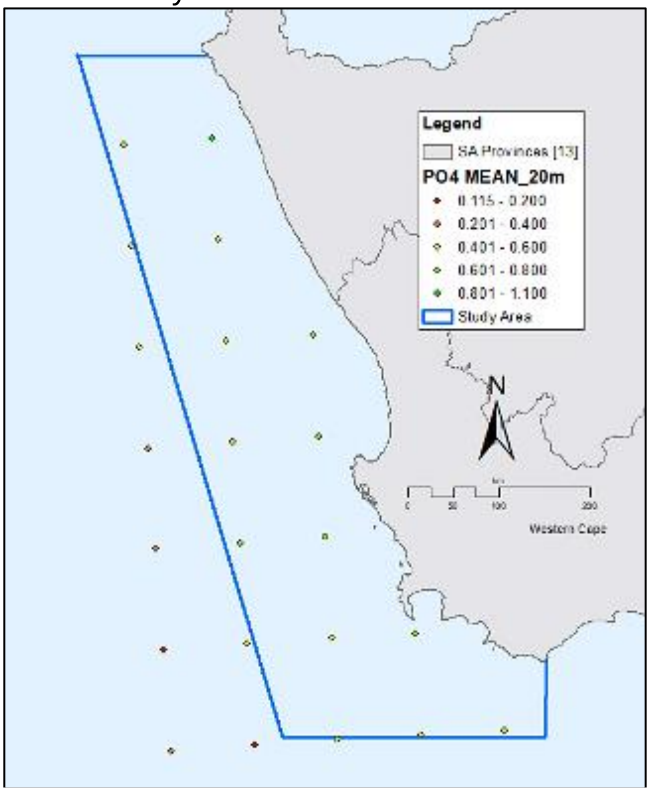


Figure 44: Mean phosphate (in µmol/kg) across the water column till 20m depth

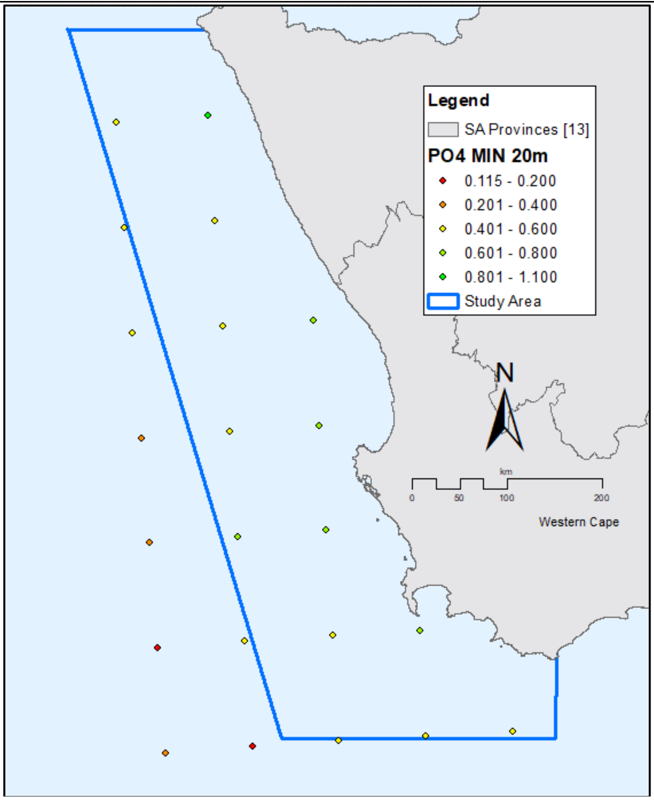


Figure 45: Minimum phosphate (in µmol/kg) across the water column till 20m depth

3.9 Salinity

Annual mean salinity data were available from the NOAA World Ocean Atlas 2018 [10] at 1/4-degree (~25 km) grid size. The annual mean salinity data were provided in slices across the whole water column (i.e. several depth-specific salinity values were provided per point). The dataset is provided as annual mean values for each depth slice at each grid point. For this project, only the slices down to 20m depth were considered, given that kelp in our waters generally only occurs up to this depth.

From these depth slices, for each point the minimum salinity value across the 20m water column (provided in 5m slices) was extracted and the respective maximum value within each water column (i.e. point). According to these data, concentrations in the study area range between 34.7558 ppt and 35.4066 ppt, so relatively little variation in the annual mean data was recorded. Referring to
Table 20, the observed salinity range is well within the tolerated salinity range of kelp.

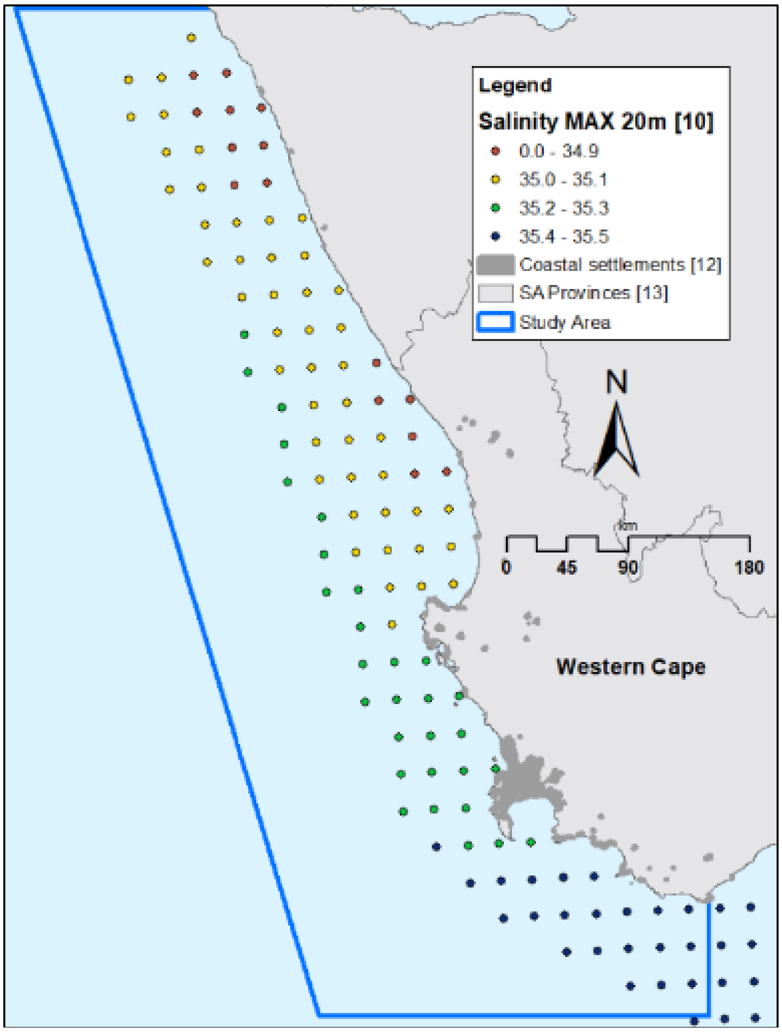


Figure 46: Maximum salinity (in ppt) across the water column till 20m depth

Maximum salinity values occur at the South African south coast, while at the west coast, upwelling and river discharge at the orange and Olifants River reduce salinity (Figure 46). Given the low range of variation in salinity, the pattern of minimum salinity does not vary significantly from the maximum salinity distribution (Figure 47).

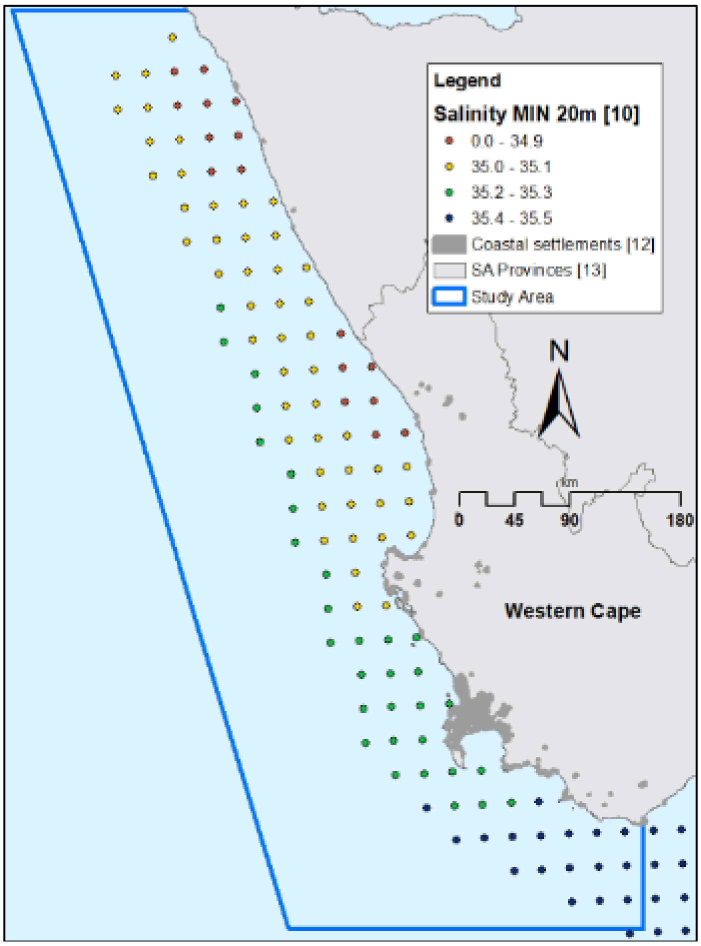


Figure 47: Minimum salinity (in ppt) across the water column till 20m depth

4 Land use considerations

As far as the relatively coarse scale of the analysis in section 3 above allow, it appears that from a natural perspective, kelp growth is possible along the entire coast (provided that rocky substrate is present).
In this section, some key land use parameters will be analysed to assess if there are potential conflicts with raft-based kelp farming activities to be expected. The analysed parameters include the presence of aquaculture development zones and protected areas, areas licensed for mineral mining and vessel traffic and oilspill risk. Table 21 briefly summarises the expected impact of each of these parameters.

Table 21: Expected impact of key land use parameters on kelp farming activities

Land use parameter	Impact on kelp growth & farming
Aquaculture development zones	Kelp farming may be prioritised
Existing marine aquaculture	Potential market for kelp and existing infrastructure
Conservation/protected	Exclusive. No farming possible.

areas/MPAs	
Mineral mining	Access restrictions and physical disturbance of rafts
Vessel traffic	Physical disturbance and damage to rafts; pollution

4.1 ADZs versus Protected areas

Figure 48 displays the location of aquaculture development zones (ADZ) and formally protected areas in the inland as well as Marine Protected Areas (MPAs). As expected, no spatial conflict arises between potential kelp farming, which will take place primarily in the ADZs, as these were strategically placed to avoid conflict with protected areas.

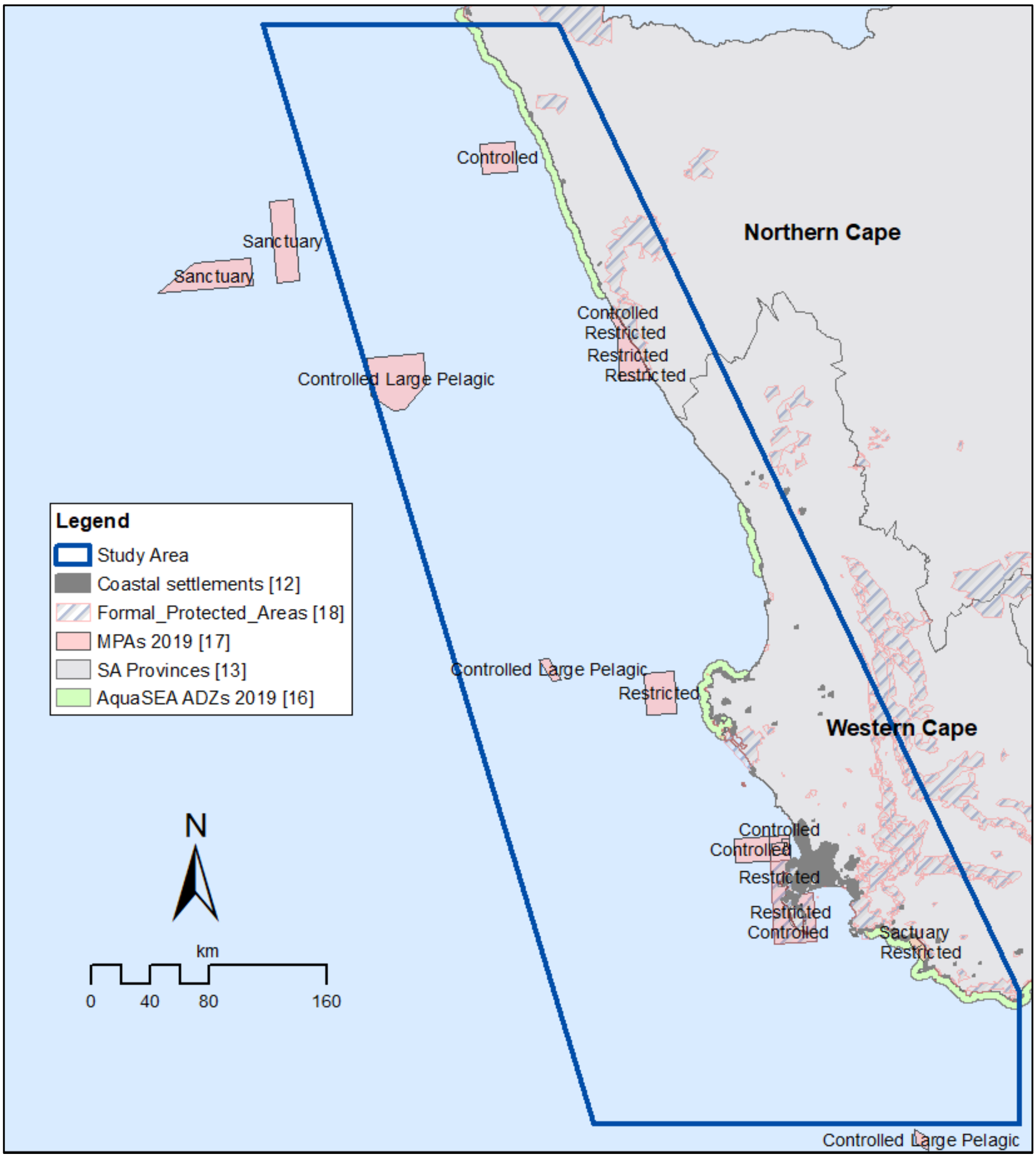


Figure 48: Aquaculture development zones versus MPAs and other protected areas

4.2 Existing Aquaculture facilities

The ADZs displayed above, coincide with areas where aquaculture facilities are established already (Figure 49). It is expected that establishment of kelp farms in the vicinity of existing marine aquaculture sites, especially those producing abalone and other bivalves that feed on kelp will contribute to the economic success of those farms. The figure below indicates that such facilities are present in all areas that will be discussed in more detail in section 5.

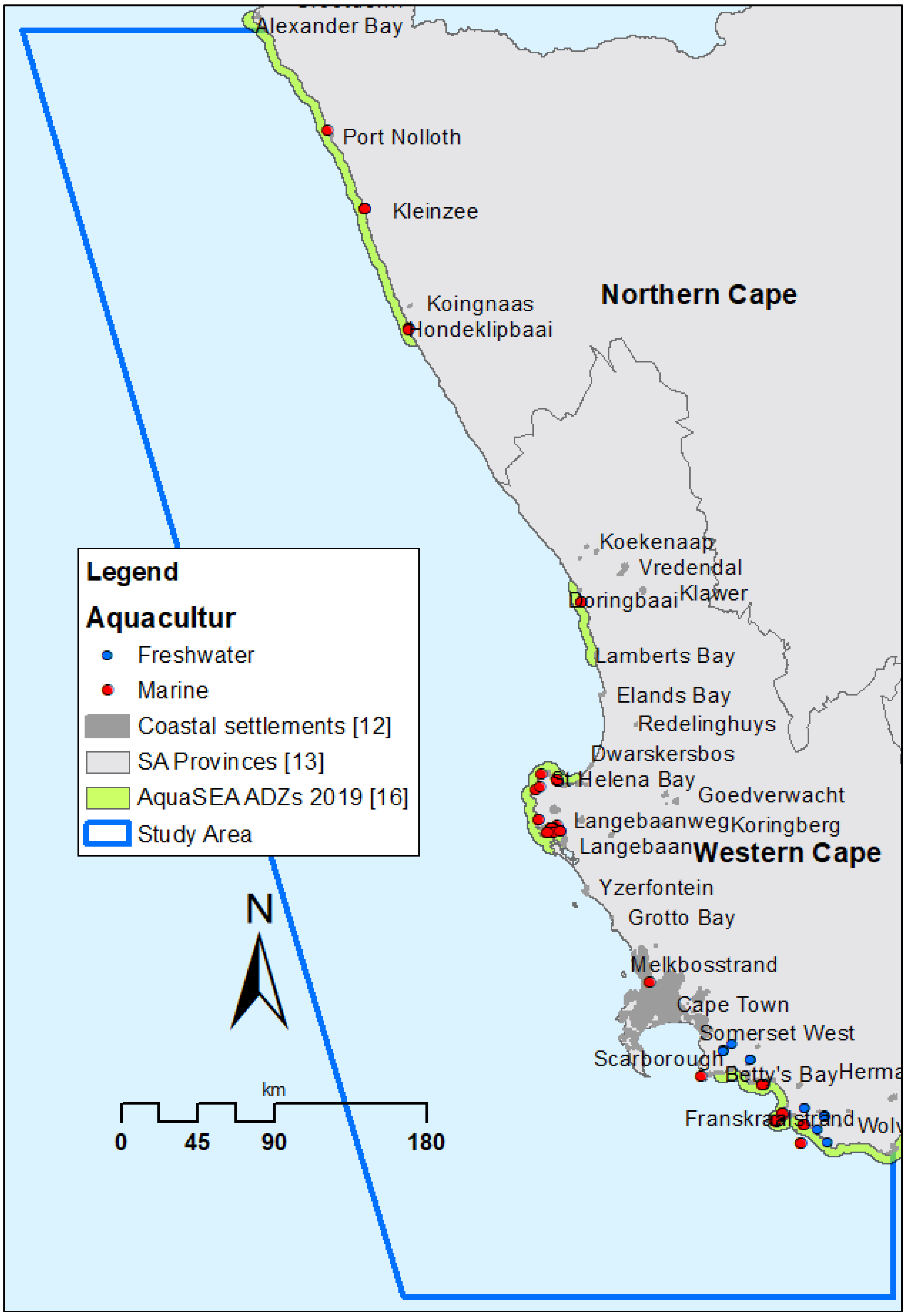


Figure 49: ADZs and existing aquaculture facilities

4.3 Mineral mining

Vast areas of the South African west coast are designated as offshore mineral and metal mining concessions (Figure 50). The data displayed were provided by the Department of Mineral Resources through the Department of Environmental Affairs in 2018.

The figure shows that active mining licenses are concentrated on the surf zone while some prospecting is licensed for the offshore. There seems to be a large overlap of the surf zone mining with the ADZ in the Northern Cape, where kofferdam mining for diamonds is currently conducted.

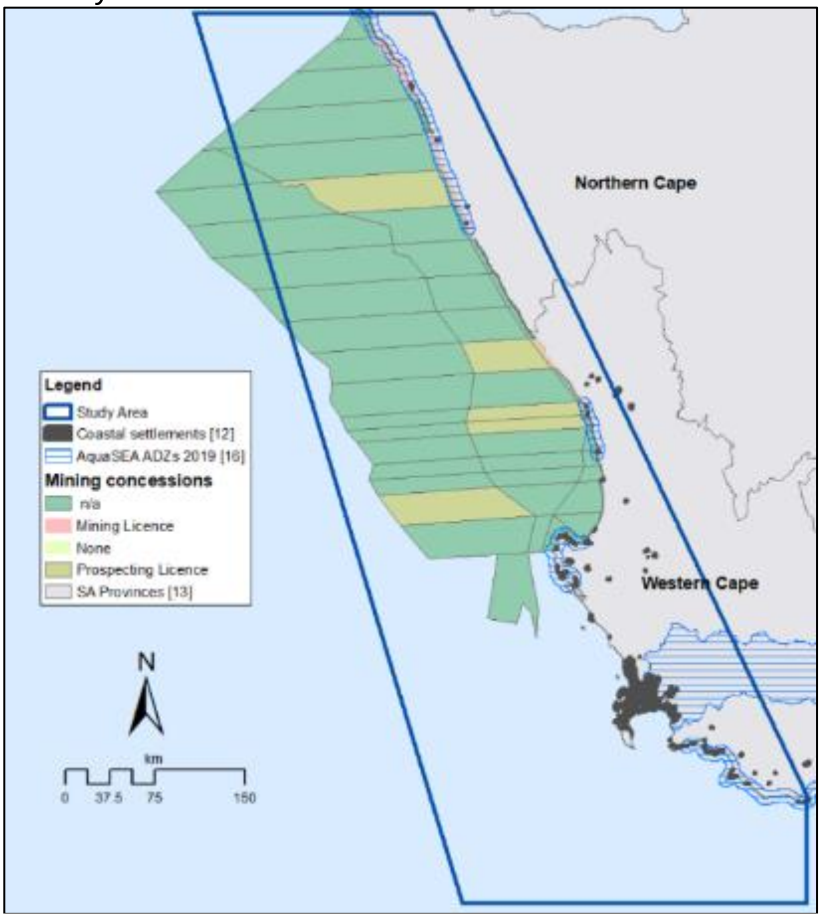


Figure 50: Offshore mining concessions as of 2018 [20]

Another dataset on the permit status provided by the Council for Geoscience shows the mining permit status as of 2013 (Figure 51). According to this figure, most of the permits were to be expired at the date of this report (2022) and all the surf zone permit are to expire by 2030.

In fact, the location of the Northern Cape ADZs in the mining permit areas that are to expire in this decade are established to provide alternative income sources for the work force being set free by the closing mines. There is some potential in the existing mining infrastructure (buildings, roads etc.) for being used for future aquaculture activities.

In short, the data available for this project do not foresee any future land use conflict between mining and kelp farming. However, the data available here were somewhat outdated, and a confirmation of these findings with more recent mining data in the next phase of the project is strongly recommended.

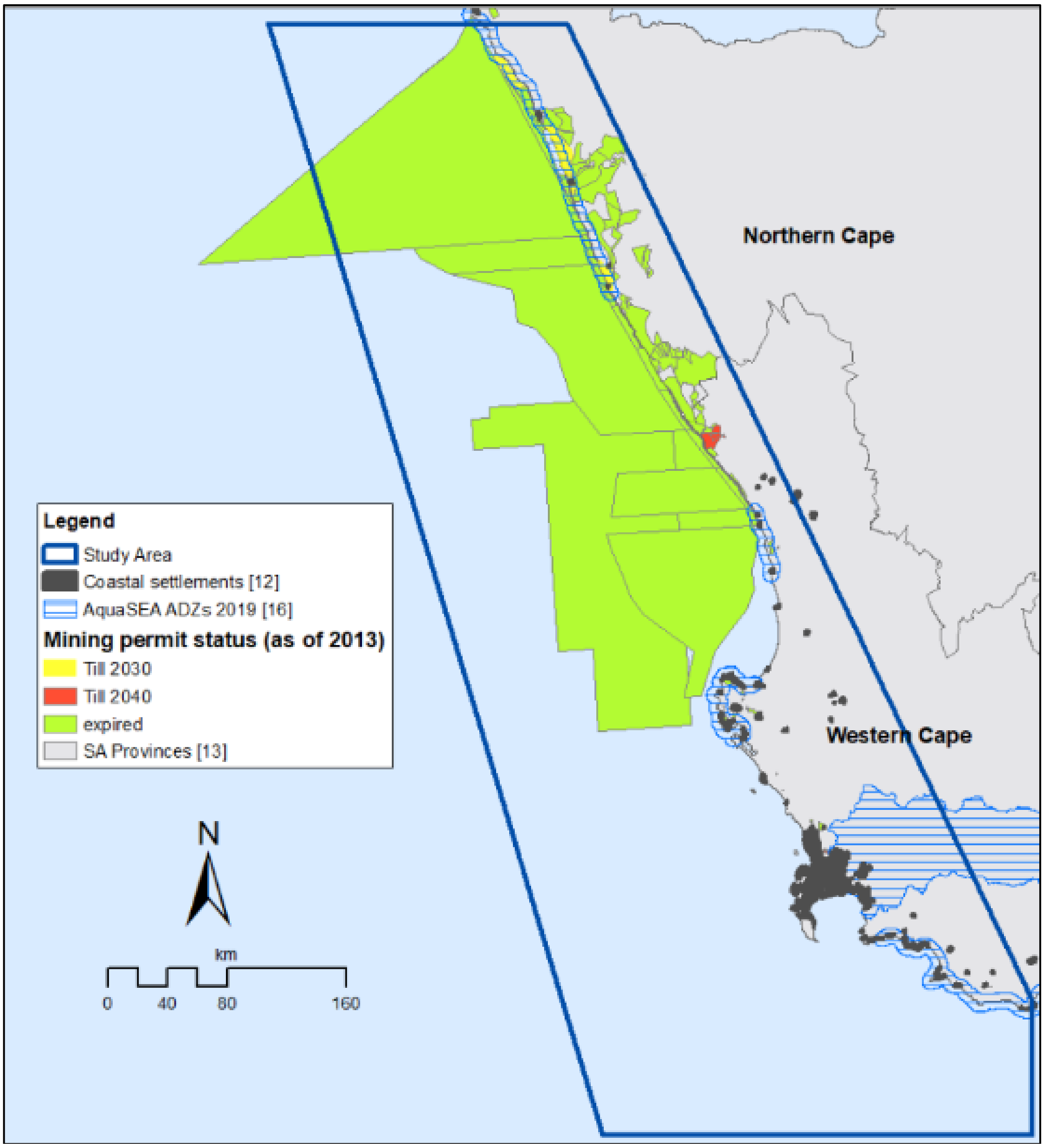


Figure 51: Mining license areas and expiry date [19]

4.4 Vessel traffic

Information about vessel traffic density was available from the World Bank's online Data Catalog [15]. Individual layers on Global Shipping Traffic Density were available for commercial (cargo) ships, fishing ships, platforms, rigs etc. for oil and gas mining, passenger ships and leisure vessels. The raster layers are based on analysis of hourly AIS positions received between Jan-2015 and Feb-2021 and represent the total number of AIS positions at a spatial resolution of about 500m x 500m.

Vessel traffic was assessed in this project, as vessels themselves as well as the waves especially the large vessels can cause are potentially hazardous to the kelp rafts and to the boats and crews servicing them.

4.4.1 Passenger, leisure and oil & gas vessels

The data show that the density of passenger vessels, Leisure vessels and oil & gas vessels is very low in the study area, and no conflict with potential kelp farming is expected (Figure 52, Figure 53 and Figure 54).

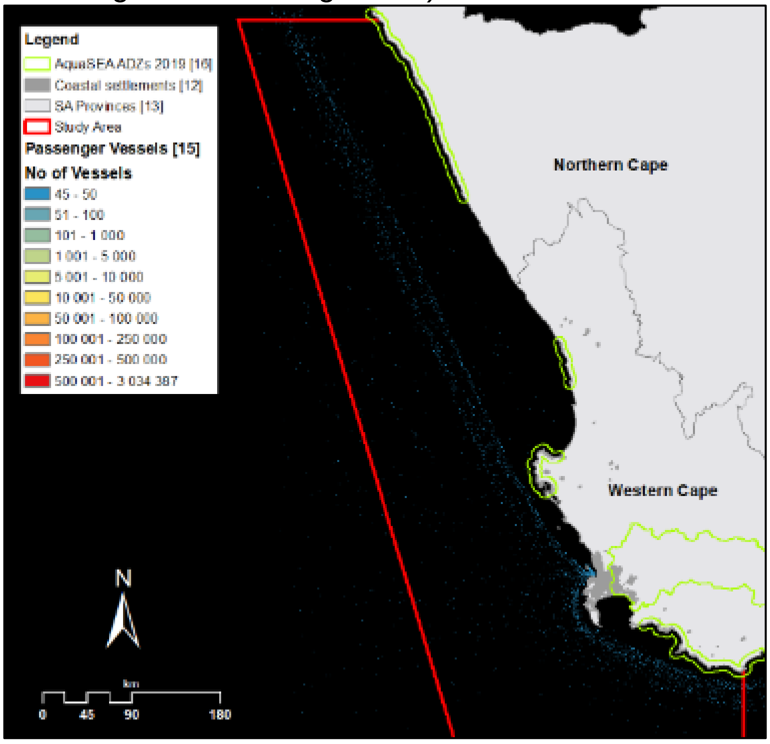


Figure 52: Passenger vessel traffic between 2015 and 2021 [15]

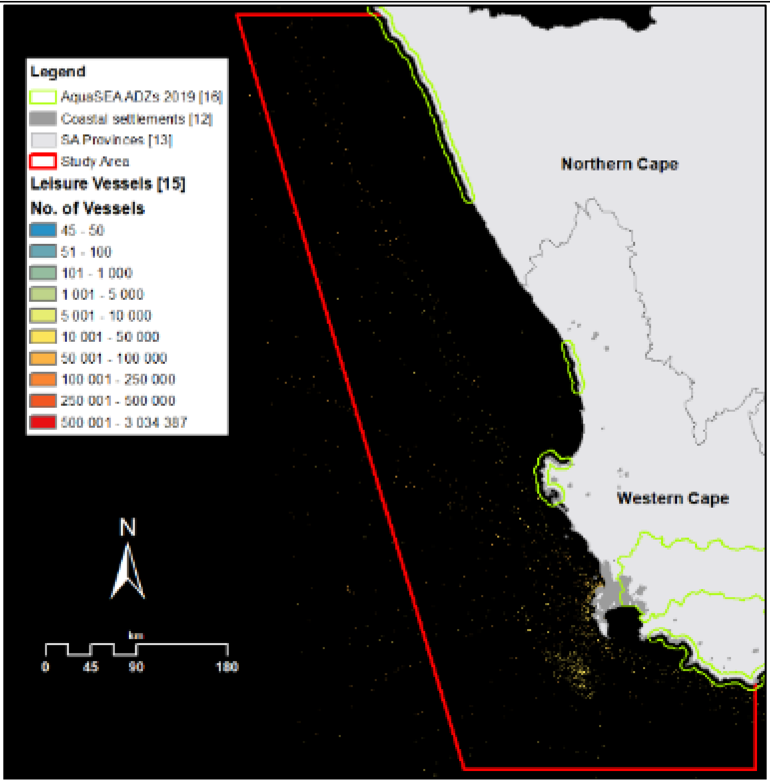


Figure 53: Leisure vessel traffic between 2015 and 2021 [15].

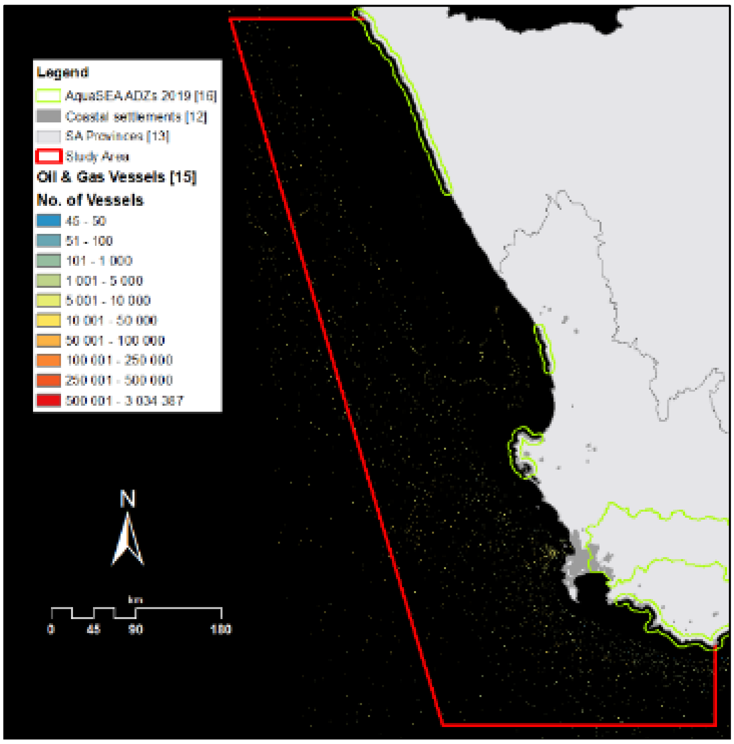


Figure 54: Oil & Gas vessel traffic between 2015 and 2021 [15].

4.4.2 Fishing vessels

Between 2015 and 2021 hardly any fishing vessels were recorded on the west coast north of Doringbaai (WC). Very high fishing activity took place however, between Saldanha and Gans Bay, mainly along the continental shelf (Figure 55).

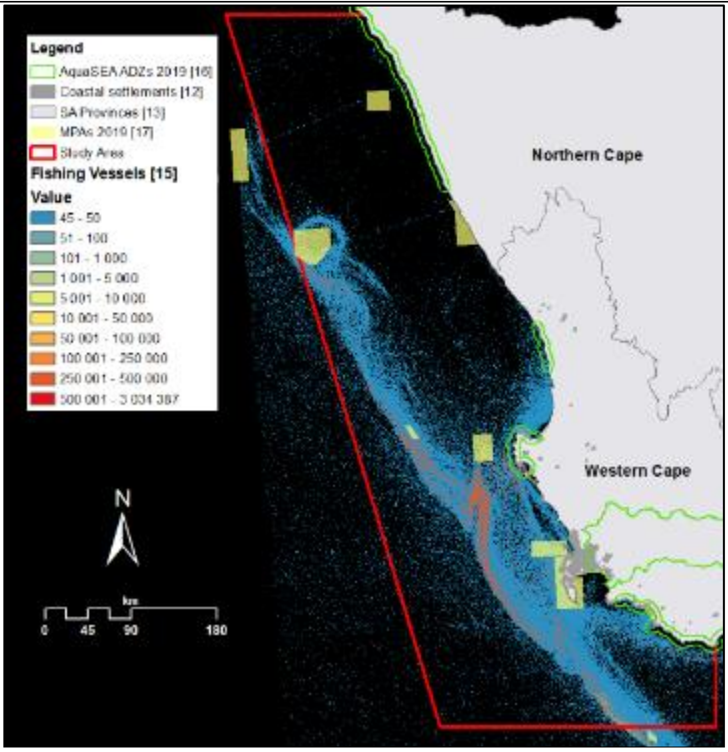


Figure 55: Fishing vessel traffic in the study area between 2015 and 2021 [15] and MPAs.

Density of fishing vessels in the ADZ between Saldanha and St. Helena Bay was relatively low, apart from a trajectory into the Saldanha fishing port and to some degree along a trajectory between Saldanha Bay and St Helena port (Figure 56). The fishing vessel activity should not impose any obstacle for potential kelp farming, apart from the ADZ in Little Bay perhaps.

The nearshore fishing vessel density between Cape Town and Cape Agulhas, including False Bay, is low as well, apart from a trajectory into the port of Simons Town in False Bay and around Gans Bay (Figure 57). Fishing vessel traffic is therefore not expected to conflict with potential kelp farming in these areas either.

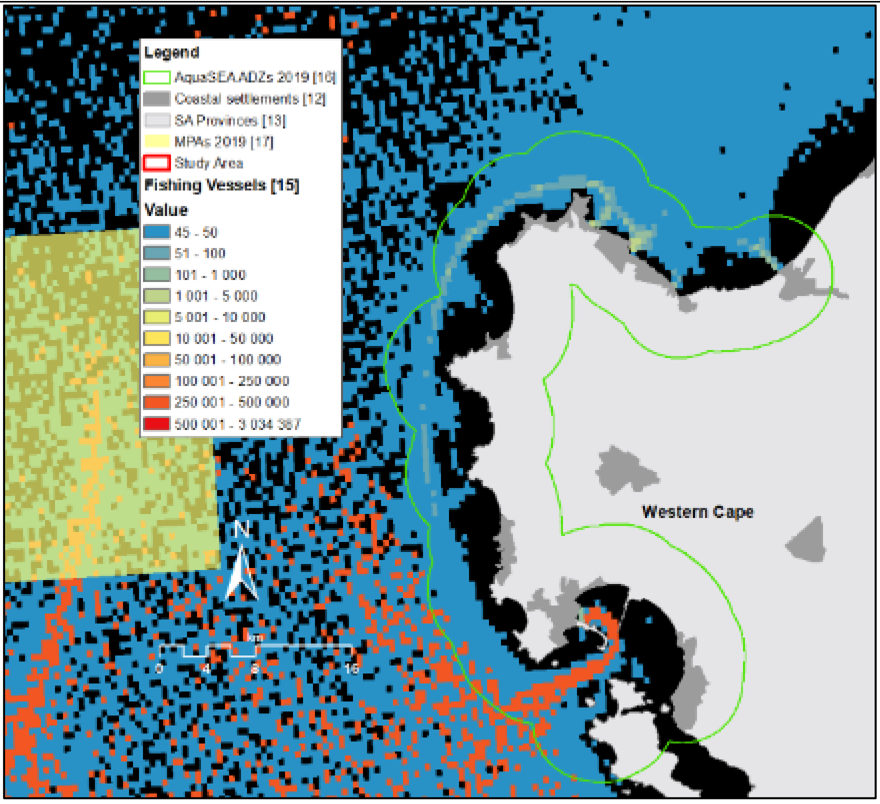


Figure 56: Fishing vessel traffic in the Saldanha – St. Helena Bay area between 2015 and 2021 [15] and ADZs.

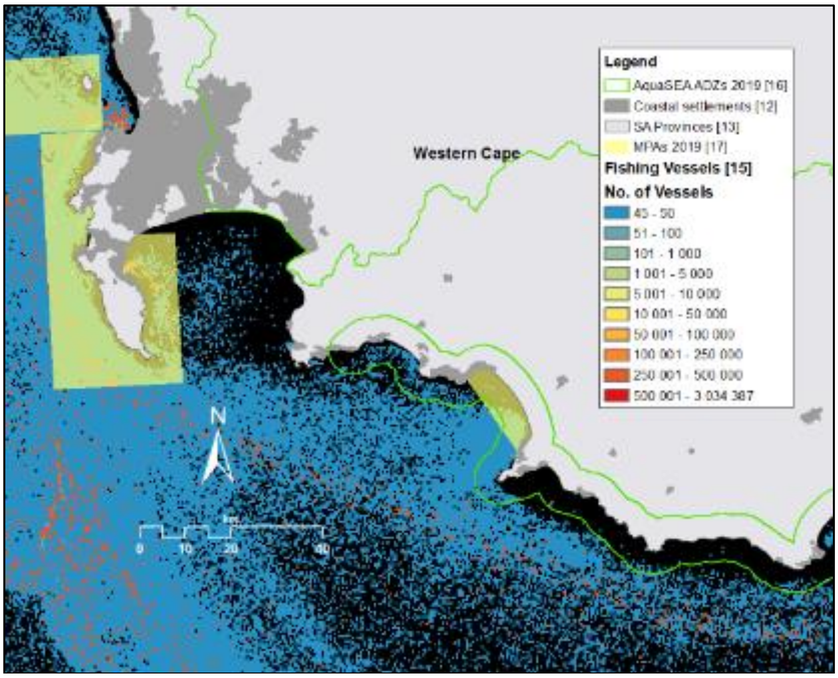


Figure 57: Fishing vessel traffic between Cape Town and Cape Agulhas between 2015 and 2021 [15] and ADZs.

4.4.3 Commercial (cargo) vessels

The density of commercial cargo vessels by far exceeds the density of any other vessel type (Figure 58), given the strategic position of the Cape on the southern tip of the African continent, making the region a bottleneck for global cargo traffic.

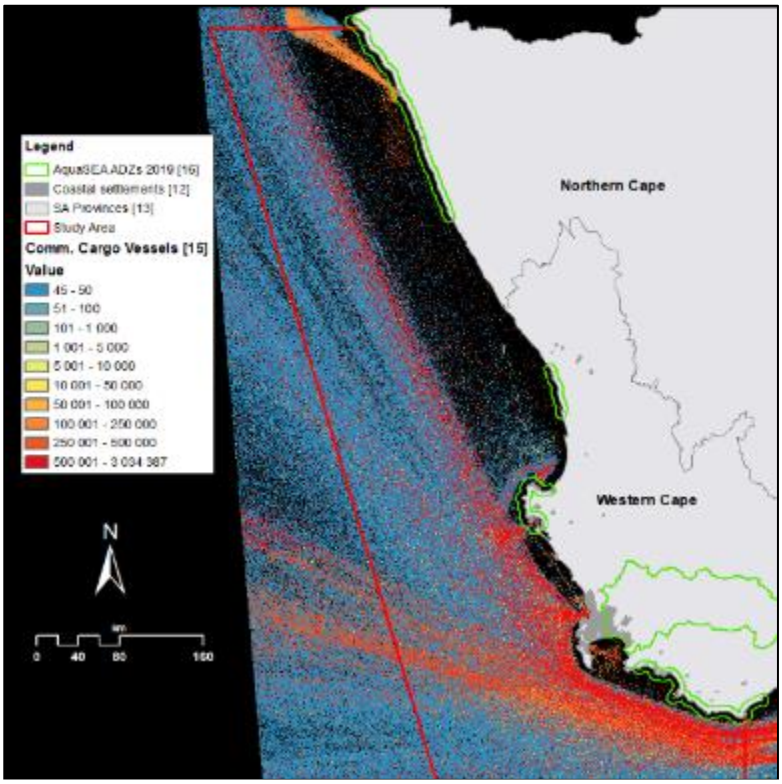


Figure 58: Commercial (cargo) vessel traffic between 2015 and 2021 in the study area [15].

On the Northern Cape coast, the ADZ area that might become relevant for kelp farming is mainly affected by commercial vessels on a dense trajectory towards the port of Port Nolloth, related to iron ore cargo from the inland mines (Figure 59). East of Kleinzee, a somewhat denser cloud of vessel presence is visible, which might be related to the offshore mining activities in that area. With the envisaged expiry of mining activities in that area in this decade, this traffic is expected to cease. No impact on potential future kelp farming of commercial vessel traffic is therefore expected for the Northern Cape coast.

As for the wider Saldanha – St. Helena Bay area, the commercial vessel traffic density is extremely high, for a large number of grid cells, between 500,000 and 3 million vessel signals being recorded (Figure 60).

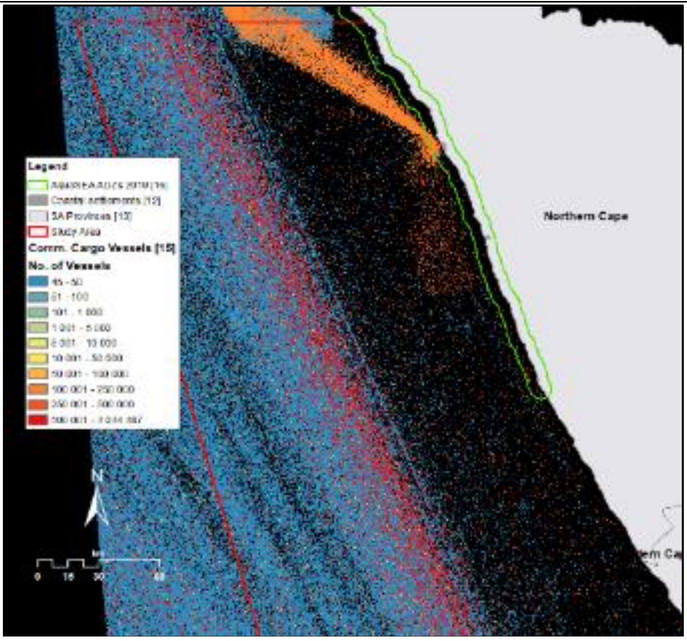


Figure 59: Commercial (cargo) vessel traffic between 2015 and 2021 on the Northern Cape coast [15].

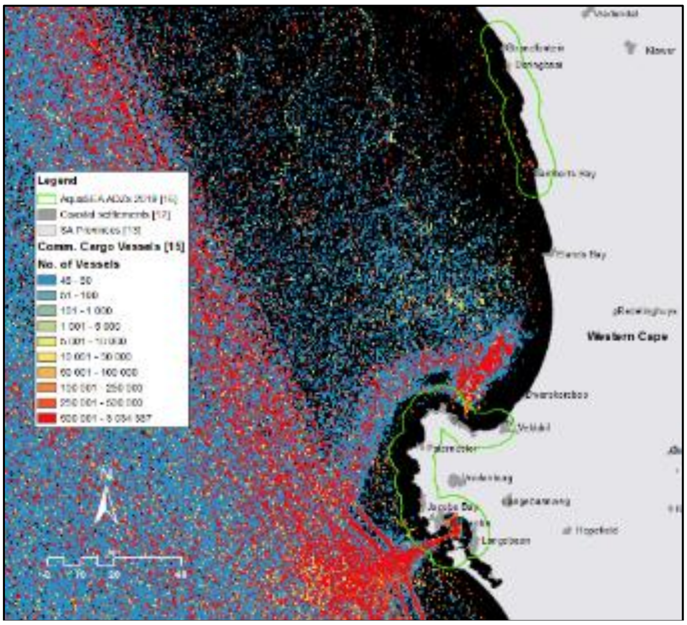


Figure 60: Commercial (cargo) vessel traffic between 2015 and 2021 on the Western Cape west coast [15].

The high density of recorded vessel signals is partly caused by vessels awaiting their turn to enter Saldanha Bay to load iron ore at the jetty between small and Big Bay (Figure 61). It has to be assessed in a subsequent study if the caused turbidity, wave motion and potential pollution would be detrimental to kelp rafts, boat-based maintenance thereof and to the health of the crop. A high occurrence of commercial vessels is recorded for St. Helena Bay off St Helena as well.

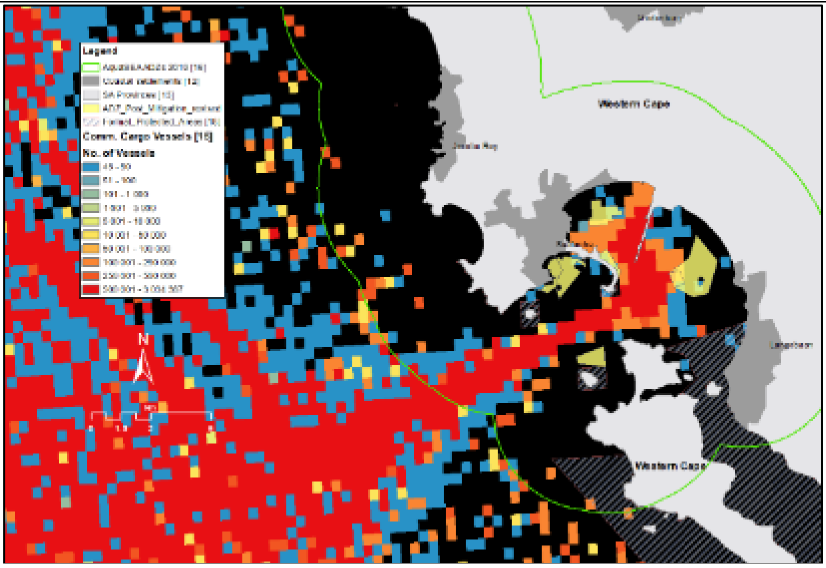


Figure 61: Commercial (cargo) vessel traffic between 2015 and 2021 in Saldanha Bay [15].

As for the coast between Cape Town and Cape Agulhas, a very high density of commercial vessels is present between the port of Cape Town, along the west coast of the Cape peninsula and around Cape Agulhas. However, this traffic does not affect the area between Cape point and Gans Bay, where vessels largely stay out of the designated ADZ area. Vessel traffic in False Bay appears to be relatively high. It has to be verified that these vessels are largely commercial whale watching and shark watching vessels for tourists, whose impact on kelp rafts are significantly lower than that of intercontinental freight and cargo vessels. If correct, False Bay would be suitable for kelp farming from this perspective as well.

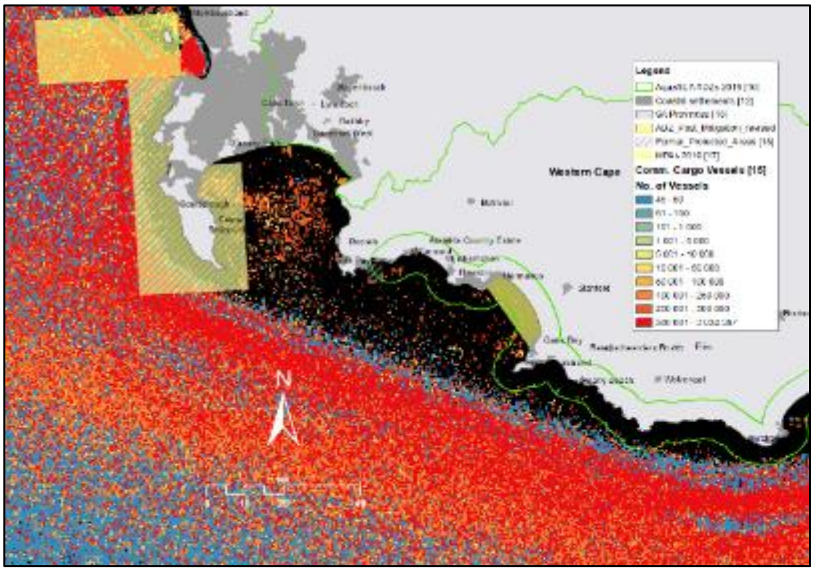


Figure 62: Commercial (cargo) vessel traffic between 2015 and 2021 between Cape Town and Cape Agulhas [15].

4.5 Vessel traffic and oil spill risk

With motorised vessel traffic, there comes a risk of pollution from machinery oil and fuel leakage which might negatively impact the health and quality of farmed kelp. In the National Coastal Assessment project (DEA & CSIR, 2020) the locations of oil spills originating from ship wrecking, bilge dump and port incidents between 2008 and 2016 was visually assessed in relation to different vessel types. In order to generate a prognosis of a general probability of oil spill occurrences in South Africa's Ocean, the point data were overlaid with different ship vessel trajectories provided by the OCIMS Vessel tracking DeST development team at CSIR Meraka. These trajectories were recorded separately for Fishing Vessels (Figure 63), Cargo Vessels (Figure 64) and Tanker (Oil & Gas) Vessels (Figure 65). In each of these three figures the increase in colour intensity of the trajectories indicates a higher vessel occurrence. The comparison of the three figures shows that the trajectories of Cargo Vessels coincide best with the oil spill occurrences. Oil spill records on the coast, i.e. not related to vessel trajectories, are largely related to locations of ports (indicating port-operations related oil spills).

Cargo vessel trajectories seem to allow prediction of oil spill occurrences on the open sea. This means that kelp farms in the vicinity of dense cargo vessel trajectories might be at higher risk of exposure to oil spills.

However, these data do not allow predicting in which direction the spillage will drift. Such predictions would require computational fluid dynamic modelling under consideration of event-based wind, wave and current conditions.

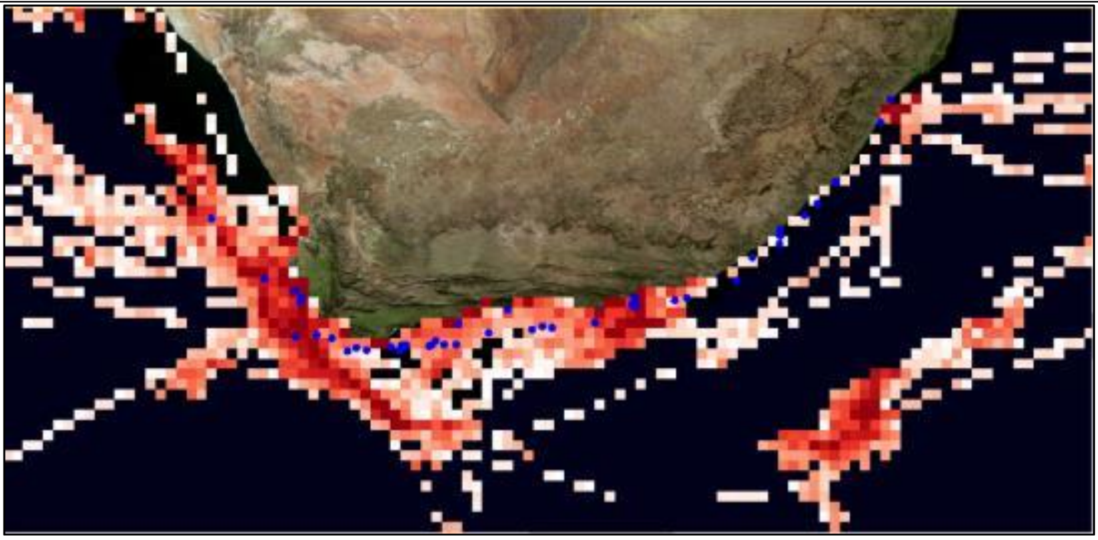


Figure 63: IVT Global Fishing Vessel Trajectories and oil spill occurrences (blue dots)

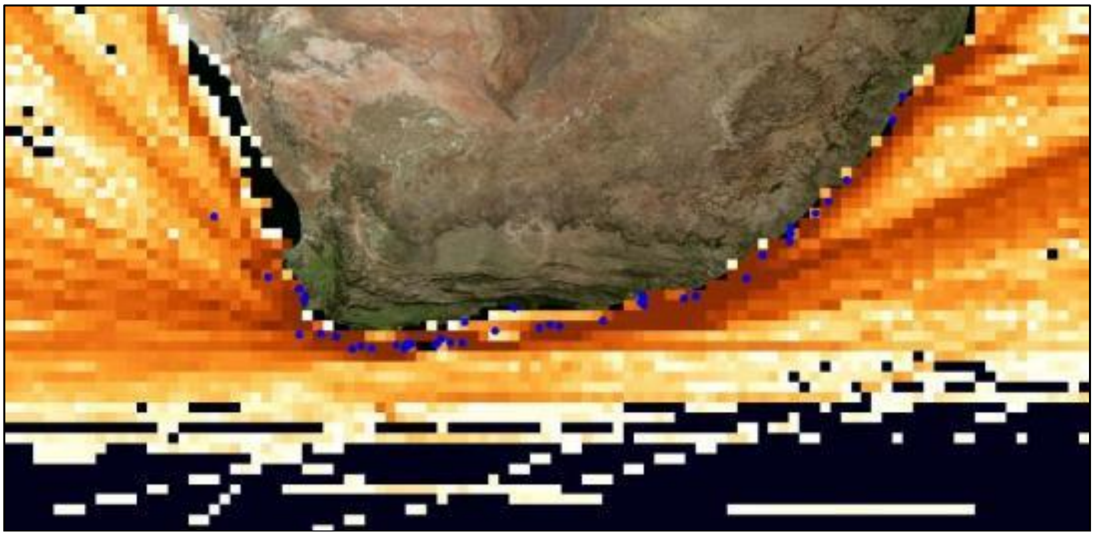


Figure 64: IVT Global Cargo Vessel Trajectories and oil spill occurrences (blue dots)

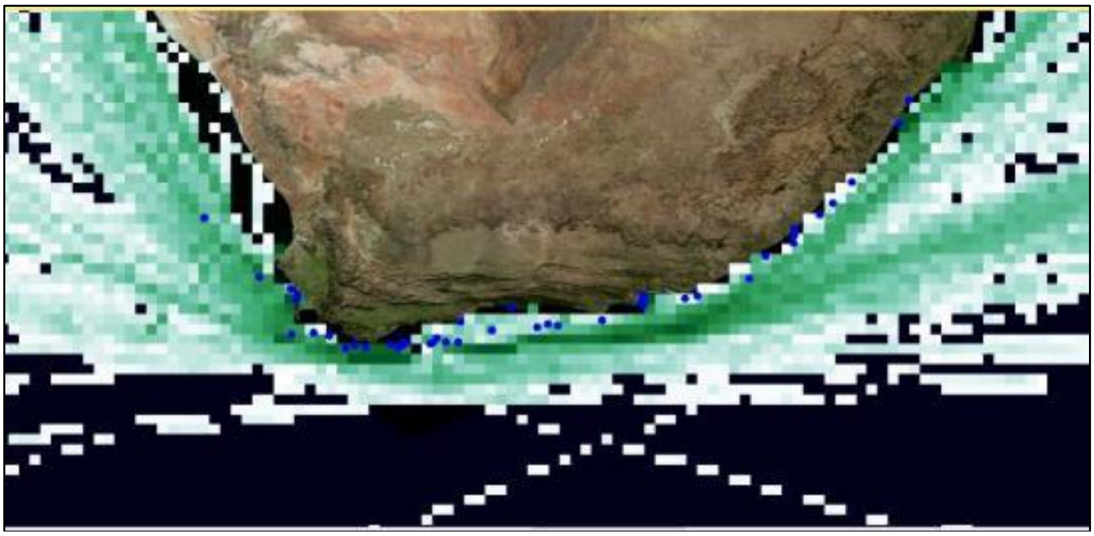


Figure 65: IVT Global Tanker Vessel Trajectories and oil spill occurrences (blue dots)

5 Synoptic assessment of relevant aspects

In this section, those aspects that have been identified as the most relevant ones in the sections above, will be analysed together.

The **water depth** is relevant firstly as limiting factor for kelp growth generally, and secondly is it might determine the technical feasibility of the placement and secure anchorage of offshore rafts. We found that kelp, probably due to water turbidity, seems to favour water depths of about 4m in South Africa, but does occur deeper where turbidity is less. In the following figures, therefore the bathymetric depth range between 20-50m is indicated (speckled black) as the assessment in section 3.4 showed that **turbidity** in this depth range drastically decreases. From the location of this depth range, also the **distance to the shore** can be deducted. Distance is relevant to make the boat trips to the rafts for maintenance and harvesting feasible, especially in the light of the increasing fuel prices.

High **wave energy**, while not detrimental to kelp growth itself, might put offshore kelp rafts at risk and makes access of the rafts difficult and dangerous.

Further, the **cargo vessel** trajectories are indicated, as these have been identified as the most limiting land use activities.

The designated **ADZs** are highlighted as those areas where kelp farming is the easiest from a permit perspective. **MPAs** have been added to display aquaculture exclusion zones. The presence of **settlements** is importance as a proxy for the provision of work force, housing, and other relevant infrastructure and potential markets.

5.1 Northern Cape coast

Figure 66 below displays the relevant aspects for the Northern Cape Coast. The conclusions drawn from the visual assessment of this map are summarized in Table 22. Figure 70 below delineates the two identified potential areas.

Table 22: Synoptic assessment for the Northern Cape coast

Aspect	Comments
Water depth & distance to coast	The coast is relatively steep, leading to the 20km bathy contour being about 2km away from the shore and the 50m bathy contour about 5km away, which is very close. From the perspective of access by boat, this is beneficial.
Wave energy	Low to moderate (up to 40kW/m) between Alexander Bay and Kleinzee. Moderate south of Kleinzee (20-60kW/m)
Vessel traffic	High around and north of Port Nolloth, low south of Port Nolloth
ADZs and MPAs	No conflict between protected and designated ADZ areas
Settlements	Some small settlements present (Port Nolloth, Kleinzee and Hondeklipbaai) with fishing and aquaculture facilities

	(and workforce) present. However, long distance to potential markets.
Conclusion	**The Northern Cape coast, with its extensive Namakwa ADZ, moderate annual wave energy and short distance to suitable water depth, should be suitable to offshore kelp farming, especially in the vicinity of the small towns.**

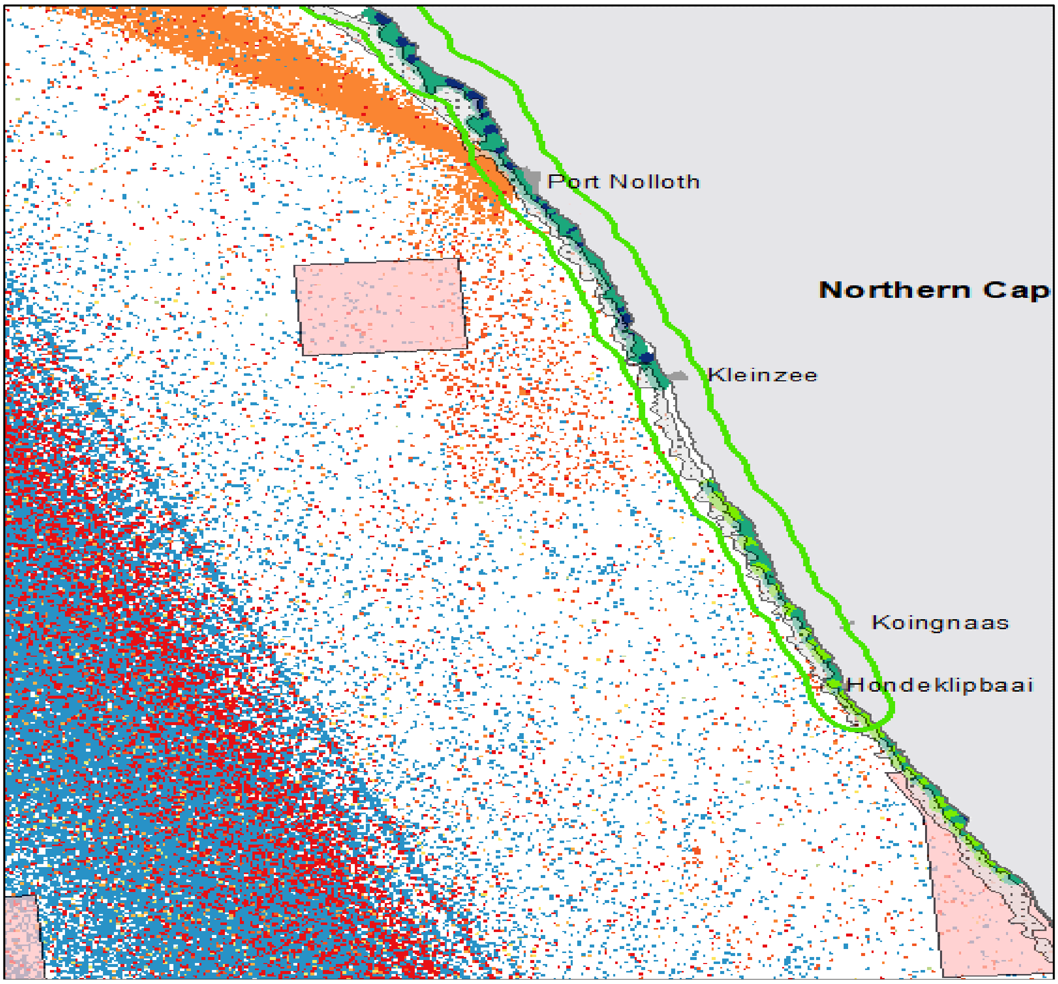


Figure 66: Water depth, cargo vessel traffic, MPAs and ADZs for the Northern Cape coast.

5.2 Saldanha – St. Helena Bay Bay area

Figure 67 below displays the relevant aspects for the Saldanha – St. Helena Bay area. The conclusions drawn from the visual assessment of this map are summarized inTable 23. Figure 70 and Figure 71 below delineate the five identified potential areas.

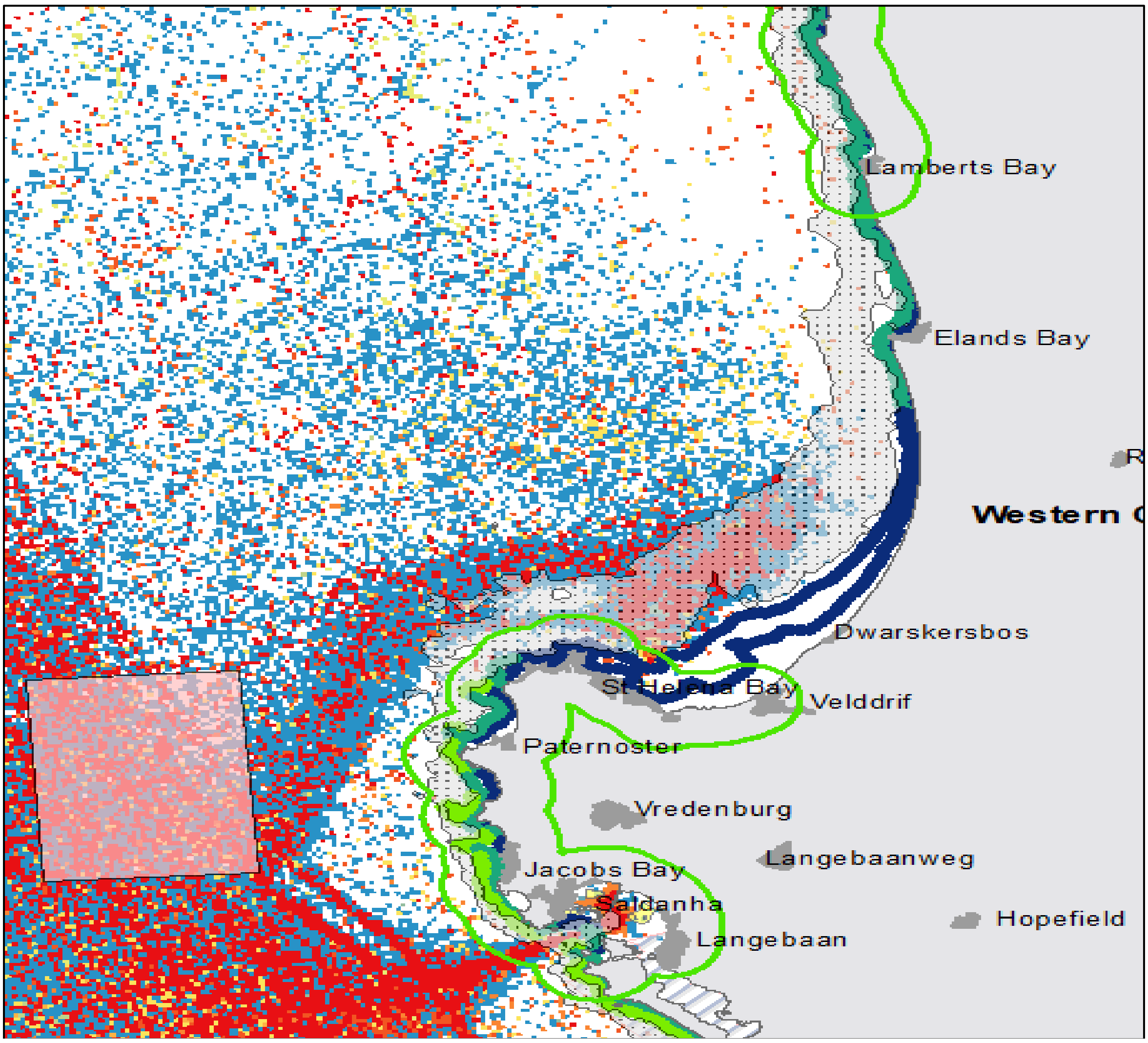


Figure 67: Water depth, cargo vessel traffic, MPAs and ADZs for the Saldanha – St. Helena Bay area.

Table 23: Synoptic assessment for the Saldanha – St. Helena Bay area

Aspect	Comments
Water depth & distance to coast	In the West Coast ADZ and the open coast of the Saldanha ADZ, the coast is relatively steep, leading to the 20km bathy contour being between 1-2km away from the shore and the 50m bathy contour about 5km away, which is very close. From the perspective of access by boat, this is beneficial. In the area of St Helena Bay the coast is very shallow, and the 20m contour is between 3-5km offshore, and the 50m

	contour between 13-20km. However, the extensive areas shallower than 20m provide ample space for kelp rafts as well.
Wave energy	The maximum annual wave energy in the area of the West coast ADZ is low to moderate (up to 40kW/m), in St. Helena Bay it is very low (up to 20kW/m), on the open coast of the peninsula north of Saldanha, wave energy ranges between low and high (20-60kW/m), depending on the location of the highly diverse coast.
Vessel traffic	Very low in the area of the West Coast ADZ, very high in the sheltered 20-50m depth zone in St. Helena Bay NE of St Helena, high at the entrance of Saldanha Bay and in Big and Small Bay Low around the Peninsula north of Saldanha Bay
ADZs and MPAs	No conflict. Extensive ADZ area in this region
Settlements	Regional service town (Saldanha) and other settlements present, with good infrastructure, work force and fishing/boating facilities. Good access to large markets (Cape Town).
Conclusion	**Best kelp farming potential in the shallow sheltered southwest area of St. Helena Bay, in waters to 20m depth, St Helena port enables easy boat launch and harvest collection.** **West Coast ADZ might be feasible too, but wave energy here is somewhat higher.** **The exposed shore of the Saldanha ADZ might be less suitable, due to stronger waves and longer access routes from Saldanha or St Helena Bay. (The inner Saldanha Bay area will be assessed separately.)**

5.3 Cape Town to Cape Agulhas region

Figure 68 below displays the relevant aspects for the southern area. The conclusions drawn from the visual assessment of this map are summarized inTable 24. Figure 72 below delineates the three identified potential areas.

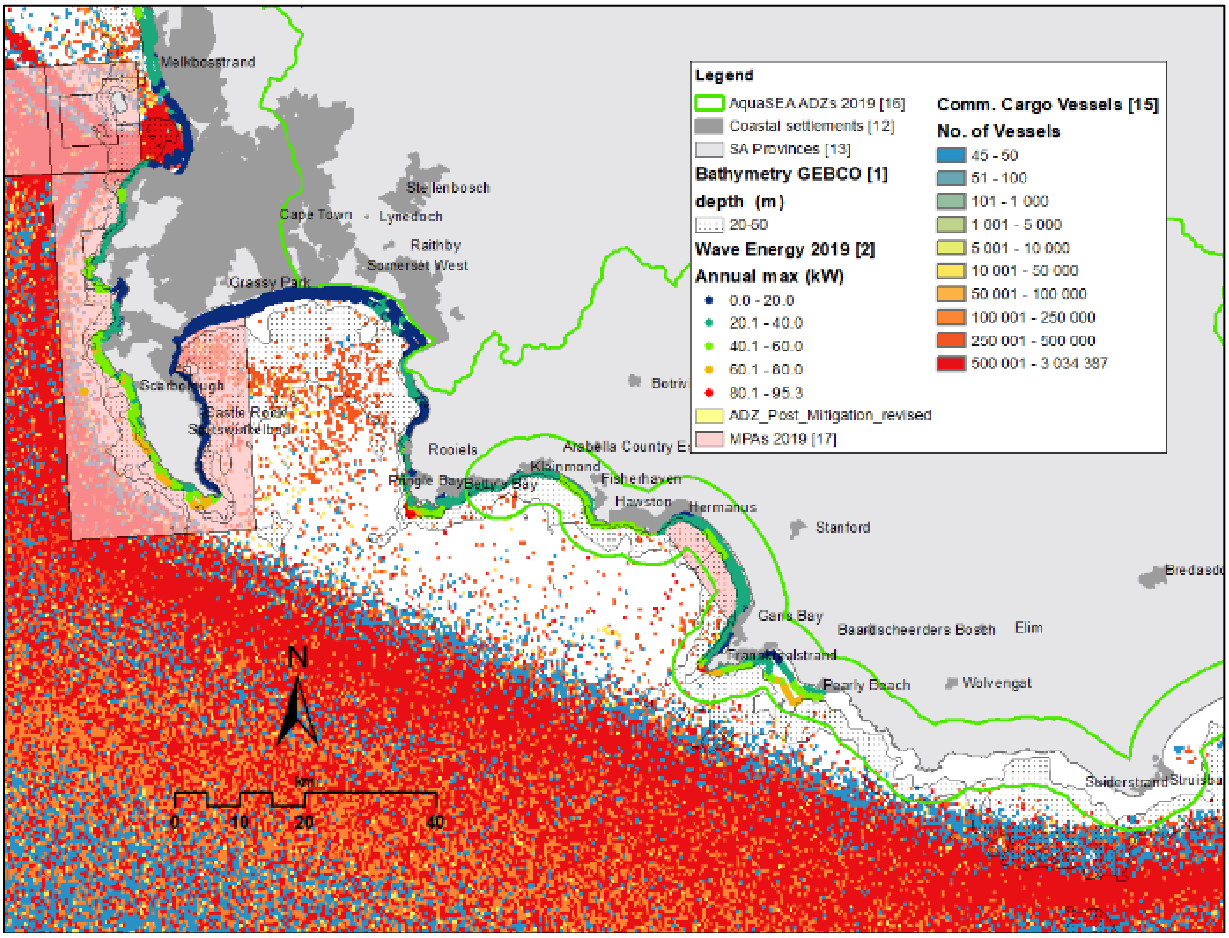


Figure 68: Water depth, cargo vessel traffic, MPAs and ADZs for the southern study area.

Table 24: Synoptic assessment for the southern study area

Aspect	Comments
Water depth & distance to coast	Extensive shallow areas in False Bay, with the 20m contour about 3-4km offshore and the 50m contour about 15km For the open shore southeast of False Bay, 20m contour between 0.5 and 4km offshore, the 50m contour about 3 – 15km offshore. The extensive areas less than 20m deep at Bettys Bay and between Franskraalstrand and Struisbaai do perhaps allow kelp farming in those areas too.
Wave energy	Very low to low in False Bay (mostly <20kW/h) low to moderate between bettys Bay and Gans Bay Low to moderate between Franskraalstrand and Pearly Beach (no data further east). However, high to very high wave energy around land tips between Pringle Bay and Bettys Bay at Danger Point and Cape Point
Vessel traffic	Very low in the potential kelp farming area on the open coast somewhat high in False Bay, however, the type of vessels here (touristic small vessels?) needs to be established
ADZs and MPAs	The whole of the Cape peninsula nd west of False Bay is MPA Entire Walker Bay is MPA Large Agulhas ADZ would enable kelp farming from Bettys Bay eastward False Bay not part of ADZ
Settlements	Simonstown and GordonsBay provide fishing infrastructure in False Bay, several well-established fishing and aquaculture facilities and towns between Pringle Bay and Pearly Beach to facilitate farming activities and provide market opportunities
Conclusion	**High potential for kelp farming between Bettys Bay and Hawston, southwest of Gans Bay and between Franskraalstrand and Pearly Beach, given high settlement density, low to moderate wave energy and extensive suitable depth zones. False Bay might be suitable, too, but is not designated ADZ.**

5.4 Location maps of potentially suitable sites

following four maps outline the areas that have been identified as potentially suitable areas for kelp farming in sections 5.1 to 5.3 above. In order to facilitate future discussions, preliminary names have been added to these ten areas.

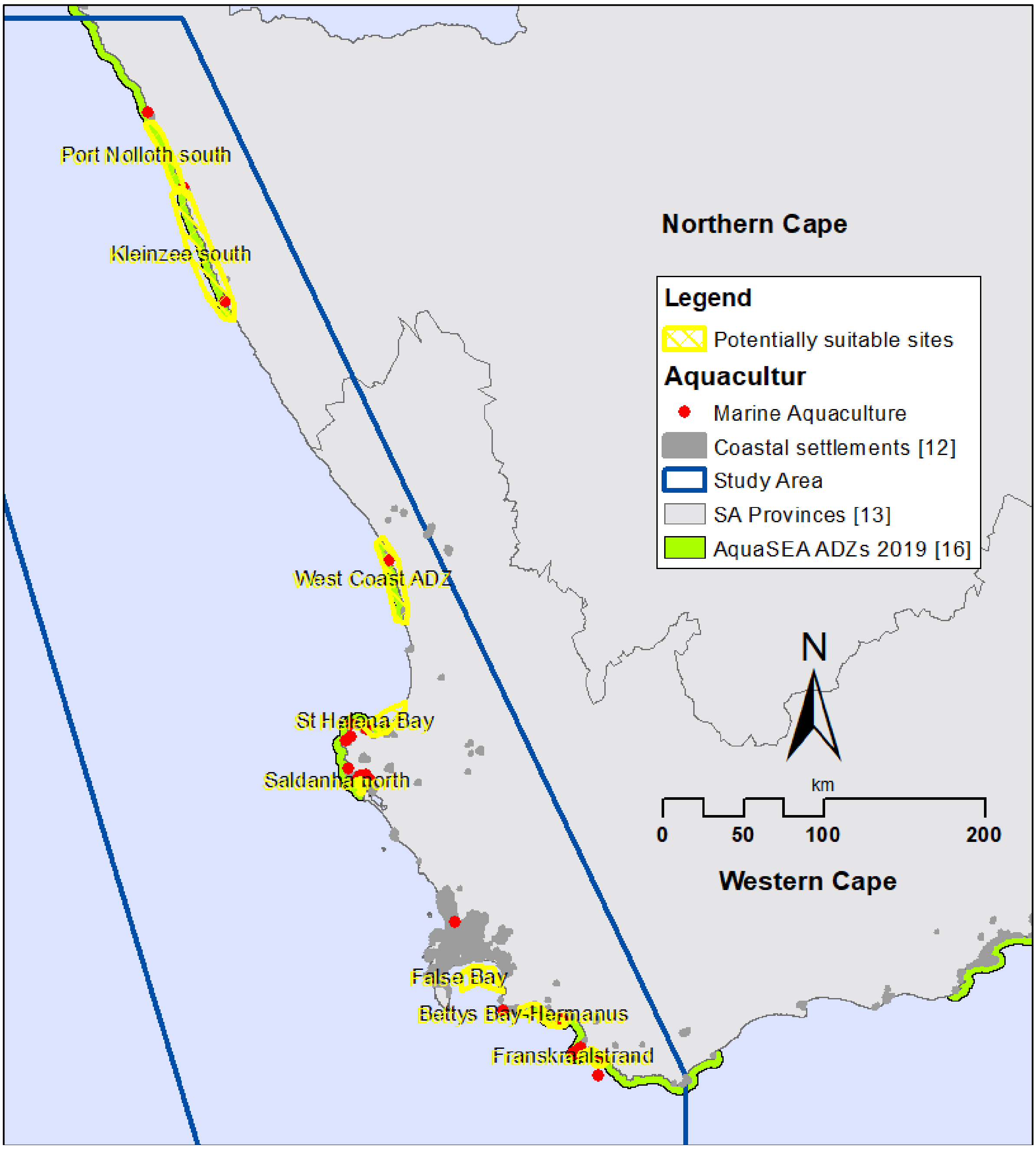


Figure 69: Location of potentially suitable kelp farming areas in the study area

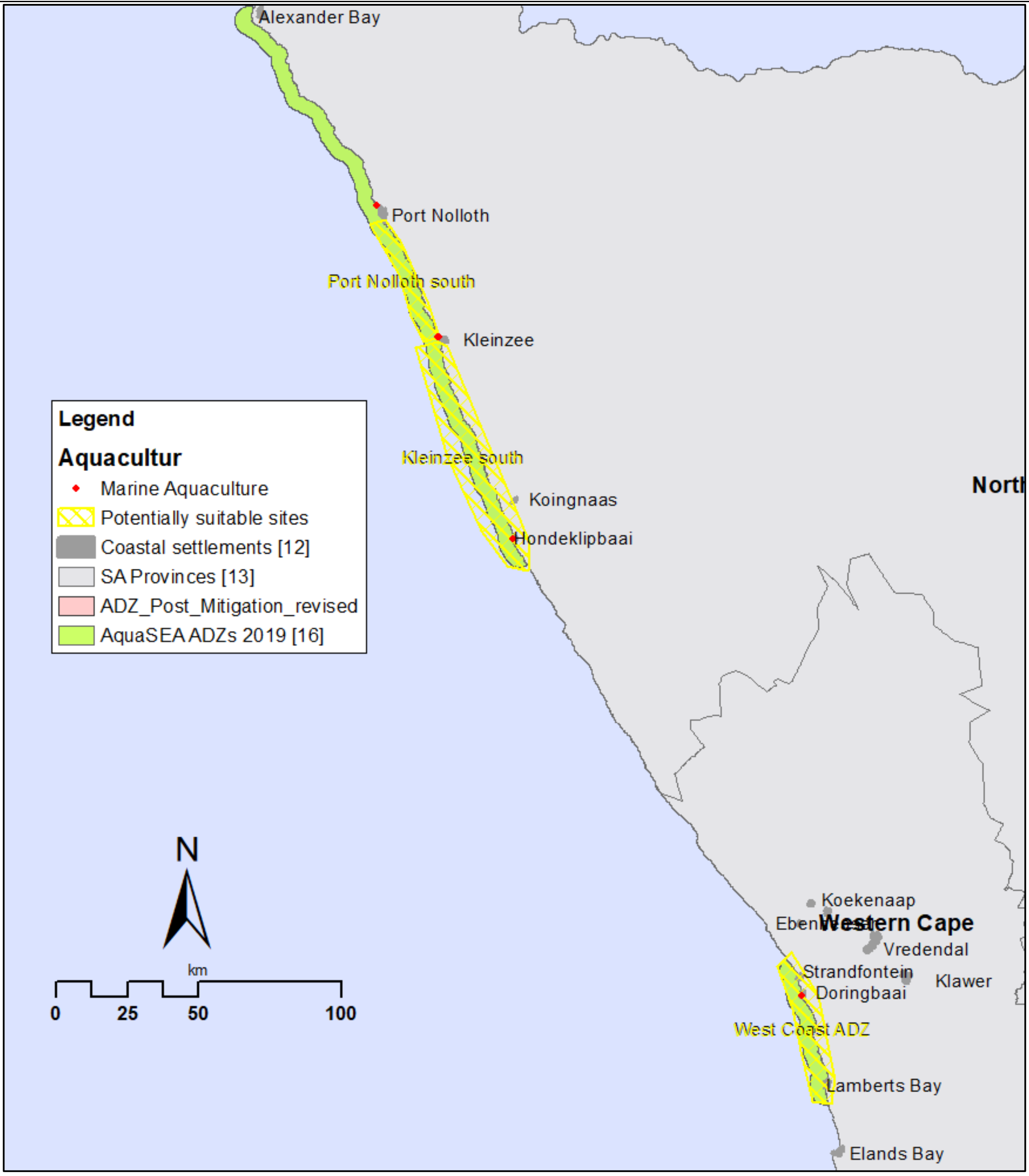


Figure 70: Location of potentially suitable kelp farming areas on the open west coast

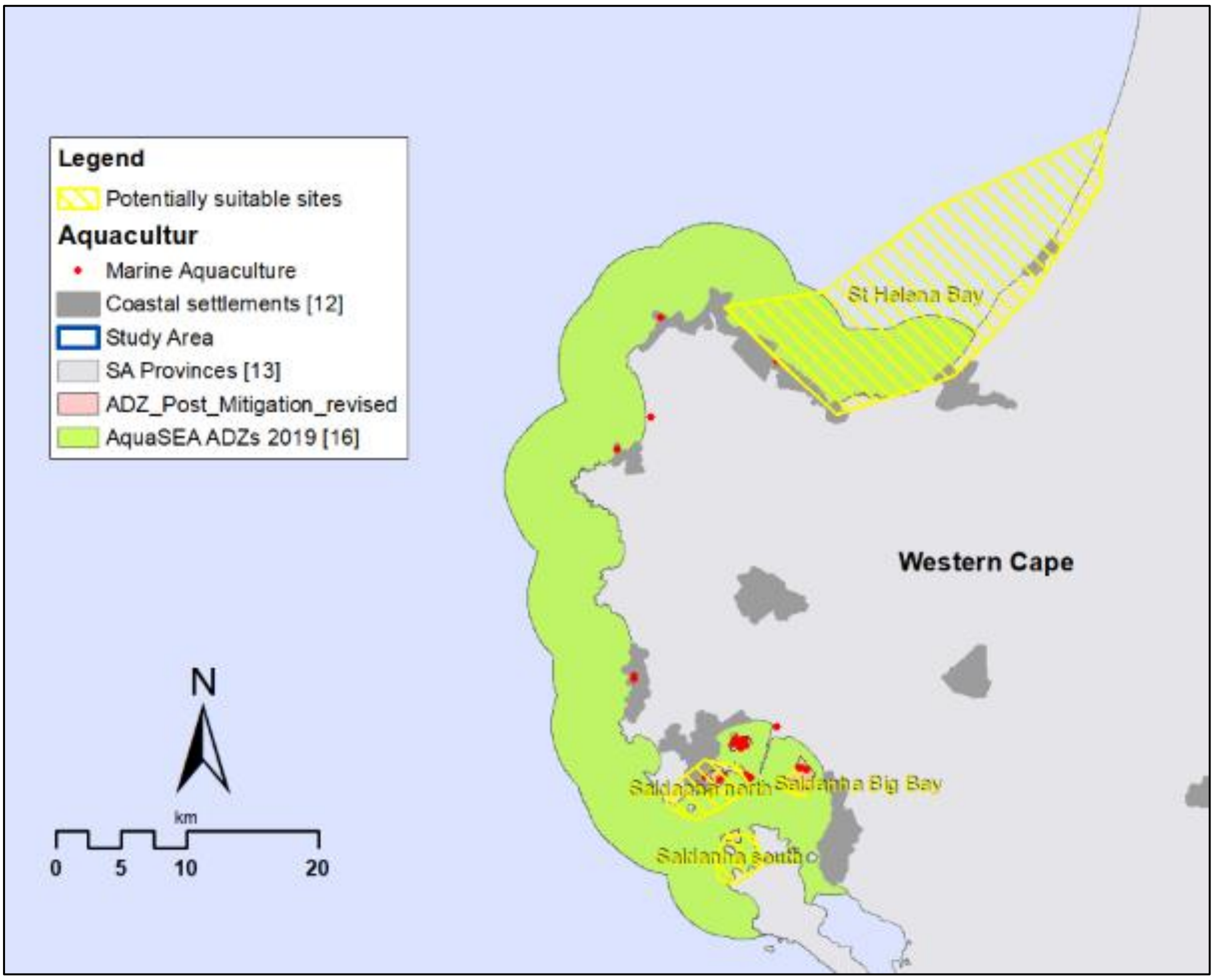


Figure 71: Location of potentially suitable kelp farming areas in the Saldanha – St Helena area

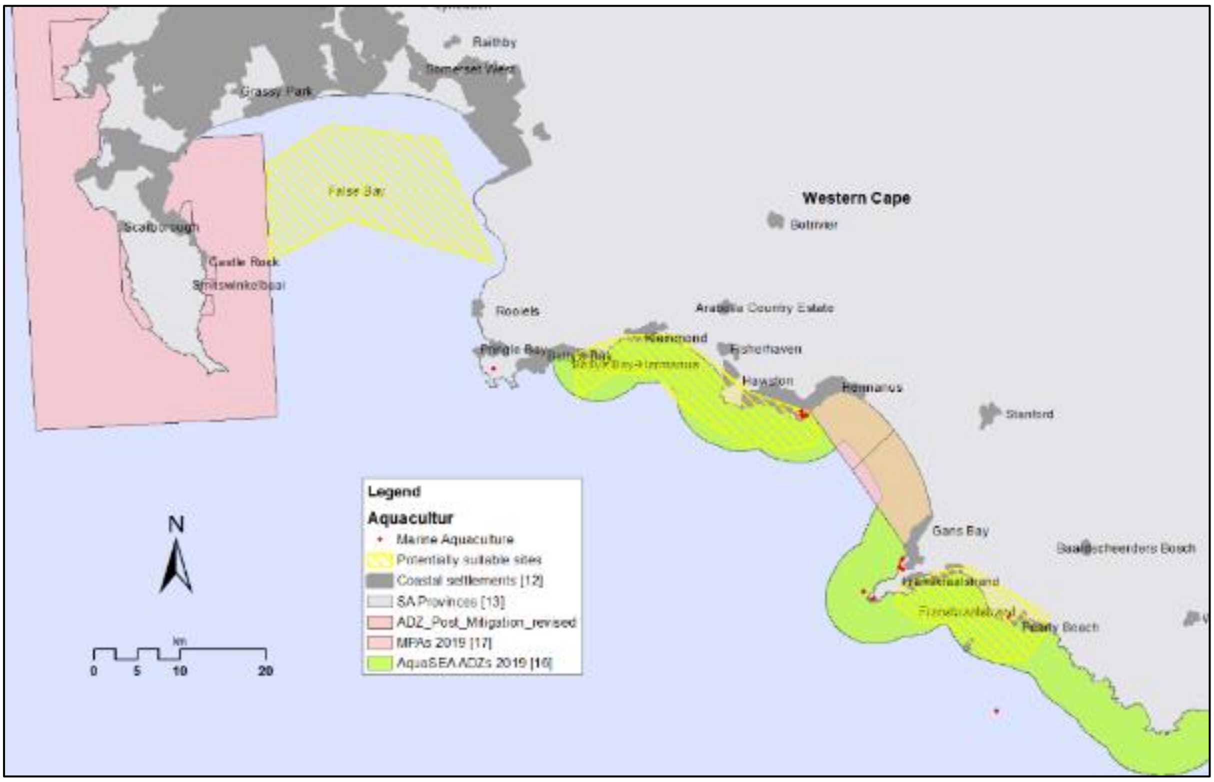


Figure 72: Location of potentially suitable kelp farming areas in the southern study area

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Dunga, L (2019). Mapping and assessing ecosystem threat status of South African kelp forests. MSc thesis in the Department of Biological Sciences, University of Cape Town, November 2019.

DEA & CSIR, 2020. The Department of Environment, Forestry and Fisheries and the Council for Scientific and Industrial Research (2020). National Coastal Assessment, Hotspot Detection Report, Final version 29 June 2020.

Appendix – Inventory of used GIS data

The number refers to the number in square brackets used in the text.

No.	Parameter	Notes/ GIS data source
4	SST mean	UN WCMC Ocean Data Viewer; https://data.unep-wcmc.org/datasets/36
1	Depth	GEBCO 2021 https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2021/
7	mean dissolved Oxygen	µmol/kg; Resolution = 1 degree (~100km) -- https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/
8	mean Nitrate	µmol/kg; Resolution = 1 degree (~ 100 km) -- https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/
9	mean Phosphate	µmol/kg; Resolution = 1 degree (~ 100 km) -- https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/
10	Salinity	Unitless; Resolution = 1/4 degree (~25 km) -- https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/
2	Wave energy (for rafts)	Wave power atlas for South Africa from 1 Oct 2019. Available from DFFE ***http://egis.environment.gov.za***
3	Current strength	No dataset available for this project
6	Turbidity	Development of RS screening tool for river plumes (unpublished). M. Lück-Vogel, CSIR Coastal Systems RG, 2017
11	Kelp forests	Dunga, L (2019). Mapping and assessing ecosystem threat status of South African kelp forests. MSc thesis in the Department of Biological Sciences, University of Cape Town, November 2019.
12	Coastal Settlements	BE stm dataset from GreenBook
13	SA Provinces	2011 Provinces_new, Municipal Demarcation Board
15	Vessel traffic	Fishing, Passenger, Leisure, Oil & Gas https://datacatalog.worldbank.org/search/dataset/0037580/Global-Shipping-Traffic-Density
16	AquaSEA ADZs 2019	Provided by Barend Stander from BSASA
17	MPAs	Provided by DFFE
18	Formal Protected areas	Provided by SANBI in 2018
19	Mining_licenses_CGS_2013_09	Mining_licenses_CGS_2013_09.shp Source: CGS 2018
20	Mining concessions	RSA_Marine_Concs.shp Source: DEA 2018
21	Existing aquaculture facilities	AquaSEA_facilities_2019.shp provided by CSIR EMS